<u>Nomination for 2012 Presidential Green Chemistry Challenge Awards Program</u>

Project: Vegetable Oil Insulating Fluid for Improved High Voltage Transformer Capability

Primary Sponsor: Cooper Power Systems

Submitted 12-31-2011

Contact Person: Kevin J Rapp, Senior Project Engineer, Cooper Power Systems, 1900 E. North Street, Waukesha, WI, 53188-3844.
kevin.rapp@cooperindustries.com Phone: 262-524-4421

Technical Contributors: Barbara C. Lippiatt from National Institute of Standards and Technology; Eugene Del Fiacco, John Luksich, C. Patrick McShane, Dwight Parkinson and Kevin J. Rapp from Cooper Power Systems

Financial Contributor: Cooper Power Systems

Project: Vegetable Oil Insulating Fluid for Improved High Voltage Transformer Capability

Most Recent Milestone: After surpassing 450,000 transformers filled with our patented vegetable oil based fluid and maintaining both US and Global leadership as a manufacturer of alternative insulating fluids, 2011 advancements in our fluid filled transformer technologies provided improved environmental and sustainable performance. Our vegetable oil based insulating liquid called Envirotemp™ FR3™ Fluid provided the increased capability in high voltage transformer design to remove as much as 15% of the fluid and 3% of other construction materials to make an already environmentally friendly product even better.

Eligible for Small Business or Academic Award: No

Identification of the EPA Award Focus Area: Vegetable oil based FR3 fluid and its use in high voltage transformers fit all three focus areas.

Description of US Components:

- Research & Development: 50% at Thomas A. Edison Technical Center, Franksville WI; 50% at Cooper Power Systems Transformer plant at 1900 E. North St, Waukesha, WI
- US Production Finished Product: Chicago IL and Wichita, KS. >98% biobased. Base of 100% US grown, crushed, and refined soy oil. Exported to over 2 dozen countries from the USA.

Abstract

Invented as a paradigm shifting vegetable fluid for electrical equipment and called the **"most successful niche-market biobased product in the world"** by the American Oil Chemists Society in 2008, Envirotemp FR3 fluid now insulates over 450,000 transformers [1]. In 2011, the chemistries of FR3 fluid and solid insulating paper were combined with advanced high voltage transformer design to produce an even greener product than earlier generation transformers.

The journey from concept, research and development, accelerated life testing and field trials to commercialization was motivated by a single goal: Provide the electric power industry a sustainable dielectric coolant with the most innocuous environmental and health profile possible. This goal was achieved with the use of over 25 million gallons of our trademark soy oil product Envirotemp FR3 fluid instead of petroleum based mineral oil.

FR3 fluid was directly compared to mineral oil by the NIST in their total life-cycle assessment called BEES® 4.0, Building for Environmental and Economic Sustainability Tech Manual and User Guide [2][3]. Using the carbon dioxide equivalent amount of greenhouse gas generated from raw materials through end of life, FR3 fluid reduced greenhouse gas emissions by >98% or over 102,000 tons to date compared to mineral oil. This essentially carbon neutral result for FR3 fluid compared to mineral oil assumes that either fluid would be placed in an equivalent transformer.

However, as the world leader in biobased transformer fluids, we established a new goal to further improve the environmental footprint of FR3 fluid filled transformers with a new generation of advanced design bio-transformers. The chemical interactions between FR3 fluid and the solid insulating structure create greater thermal capacity that allows for an optimized bio-

transformer design. With this increased capacity, we removed 3% to 15% of fluid volume and 3% of construction materials from the bio-transformers depending on the specific design. Using the BEES analysis on 25 million gallons of FR3 fluid as an example, the new generation of bio-transformers could save an additional 2,000 tons of greenhouse gas emissions.

Other important advantages of bio-transformers are improved fire safety, accidental spill remediation and sustainable supply benefitting US farmers.

The Chemistry of New Bio-Transformer Technology

The familiar slogan, “Tastes Great, Less Filling,” described a popular lite beer for the past thirty years. However, replacing one word to get “works great, less filling” would describe Cooper Power Systems Envirotemp™ FR3™ fluid combined with our new advanced design bio-transformer. The FR3 fluid filled transformer product transforms power to meet new Department of Energy efficiency ratings for their expected life, but with less fluid, less flammability, less size and less burden on the environment.

FR3 fluid is a soybean oil based fluid that was patented by Cooper to insulate and cool high voltage electrical transformers. Our on-going research and development program found that we could combine the chemistries of vegetable oil and insulating paper with advanced transformer design concepts to offer a new generation of bio-transformers. These would be an improvement upon the roughly 450,000 transformers that now contain FR3 fluid instead of petroleum based mineral oil. The new transformer designs with FR3 fluid will be available in 2012.

High voltage electrical transformers have contained predominately petroleum based mineral oil as the liquid insulation and coolant for well over one hundred years. Polychlorinated biphenyls (PCB) and mixtures with mineral oils share a portion of that history. PCB’s and fluids containing them were banned for environmental reasons. Mineral oil is a proven dielectric fluid and currently is the leading electrical insulating fluid, but does have safety and environmental drawbacks. FR3 fluid, made from greater than ninety-five percent soy oil, was invented to be a safer, non-toxic and environmentally friendly alternative insulating fluid compared to other common dielectric liquids as shown in Figures 1 and 2.

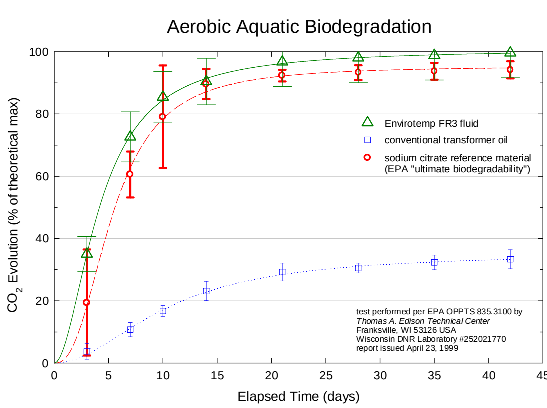

Figure 1: FR3 fluid compared to mineral oil

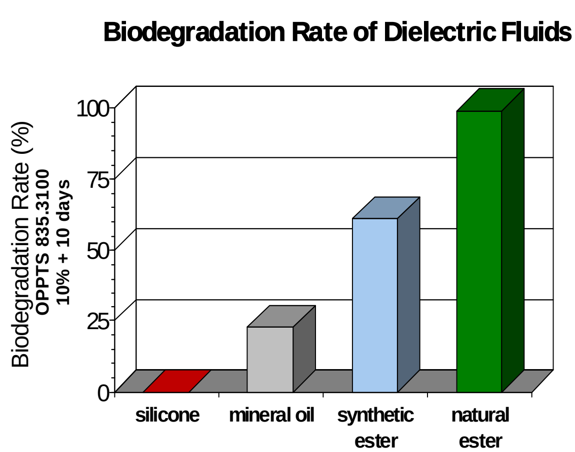

Figure 2: FR3 fluid compared to other oils

The advantage of FR3 fluid for high voltage transformers is not related to any complexities in the chemical formulation, but in its inherent functional properties (e.g. chemical stability, electrical performance, thermodynamic performance, material compatibility, and ignition resistance) and its interactions with cellulosic insulation structures while possessing improved environmental and sustainable qualities. FR3 fluid is manufactured from food grade soy oil and only small amounts of additives are required for long term performance.

FR3 fluid is a natural ester fluid otherwise known as a triglyceride. The chemistry relies on the carbonyl structure (O-C=O), long carbon chains, carbon-carbon double bonds and their position within the long chains. Esters are formed naturally from a reversible reaction of a long chain carboxylic acid and an alcohol as shown in Figure 3. The "R" groups vary in carbon chain length and numbers of carbon-carbon double bonds depending upon the particular type of plant or animal source for the triglyceride.

$$R - \overset{\overset{\displaystyle O}{\|}}{C} - OH \;+\; R^{I} - OH \rightleftharpoons H_2O \;+\; R - \overset{\overset{\displaystyle O}{\|}}{C} - O - R^{I}$$

Figure 3: organic acid + alcohol = water + ester

The reversible reaction in Figure 3 shows the ester plus water forming the original starting compounds. This reaction is known as hydrolysis, which provides FR3 fluid with its primary benefit toward maintaining the integrity of the solid insulation system of a high voltage transformer [4]. A build up of water in the insulating paper and pressboard structures of transformers causes accelerated aging of the cellulosic materials, reduced life and reduction in electrical strength. The basic structure of FR3 fluid and triglycerides are detailed in Figure 4A.

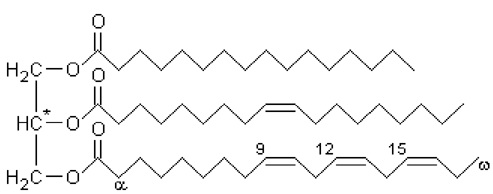

Figure 4A – Triglyceride

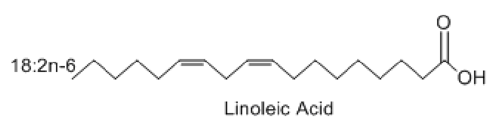

Figure 4B – Linoleic acid

The glycerol (alcohol) portion of the structure in Figure 4A is the three carbon chain at the very left-side of the molecule, highlighted by an asterisk at the central carbon. The three carboxylic acid types (known as R-groups) in Figure 4A consist of a sixteen carbon side chain of palmitic acid ester at the top, an eighteen carbon chain from oleic acid ester in the middle and an eighteen carbon chain from linolenic acid ester on the bottom. About 60% of "R-group" long chains of FR3 fluid consist of linoleic acid, which has eighteen carbons in length with two double bonds as shown in Figure 4B. The number of double bonds in the side chains relate to various fluid properties, such as viscosity, oxidation stability, cold temperature flow and biodegradability.

For a transformer, the fluid must function efficiently at high temperature with low viscosity and at low temperature by maintaining fluid flow. Thus, the higher levels of unsaturation of soy oil are important in the function of FR3 fluid. The R&D project to develop FR3 fluid included many compatibility studies to test interactions of the fluid with cellulose, such as paper and pressboard, rubber gasket compounds and various metals. After verification of acceptable compatibility, the aging characteristics of solid and liquid insulation materials required study. The weakest material links in a transformer are the cellulose paper, wood and pressboard insulation structures, which determine the ultimate life of a transformer related to increasing loads and high temperature operating conditions.

Our aging studies of cellulose and FR3 fluid provided surprising observations compared to the same studies in mineral oil [5][6][7][8][9]. Cellulose was observed to last from two to eight times longer in FR3 fluid than in petroleum mineral oil based upon multiple studies. Our research found that the protection of the cellulose in FR3 fluid increased with temperature up to a threshold, whereas in mineral oil cellulose ages rapidly. Figure 5 shows a dramatic comparison of papers aged in FR3 fluid compared to mineral oil. The contrast in the paper has been a consistent observation.

Figure 5: Thermally upgraded papers aged in FR3 fluid and mineral oil for varying times at 170°C

The chemistry of soy based FR3 fluid is responsible for the huge aging differential compared to mineral oil. Paper produces water as a by-product of thermal aging, which acts as a catalyst for continued degradation. Mineral oil is hydrophobic so the water stays in the paper. FR3 fluid is comparatively hydrophilic so the fluid will absorb water as it is produced. At room temperature, FR3 fluid can dissolve over 1000 mg/kg of water to become saturated compared to 60 mg/kg for mineral oil. However, the water saturation difference between the fluids is only partially responsible for the paper aging difference.

Hydrolysis of the soy oil is actually more important to the paper aging difference between FR3 fluid and mineral oil, especially as the temperature increases. As the dissolved water increases in the FR3 fluid with operating temperature, the hydrolysis reaction utilizes the water and acts as a dehydration process for not only the fluid, but more importantly for the paper. Less water in the paper promotes stability and longer life.

A further consequence of the hydrolysis reaction of FR3 fluid is the subsequent reaction of the long-chain carboxylic acid with cellulose. This reaction can be described as transesterification, which in a transformer is driven toward completion by high temperature and concentration of the acid. The reaction that takes place is between the hydroxyls attached to cellulose and the long-chain acids. The resulting product is stabilized cellulose with a bonded long chain that acts as a blocking group to protect the cellulose backbone [10][11]. Figure 6 depicts cellulose as a monomer, while the overall reaction is shown in Figure 7.

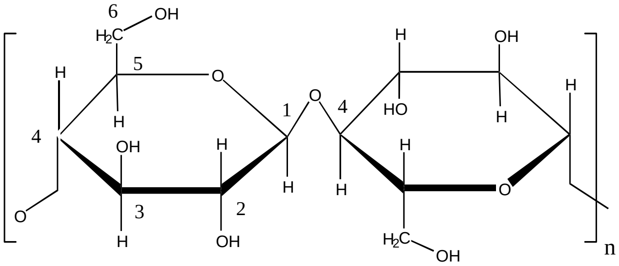

Figure 6 – Cellulose monomer unit of paper [6]

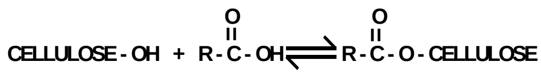

Figure 7 – Reaction of cellulose and long chain acid

Cellulose has three different hydroxyl groups that can react via transesterification. The predominant reaction is with OH on the primary carbon C6 as compared to the hydroxyls on the more stable secondary carbons at C2 and C3. A bonded long chain of eighteen carbons esterified at the primary C6 position offers increased stability to the cellulose insulation at higher operating temperatures. As can be visualized in Figure 6, the attached long chain at C6 will protect the main linkage at the 1-4 position.

As stated previously, FR3 fluid in transformers works great with less flammability and less environmental impact. Table 1 shows the greenhouse gases attributed to FR3 fluid compared to mineral oil for their complete life cycle.

Table 1. Greenhouse gases[a] attributed to transformer fluid for its complete life cycle.

	grams per unit[b]		tons per 1000 gallons	
Catagory	Mineral Oil	FR3 Fluid	Mineral Oil	FR3 Fluid
Raw materials	1,048,184	-381,590	2.306	-0.839
Manufacturing	544,363	160,212	1.198	0.352
Transportation	122,478	71,498	0.269	0.157
Use	154,124	153,450	0.339	0.338
End of Life	30,825	30,690	0.068	0.068
Total	1,899,973	34,260	4.180	0.075

[a] carbon dioxide equivalents
[b] In BEES 4.0e, one unit is a 1000 kVA transformer containing 500 gallons of fluid

The cost of mineral oil, in terms of carbon emissions, is considerably greater than FR3 fluid, about 8.2 lbs/gal less greenhouse gas emitted to produce FR3 fluid. In their Use and End of Life calculations, the BEES software makes some assumptions [3], such as reprocessing the oil in a transformer every five years, which may not apply to distribution transformers. Therefore, a more accurate assessment can be made by just subtracting the use value from the total, which makes FR3 fluid a net consumer of CO_2 (-0.263 tons per 1000 gallons). Figure 8 provides the carbon footprint comparison for each $1M of transformers purchased.

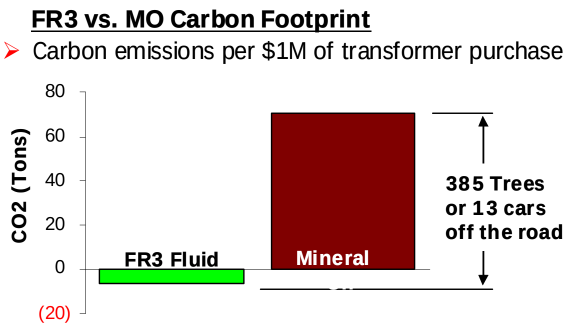

Figure 8 – Carbon footprint comparison

Figure 9 – Mineral oil power transformer fire

Electrical devices such as transformers sometimes experience high energy faults that can create hazardous conditions of fire and explosion, resulting in spills of insulating liquid. The use of petroleum based mineral oils as the most common electrical insulating fluid increases the probability of fire, explosion and spills. FR3 fluid greatly decreases the probabilities of fire and explosion resulting in spills, due to the relatively large sizes and stabilities of the molecular structures and long chain lengths. The inherent molecular stability is responsible for twice the flash and fire points compared to mineral oils. In fact, Envirotemp FR3 fluid has the highest flash and fire points of all common dielectric fluids. There have been no known explosions or fires of the 450,000 transformers filled with FR3 fluid.

The slogan, "works great, less filling" certainly describes Cooper Power Systems new advanced design bio-transformer filled with FR3 fluid. In fact, the newer transformers contain 3-15% less FR3 fluid volume and about 3% less construction materials than past designs. Table 2 shows the greenhouse gases attributed to production of solid transformer construction materials. A 3% reduction in material usage amounts to over 0.6 tons of CO_2 per ton of construction materials.

Table 2. Greenhouse gases attributed to production of transformer materials

Material	Tons of CO_2[a] per Ton of Material	Average	Reference
Aluminum	12		12,13
	13.9 – 15.5	13.35	17
Steel	1.36		15
	2.7		16
	2.3 – 2.7	2.19	17
Copper	7.1		14
	2.02	4.56	18
Paper	0.5		19
	2.34	1.42	20

[a] carbon dioxide equivalents

If we assume an equivalent amount of future success with our new advanced bio-transformer designs as we have to date with the roughly 450,000 transformers installed, the environmental future looks even brighter. The chemical interactions and higher thermal capacity of FR3 fluid in conjunction with the cellulose insulation paper allows for less fluid, less construction materials, less size, less flammability and, of course, less burden on the environment.

References:

US Granted Patents

- 5,766,517
- 6,037,537
- 6,184,459
- 6,352,655
- 6,485,659
- 6,613,250
- 6,726,857
- 6,905,638
- 7,524,440

Peer Reviewed Publications

1. Watkins, C., "Transforming the Transformer Industry", inform magazine, American Oil Chemists Society, August 2008 pgs 524-526
2. BEES, Version 4.0e, Building and Fire Research Laboratory, National Institute of Standards and Technology, August 2007, http://www.bfrl.nist.gov/oae/software/bees/
3. B.C. Lippiatt, "Technical Manual and Users Guide", BEES 4.0 Building for Environmental and Economic Sustainability, Office of Applied Economics, Building and Fire Research Laboratory, National Institute of Standards and Technology, U.S. Dept. of Commerce, August 2007
4. Lemm, A.W., Rapp, K.J., Luksich, J., "Effect of Natural Ester (Vegetable Oil) Dielectric Fluid on the Water Content of Aged Paper Insulation", EIA/IEEE 10th Insucon IEI Conf., Birmingham, UK, May 24-26, 2006
5. McShane, C.P., Gauger, G.A., Luksich, J., "Fire Resistant Natural Ester Dielectric Fluid and Novel Insulation System for Its Use," 1999 IEEE/PES T & D Conference & Exposition, New Orleans, LA, April 12-16, 1999
6. McShane, C.P., Rapp, K.J., Corkran, J.L., Gauger, G.A., Luksich, J., "Aging of Paper Insulation in Natural Ester Dielectric Fluid," 2001 IEEE/PES T & D Conference & Exposition, Oct. 28 – Nov. 2, 2001, Atlanta, GA
7. McShane, C.P., Rapp, K.J., Corkran, J.L., Gauger, G.A., Luksich, J., "Aging of Plain Kraft Paper in Natural Ester Dielectric Fluid," IEEE/DEIS 14th ICDL, July 7-12, 2002, Graz, Austria
8. McShane, C.P., Rapp, K.J., Corkran, J.L., Luksich, J., "Aging of Cotton/ Kraft Blend Insulation Paper in Natural Ester Dielectric Fluid," 4th TechCon Asia-Pacific Conf., May 8-9, 2003, Sydney, Australia
9. McShane, C.P., Corkran, J.L., Rapp, K.J., Luksich, J., "Aging of Paper Insulation Retrofilled with Natural Ester Dielectric Fluid," IEEE/DEIS International CEIDP, Oct. 19-22, 2003, Albuquerque, USA
10. Rapp, K.J., McShane, C.P., Luksich, J., "Interaction Mechanisms of Natural Ester Dielectric Fluid and Kraft Paper," Proceedings of 15th ICDL, Coimbra, Portugal, June 26 – July 1, 2005
11. Rapp, K.J., Luksich, J., "Reaction Rates of Paper Aged in Natural Ester Dielectric Fluid," 2001 IEEE/DEIS Conference on Electrical Insulation and Dielectric Phenomena," Oct. 14-17, 2001, Kitchener, Ontario, Canada
12. J. Harnisch, I.S. Wing, H.D. Jacoby, and R.G. Prinn, "Primary Aluminum Production: Climate Policy, Emissions and Costs", Report No. 44, Joint Program on the Science and Policy of Global Change, December 1998, MIT, http://web.mit.edu/globalchange/www/rpt44.html
13. R. Huglen and H. Kvande, "Global considerations of aluminum electrolysis on energy and the environment", Light Metals 1994, 373-380
14. Sustainable Development Report, Kennecott Utah Copper, 2004, http://www.kennecott.com/library/media/papers/pdf/sustainableDevelopment2004.pdf
15. "CO2 Monitoring in the Steel Industry", Energy Management, Technology and Research, Stahl-Zentrum, http://www.stahl-online.de/english/research_and_technology/power_and_environmental_technology/.asp
16. T. Jamieson, "Voluntary Agreements to Limit Carbon Dioxide Emissions", Energy Management of New Zealand, 1996, http://www.ema.org.nz/publications/papers/jamieson1996.pdf
17. "Life Cycle Greenhouse Gas Emissions Study Reveals No Conclusive Evidence That Aluminium-Intensive Vehicles Reduce Greenhouse Gas Emissions", World Auto Steel, Automotive Group, International Iron and Steel Institute, 2006, http://www.ulsab.org/article200610102006b.html
18. Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks, 3rd Edition, US EPA, 2006, http://www.epa.gov/climatechange/wycd/waste/downloads/chapter2.pdf
19. "Draft Project Design Document, Paper Factory Stambolijski Joint Implementation Project, Biomass and Energy Efficiency Project", TÜV SÜD Industrie Service GmbH, 2004, http://www.netinform.de/KE/files/pdf/PFS%20JI%20PDD%20Final%20040930.pdf
20. "Life Cycle Inventory of Packaging Options for Shipment of Retail Mail-Order Soft Goods - Final Peer-Reviewed Report", Frankling Associates for Oregon Department of Environmental Quality and U.S. EPA Environmentally Preferable Purchasing Program, April, 2007, http://www.deq.state.or.us/lq/pubs/docs/sw/packaging/LifeCycle02.pdf