Some Considerations for New and Retrofill Applications of Natural Ester Dielectric Fluids in Medium and Large Power Transformers -REVISITED-

S. P. Moore, *Senior Member, IEEE*

***Abstract*—Waukesha Electric Systems has been actively involved in exploring and developing the application of natural ester dielectric fluid in medium and large power transformers in both new and retrofill applications. Initial applications of this material have primarily been to take advantage of the fire safety properties it offers. Many of the initial retrofills have been in power generating plants. There are now a significant number of transmission inter-tie, distribution and industrial installations. Environmental biodegradability has been the second major reason for use of this material. The slower aging rate of cellulose insulation in natural ester fluid has become an attractive attribute. The significantly reduced carbon footprint of natural ester fluid versus mineral oil will likely become another highly desirable attribute. Application consideration for use with de-energized tap changers, load tap changers and forced oil pumps will be discussed. Application considerations of higher viscosity, higher oil temperature rise and transformer ratings will be discussed. Application in mobile transformers will be discussed.**

***Index Terms*—Natural ester dielectric fluids, retrofill, generator step-up transformer, unit auxiliary transformer, station service transformer, excitation transformer, mobile transformer, fire safety, environmental biodegradability, slower aging rate of cellulose insulation.**

I. Nomenclature

Natural ester insulating fluids are dielectric coolants whose base is derived from vegetable oils. Retrofills are transformers that were originally manufactured and filled with mineral oil and that are subsequently drained and filled with alternative fluids such as natural esters. Less- flammable high flashpoint oils refer to a class of insulating oils that have flashpoints in excess of 300 C. Tapchangers are multiposition switches that are intended for connecting alternative winding taps in power transformers, to obtain desired voltage ratios. Tapchangers for de-energized operation are designed for switching connections only when the transformer is de-energized. Load tap changers are designed for switching when the transformer is energized and carrying full load.

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S. P. Moore is with Waukesha Electric Systems, Waukesha, WI 53186 USA (e-mail: steven.moore@waukeshaelectric.spx.com).

II. Introduction

THIS document will revisit several application considerations of natural ester based fluids in power transformers that were discussed in the original version of this paper presented in 2006. There has been ongoing laboratory experimentation and field experience that will add to the value of the original paper. Application at power generating plants has been primarily to take advantage of this material's fire safety properties. Application in mobile transformers will be discussed as it seems a good fit for all of the beneficial properties that natural ester dielectric fluids have over mineral oil, these being 1) fire safety, 2) environmental biodegradability 3) slower rate of aging of cellulose insulation and 4) reduced carbon footprint. Natural ester dielectric fluids appear to be more stable than mineral oil and silicone for use with de-energized tap changer materials in common use today. Some possible solutions for application in load tap changers will be discussed. Forced oil pumps would normally be addressed in a new transformer application due to the materials higher viscosity and should be addressed in a retrofill application to insure the pumps function as expected.

III. Application of Natural Ester Fluid Filled Transformers

A. De-rating or re-rating of power transformers after retro-filling with natural ester dielectric fluid

The author's company has taken the position that mineral oil filled transformers can be retrofilled with natural ester fluids and even thought they will run hotter than with mineral oil, the slower aging rate of the cellulose insulation in natural ester fluid will allow the cellulose to last longer in the hotter natural ester fluid than when operating in the cooler mineral oil. This position is taken based on the work described in a paper by C. P. McShane [1] of Cooper Power Systems which describes how cellulose insulation can operate at 21°C higher temperature rise in natural ester dielectric fluid and have the same loss of life as cellulose insulation operating in mineral oil. New test data discussed in the *Temperature Rise* section of this paper will add further details supporting the premise that the temperature rise of the retrofilled unit will likely be less than 21°C hotter.

B. Generating station transformers

Since the original version of this paper there have been a number of generating station transformers that have been retrofilled with natural ester fluid or built new with natural ester fluid. One large utility in the Midwestern United States has been systematically retrofilling their generator step-ups, station service and unit service transformers with natural ester fluid primarily for fire safety and life extension reasons. These have been mainly at thermal power stations. As of the last writing the largest size unit retrofilled to date has been a 200 MVA generator step-up transformer with a high voltage rating of 161 kV. Since then a new generator step-up transformer has been built rated 212 MVA with a high voltage rating of 230 kV.

Factory Mutual Global [2] has rated Natural Ester as a less flammable fluid. As such, they allow a transformer filled with this material to be located nearer to buildings without the use of deluge systems or firewalls to protect the building. There have been some cases where fire suppression did not exist and the utility's insurance carrier insisted that fire suppression be installed. Generally the options were a deluge system, fire wall(s) or both or retrofill with a less flammable fluid such as a natural ester based fluid. In the situations that the author is aware of, retrofilling with a natural ester based fluid was the most economical and expeditious method to achieve the desired fire safety. In one case the retrofilling option was about half of the deluge system / firewall cost estimate. Since the last writing of this paper, Factory Mutual Global has revised their Property Loss Prevention Data sheets describing the shorter distances allowed for transformers filled with a less flammable fluid between these transformers and various buildings of various construction and also between transformers. These shorter distances can save considerable money in real estate when designing a new station or adding more equipment to an existing station.

C. Application in mobile transformers

Mobile transformers are expected to be a good application for natural ester dielectric fluids, as they would benefit from all four major attributes of these fluids. Mobile transformer designs often sacrifice cellulose insulation life due to higher operating temperatures, in an effort to get the transport size and weight down. It is not uncommon for a mobile transformer to be designed with a 75°C top oil temperature rise. This higher operating temperature will reduce the size and weight of the transformer. However, this higher operating temperature will also significantly shorten the life of the cellulose insulation. Extended insulation life would seem the primary benefit of retrofilling a mobile transformer with a natural ester dielectric fluid but the other two fluid properties may also be significant for this application. The high environmental biodegradability could be beneficial in the event of a leak where insulating fluid can be spilled on the ground especially when moving. Mobile transformers get moved far more than normal transformers and may be more susceptible to leaks due to this duty cycle. As a mobile is typically used for emergency power restoration, they may be operated with less oil containment capability than permanent transformer applications. Also as emergency equipment, mobiles may be operated closer to other equipment increasing risk if it caught fire.

It is common for some Nomex® to be used in these higher temperature mobile transformers. The author is not aware of any test data for Nomex paper life in natural ester fluids so there may not be any life extension of this material. However it might be advantageous to use cellulose in some areas like radial spacers with natural ester fluids. Also non-cellulose materials might be replaced with lower cost pre-compressed cellulose board.

D. Application at hydroelectric power generation plants

It is not uncommon for Generator step-up transformers at hydroelectric generating plants to be located on the backside of the dam directly over the water. As many of these dams existed before current oil containment rules came into being, sufficient oil containment may be difficult if not impossible due to tight physical constraints. This would seem a natural application for natural ester dielectric fluids considering their high biodegradability and significantly lower toxicity levels to fish.

Natural ester fluids have been tested for biodegradability and can be classified in the most favorable EPA classifications of "ultimately biodegradable" and "readily biodegradable" [3, 4]. The natural ester fluids have also been tested for acute aquatic toxicity with zero trout mortality through the standard test period of 96 hours at 1000 mg/kg [5, 6]. If a leak were to occur on a transformer mounted on or in a dam, the oil might well enter the surrounding waterway. This could cause significant environmental harm, high cost of clean up and unfavorable public relations. Retro-filling these transformers with natural ester dielectric fluids would seem to lessen these ill effects.

E. Considerations for forced oil pumps

Some medium and large power transformers use electrically driven pumps as part of the cooling system to force the oil to flow faster. Typical natural ester based fluids have a higher viscosity than does mineral oil. In a new transformer design application, the pump designer would take this higher viscosity into account when selecting the appropriate pump for the application. When considering retrofilling a transformer that has forced oil pumps, the rating of the pump and motor need to be reviewed to determine if they will function properly when operating with a more viscous fluid. There has been concern expressed about cold starting units with forced oil pumps with natural ester fluids trying to pump a gel or causing cavitation. To the author's knowledge, these units have been pre-heated prior to energization to eliminate this issue. More study needs to be done in this area.

F. Considerations for de-energized tap changers

In an IEEE paper presented by Larry Dix and Phil Hopkinson in 2005 [6], these authors test data show that silver-silver, silver-copper and copper-copper contact pairs as might be found on de-energized tap changers did not have appreciable temperature rise or resistance rise when subjected to an accelerated life test in natural ester fluid. Similar tests were also performed in mineral oil and silicone oil but with different, typically less favorable results.

G. Considerations for Load Tap Changers

Many load tap changers in service today and available on new power transformers are housed in free breathing compartments. There is typically a dehydrating breather at the point the compartment opens to the atmosphere so that the dehydrating material (typically silica gel) removes a significant amount of moisture from the air before it enters the LTC in an attempt to keep the insulating oil dry. The primary reason that these compartments are normally free breathing is to allow arcing gasses created during a tap change operation to escape. Natural ester dielectric fluids have a higher rate of oxidation than does mineral oil and will slowly polymerize if left exposed to the atmosphere. This is one of two reasons that natural ester dielectric fluids have not been applied to free breathing load tap changers.

A solution for this would be to use an on-site nitrogen generator and bleed a small amount of nitrogen continuously across the gas space of the tap changer. This would serve to exclude moisture, exclude oxygen and also to sweep away arcing gasses that partition into the gas space. Even some vacuum type tapchangers use shunt contacts around the vacuum interrupters so there may still be some arcing gasses generated that should be vented.

The second reason natural ester fluids have not been employed in load tap changers has been the higher viscosity of natural ester fluids, particularly at colder temperatures. The author's company has conducted tests on the load tap changer it makes and found that the switching time was unchanged until the temperature of the natural ester fluid got near the pour point of -18°C. Limiting tap changer operations below -10°C would seem a prudent measure. One way of doing this would be to use a thermal sensor to block operation of the load tap changer below -10°C but then the regulation benefits of the tap changer are lost. Another strategy would be to heat the fluid to keep it above this temperature thus preserving the regulation functionality. At least one company is testing this method.

H. Temperature Rise

The previous paper stated that the author's company made a series of temperature rise calculations for dozens of existing designs of power transformers. The range of temperature rise differentials between mineral oil and natural ester fluid was a low of 1 °C and a high of 20 °C with the natural ester fluid design always being higher than the mineral oil design. Typically the natural ester fluid designs had a 5-10 °C higher rise than did the same design assuming mineral oil in the calculation.

Table 1

TEMPERATURE RISE TEST

TOP LIQUID TEMP °C	BOTTOM LIQUID TEMP °C	AVE LIQUID TEMP °C	AVE WINDING RISE HV °C	AVE WINDING RISE LV °C	CALC HOTTEST SPOT RISE °C
109.6%	82.9%	102.4%	110.5%	112.4%	
115.6%	73.2%	107.8%	111.8%	115.2%	110.9%

The author's company tested 4 transformers with mineral oil and then retrofilled the transformers with natural ester fluid and reran all of the tests. The results of the temperature rise tests are summarized in Table 1. The top row of data is for the base rating of the transformer and the bottom row of data is for the maximum nameplate rating. The data show the natural ester test value as a percent of the mineral oil test value with 100% being the same as.

As was expected, all of the temperature rises were hotter with natural ester fluid than with mineral oil with the exception of the bottom oil temperature being lower. The hypothesis is that the higher viscosity of natural esters causes a slower flow rate of the fluid so it spends more time in the radiators and is cooled to a lower temperature. All of the tested values aligned closely with the calculated values. In the above table, the hottest spot rise shows as being less than the average winding rise but this is in percent increase. In all cases the hottest spot temperatures in °C were higher than the average winding rise.

I. Capacitance

Manufacturers and users of transformers filled with natural ester dielectric fluids should be aware of the differences in transformer parameters due to the inherent differences between mineral oil and natural ester dielectric fluids. My previous paper stated that the winding capacitance would likely measure higher with natural ester dielectric fluids than with mineral oil and that there was not a large enough data sample size to accurately state anticipated capacitances but increase in the 5% to 50% range would not be surprising. Table 2 below summarizes data from factory tests made on 4 different transformers first filled and tested with mineral oil and then filled with natural ester fluid and retested. The data is expressed as the natural ester test value divided by the mineral oil test value with 100% being same as. The data show that the increased capacitances were within the 5% to 50% greater range as expected.

Since the change in the dielectric constant affects both the series capacitance and the ground capacitance of the coil, the higher dielectric constant of the natural ester is not expected to change the ratio of these capacitances. Therefore the overall impulse voltage distribution of the coil using the natural ester is expected to be similar to the voltage distribution with mineral oil. Impulse tests conducted with natural ester fluids were all successful suggesting that there was not a negative consequence of these higher capacitances but this data cannot be used to prove that there was a positive consequence to these higher capacitances.

Table 2

CAPACITANCE

HV-LV+GRD pF	HV-GRD, LV GUARD pF	LV-GRD+HV pF	LV-GRD, HV GUARD pF
124%	114%	124%	122%

J. Insulation Dissipation Factor

The previous paper suggested that the insulation power dissipation factor would be higher with natural ester fluid than with mineral oil. In fact, the data of two field tests did have higher values when tested a couple of months after the initial retrofill with natural ester fluid. The data shown in Table 3 is for 4 units tested at a factory first with mineral oil and then with natural ester fluid. This data shows that the insulation power dissipation factor did not change after retrofilling with natural ester fluid and went down slightly in those tests with guard. A hypothesis about this is that the mineral oil is retained in the paper after a retrofill and these tests are stressing the conductor wrap insulation with predominantly mineral oil content. Thermal cycling will heat the mineral oil in the paper causing it to expand out into the bulk fluid. As the paper cools it will pull in the bulk fluid at a much higher concentration of natural ester fluid and after some amount to thermal cycling, the fluid in the paper will be of the same mineral oil concentration as the bulk fluid. After some amount of thermal cycling it is still expected that the power dissipation factor will still increase above values with mineral oil.

Inherently higher power factor is neither good nor bad, it is just different. Higher dielectric loss may actually improve the transformer's ability to absorb and damp high frequency transients.

Table 3

INSULATION POWER FACTORS

HV-LV+GRD	HV-GRD, LV GUARD	LV-GRD+HV	LV-GRD, HV GUARD
100.0%	82.4%	100.0%	84.8%

J. *Insulation Resistance*

My previous paper stated that the insulation resistance of natural ester fluid was about an order of magnitude lower than mineral oil. Table 4 summarizes the factory test results on 4 transformers as being lower with natural esters but not as much as previously thought. The volume resistivity for one brand of natural ester fluid is in the range of 1-5 x 10^{13} ohm-cm versus 1-5 x 10^{14} ohm-cm for mineral oil. The data in Table 4 is within this range. This data is expressed as the tested value in natural ester fluid divided by the tested value in mineral oil with 100% being same as. Again, this doesn't mean it is good or bad, it is just different and may prove to be beneficial to high frequency damping performance as stated above. In addition, some experts have theorized that this lower d.c. resistance can reduce the risk of static electrification developing. Both phenomenon need more investigation and are beyond the scope of this paper.

Table 4

INSULATION RESISTANCE

HV+LV-GRD MΩ	HV-LV+GRD MΩ	LV-HV+GRD MΩ
19%	17%	23%

K. *Dissolved Gas Analysis*

This very useful diagnostic tool for assessing the condition of mineral oil filled transformers is also a useful tool for natural ester dielectric fluid filled transformers. The key gas analysis as described in ANSI C57.104 [3] is still valid for use with natural ester dielectric fluid filled transformers. For example a DGA showing acetylene is still indicative of a high-energy discharge and likely to be a problem that should be investigated further.

There are different gas ratios used to help distinguish among different possible causes of gas generation. Unfortunately, these ratios are not calibrated for natural ester dielectric fluid filled transformers due to the different rates of gas generation and gas solubility and should not be used in their present form. There is currently an EPRI study being conducted that will provide gas generation rates for the different modes of failure that will be provided to the IEEE Transformers Committee for use in recalibrating these ratio methods for natural esters.

L. *Dew Point to Moisture Content of Paper Conversion*

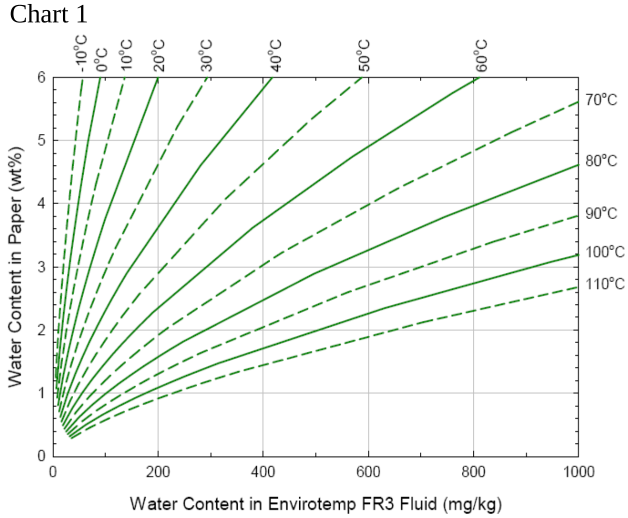
It is common practice to check the dew point of a sealed transformer that has been empty of oil for some time. Knowing the dew point and temperature of the gas in the empty sealed transformer, one can use this data to estimate the relative humidity of the gas in the drained transformer. While various conversion charts are available to estimate the surface moisture content of the cellulose insulation, the charts are based on mineral oil impregnation. These conversion charts are not presently calibrated for natural ester dielectric fluids and should not be used. However, we do expect that the same levels of relative humidity for transformers containing a natural ester are acceptable if the transformer contained mineral oil. This is another area where additional research is needed.

M. *Moisture Content of Liquid to Moisture Content of Paper Conversion*

This means of estimating moisture content in paper is similar to the paragraph above describing the dew point to moisture content in paper conversion. A method used to determine the moisture content of paper in transformers that are filled with mineral oil is to take a sample of oil and determine the content of water in the oil. Various charts have been devised to estimate moisture content in paper knowing the temperature at which the oil sample was taken and the moisture content of that oil. There tends to be significant variability among the different charts that have been developed for this purpose. Ideally the oil sample should be taken when the temperature of the transformer is stable and above 50°C.

Chart 1 below was produced by Cooper Power Systems and shows the water content of the paper if the water content of the natural ester fluid and its temperature are known. This chart is as useful as similar charts for mineral oil and also temperatures below 50°C are suspect of significant error.

Chart 1



N. *Moisture Content in Natural Ester Dielectric Fluids*

The author believes that natural ester fluids can be used to dry out the paper insulation in a transformer. The natural ester fluid holds several times more water in solution than does mineral oil. A paper presented by C. P. McShane [1] describes this attribute further. However 99% of the water in a transformer is in the paper so even if the fluid holds 10 times more water than mineral oil, there is still a very significant percentage of the water in the paper.

Once the water has migrated from the paper to the natural ester fluid, hydrolysis will form new long chain fatty acids from this water and the natural ester fluid. The water is now locked up in these new compounds and unavailable to go back into solution in the fluid or back into the paper. The fluid now has less moisture and will draw more water out of the paper. This process seems to continue until a very low level of moisture is left in the paper.

Additionally, a process called transesterification is where these long chain fatty acids bond with the OH groups in the glucose ring of the cellulose. This reduces the probability that these OH groups will bond with a detrimental compound such as water that might cause the chain to break at that point causing shorter cellulose chains which have less tensile strength.

O. *Design Considerations for New Power Transformers*

The author's company has approved one supplier's brand of natural ester dielectric fluid for use in any transformer we make.

This material has some better dielectric properties than mineral oil. Also, the dielectric constant of natural ester dielectric fluids is closer to that of paper thus lowering the dielectric stress level at the paper / liquid interface. For these reasons, the dielectric designs used are directly suitable for use with natural ester dielectric fluid.

Thermally there are two options when new transformers are bid. One option is to make a design wherein the 65°C top oil and 80°C hottest spot temperatures are met assuming the thermal characteristics of natural ester fluid. A second option is to make a design assuming mineral oil as the dielectric coolant but filling the transformer with natural ester fluid. This design will have operating temperatures that may exceed the mineral oil temperatures. The OEM should have a good thermal design program that will make accurate calculations of temperature with natural ester fluid and can advise what these higher temperatures will be. If you want a temperature rise test to be performed, you must so specify.

P. *Low Carbon Footprint*

NIST the National Institute of Standards and Technology developed BEES® 4.0 (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability) [8] which is a carbon footprint calculator. Using this tool, NIST calculated the amount of carbon dioxide or carbon dioxide equivalents of other gasses, released into the atmosphere for both naphthenic based transformer mineral oil and for Cooper Power Systems Envirotemp® FR3® dielectric fluid. The carbon footprint was calculated to produce a gallon of mineral oil including carbon contributions due to crude oil extraction, refining, transportation, use and disposal. A similar calculation was made for Envirotemp FR3 dielectric fluid including growing of soybeans, manufacturing, transportation, use and disposal. As can be seen from the chart below, the natural ester fluid has a much smaller carbon footprint than does mineral oil. This is primarily a function of soybeans absorbing carbon dioxide as they grow. For those interested in lowering their carbon footprint, purchasing natural ester fluid instead of mineral oil would seem an easy choice.

Table 5 [8]

Note: Lower values are better

Category	MineralOil	Envirotemp
1. Raw Materials	1048184	-381590
2. Manufacturing	544363	160212
3. Transportation	122478	71498
4. Use	154124	153450
5. End of Life	30825	30690
Sum	1899973	34260

IV. References

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[2] FM Global Property Loss Prevention Data Sheet 5-4, "Transformers", January 2007.

[3] "Aerobic Aquatic Degradation," OPPTS 835.3100, "Fate, Transport, and Transformation test Guidelines, "EPA Publication 712-C-98-075, Office of Prevention, Pesticides, and Toxic Substances, US Environmental Protection Agency, January 1998.

[4] "Ready Biodegradation," OPPTS 835.3110, "Fate, Transport, and Transformation test Guidelines, "EPA Publication 712-C-98-076, Office of Prevention, Pesticides, and Toxic Substances, US Environmental Protection Agency, January 1998.

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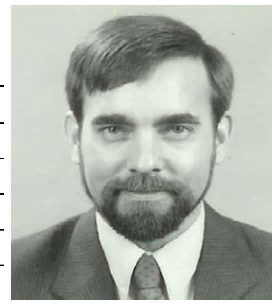
[10] The Environmental Technology Verification Program (ETV), U.S. Environmental Protection Agency and California Environmental Protection Agency, ETV Joint Verification Statement, Technology Type: Vegetable oil-based insulating dielectric fluid, Application: Vegetable oil-based insulating dielectric fluid for use in electrical apparatus requiring a liquid dielectric coolant, Technology Name: Envirotemp®FR3™ Insulating Dielectric Fluid, VS-R-02-02, June 2002.

V. Biography



Moore, Steve was born in Wilmington, Delaware in 1952. He graduated from the Milwaukee School of Engineering in 1974 with a B. S E.T.-E. degree. He has also attended month long management seminars at the Schools of Business of the University of Wisconsin, Madison and the University of Southern California. His employment experience has all been with Waukesha Electric Systems and all of it's previous company names. He spent 26 years in new transformers in various marketing capacities including Sr. Application Engineer, Product Manager and Market Manager. He spent 2 years working as Business Development Manager for WES's Power Systems Development subsidiary developing EPC substation projects. Steve spent 3 years as Market Development Manger for WES's Service business unit. For the last 2 years Steve has been the Load Tap Changer and Natural Ester Fluids Product Manager for Waukesha Electric.

Steve has been an IEEE member for 35 years and was elected to the grade of Senior Member in 1990. Steve and other colleagues were the recipients of The Institute of Management Sciences Franz Edelman Management Science Achievement Award for 1989 for Waukesha Electric System's use of innovative management science. Steve is also listed in the Acknowledgements of NBS Technical Note 1204 titled Calibration of Test Systems for Measuring Power Losses of Transformers, for having made significant contributions to this effort.