CERTIFIED TEST REPORT

COOPER POWER SYSTEMS
FIELD ANALYSIS OF ENVIROTEMP® FR3™ FLUID IN SEALED VERSUS FREE-BREATHING TRANSFORMERS

CERTIFICATION

Statements made and data shown are, to the best of our knowledge and belief, correct and within the usual limits of commercial testing practice.

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1. Scope

The dielectric fluid in a transformer is required for cooling and electrical insulation. Transformers of sealed design protect internal components from exposure to the elements. In the event that a transformer does develop a leak above the fluid level, the insulating fluid is exposed to water and oxygen. These substances are known to cause acids and sludge formation in conventional mineral oil, while in natural ester fluids the potential for oxidative polymerization is recognized. While oxidation inhibitors are added to both mineral oil and natural ester fluid to protect the insulating fluid, extended free-breathing operation will eventually have adverse affects on both fluids and on transformer components.

The natural ester, Envirotemp® FR3™ fluid, has demonstrated stable operation in sealed-design transformers for the past eight years. FR3 fluid samples, from intentionally free-breathing-design units over this same time period, showed signs of oxidation and hydrolysis as exhibited by a gradual increase in dissipation factor, a decrease in interfacial tension and slightly increased viscosity. Although the initial stages of oxidation are detected, the fluid's functionality has not changed. The transformers continue to function normally and pass periodic stress tests.

This report documents the condition of the Envirotemp FR3 fluid sampled from four transformers. Two sealed transformers installed in 1996 have operated continuously at 90% of full load. Two intentionally free-breathing units have operated under various load cycles since 1997. The results show that FR3 fluid can cool and electrically insulate a transformer under load cycling for at least eight years in a free-breathing condition.

2. Experimental

Fluid samples from two 225 KVA 3-phase 4160/240 volt sealed-design transformers filled with Envirotemp FR3 fluid have been taken and tested annually since they were installed in 1996. The transformers are continuously loaded at about 90% of nameplate rating and are part of the power system at one of Cooper's factories.

Fluid samples from two intentionally free-breathing 25 KVA single-phase 7200/240 volt pole transformers have been taken and tested regularly over the past eight years as well. Each transformer had a 1.65 mm vent hole that allowed the unit to free-breath. Pressure transducers verified free-breathing operation. The transformers are part of a test project that was made up of four different aging test periods, each with different aging and loading cycles as follows.

The first test period was 4800 hours of indoor operation at 65ºC top oil temperature for FR3 fluid unit B-9 and 4800 hours at 65ºC + ambient for the other FR3 fluid unit C-9. Each transformer contained a thermocouple in the top oil that measured the temperature, which was controlled by varying the primary current. A data logger was used to monitor the primary current and excitation voltage. The first test period began January 22, 1997 and ended on February 16, 1999. End point tests were done every 600 hours which included: 1) 60 Hz high potential for 1 minute with 22 kV on the primary and 7 kV on the secondary, 2) induced potential (400 Hz) with 130% of operating voltage (156 volts) applied to the 120 volt winding for 18 seconds, 3) 1.2 x 50 µs impulse withstand at 62 kV (two shots per terminal), and 4) fluid analysis.

Analysis of the FR3 fluid samples from the sealed and vented transformers was performed in accordance with the following ASTM methods:

Fluid Property	**Test Method/specification**
Moisture Content	ASTM D1533
Dielectric Breakdown	ASTM D877 for TP #1-3, then ASTM D1816
Dissipation Factor at 25°C	ASTM D924
Volume Resistivity	ASTM D1169
Neutralization No.	ASTM D974
Interfacial Tension	ASTM D971
Flash/Fire Points	ASTM D92
Viscosity at 40/100°C	ASTM D445
Color	ASTM D1500

The second test period was measured in cycles and was designed to approximate the thermal cycling conditions of actual transformers in operation, but in this case, under vented indoor operation. The vented units were tested for a total of 87 cycles. Each cycle combined 8 hours of load necessary to reach 65ºC or 65ºC + ambient top oil temperatures with 16 hours at 25% of the load. The test commenced on May 7, 1999 and ended on August 27, 1999. Transformer electrical tests and fluid analyses were performed at several times during the second test period.

In December 1999, the free-breathing units were relocated to an outdoor installation where they are located at this time. During the third test period, the transformers were energized at 7200 volts continuously on the primary, with the secondary floating (no loading). As a result of the energizing voltage and solar radiation, the top oil temperatures fluctuated from 2 to 15ºC above ambient. The units were placed outdoors and energized on December 15, 1999 until the completion of the third test period on October 29, 2002. Fluid analyses were performed at several times during the third test period.

The fourth test period began November 5, 2002 with the transformers energized with 7200 volts continuously and loaded at 100 % for 8 hours per day and no load for 16 hours. The transformers continue to operate under the fourth test period conditions. Transformer electrical tests and fluid analyses were performed at several times during the current fourth test period.

The time in years of operation was tabulated from the total number of hours that the transformers were energized with voltage in a vented condition. Downtime during end point testing and fluid sampling was not logged.

Analysis for oxidation inhibitor content was performed after approximately 5 years of operation on both sealed and free-breathing units. The FR3 fluid was analyzed using capillary gas chromatography.

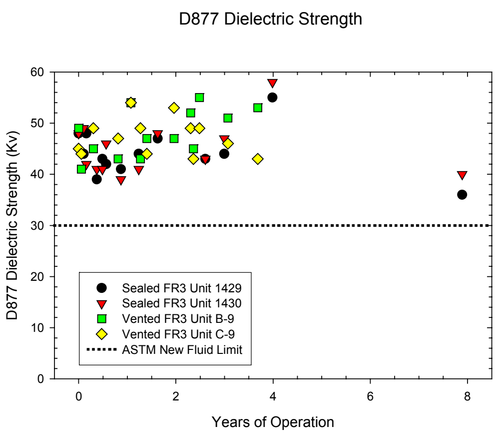
3. Results & Discussion

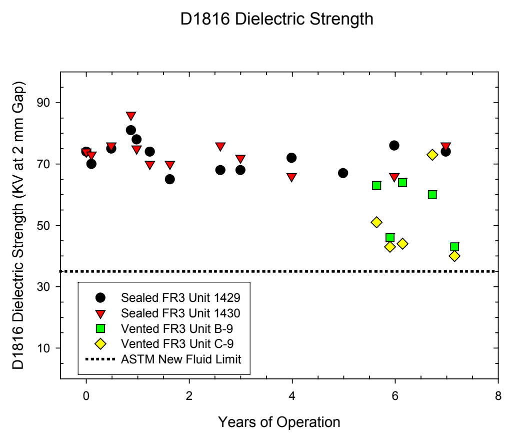
The samples of the FR3 fluid indicate that a measurable change in several properties can be attributed to oxidation in the free-breathing units, relative to the fluid properties from the sealed units. In the free-breathing units, not only is oxygen introduced, but moisture in the air as well. For some properties, hydrolysis also contributed to these changes. The relative property changes are discussed below, beginning with the most performance related property to the non-performance related and strictly diagnostic tests. While the ASTM color has no performance related value for a natural ester fluid in a transformer, the change in color has utility as an indicator of both oxidation and hydrolysis. Oxidation and hydrolysis are detected from a comparison of the viscosity, dissipation factor, acid number and color of the free-breathing versus the sealed units.

A greater change in FR3 fluid properties was displayed by free-breathing unit C-9 which was loaded and insulated to obtain a top oil temperature of 65°C plus ambient. Actual top oil temperatures in the first test period fluctuated between 60-75°C for unit B-9 and 85-105°C for unit C-9. This temperature differential was a factor for the difference in FR3 fluid properties between the free-breathing units B-9 and C-9.

3.1. Dielectric Strength

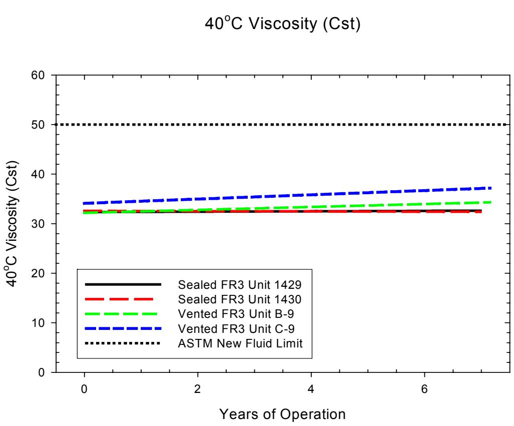
The dielectric strength of the fluid is practically unchanged after seven years. The ASTM D877 dielectric strength was measured routinely in the early years of transformer operation, however the focus was changed to the ASTM D1816 measurement after four years. This test is considered more sensitive to moisture and fluid contaminants. It is now the IEEE standard dielectric strength measurement – IEEE no longer references D877 in its maintenance guide. The data from both dielectric strength test methods are given below.

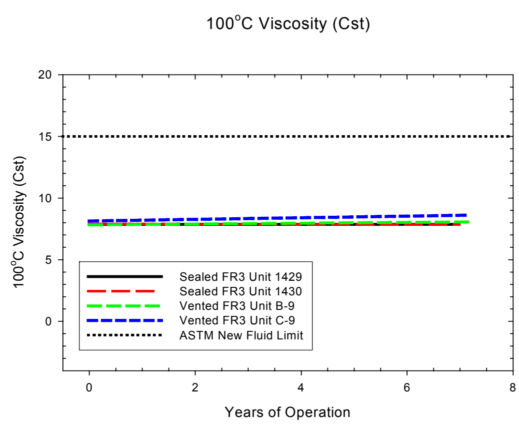




3.2. Viscosity

The change in viscosity of natural esters is the most reliable indicator of oxidation. The gradual change in viscosity of the free-breathing units compared to the sealed units confirmed the primary effect from exposure to oxygen. The FR3 fluid in the free-breathing units showed a modest increase after seven years. Although the viscosity remains well within the ASTM limits for new natural ester fluid, the increase suggests that natural ester fluid may increase in viscosity sufficiently over the expected performance life in free-breathing designs to eventually affect transformer cooling. As expected, in the sealed designed units there was essentially no change in the viscosity.

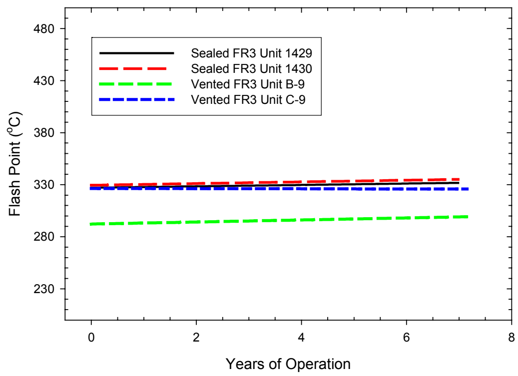




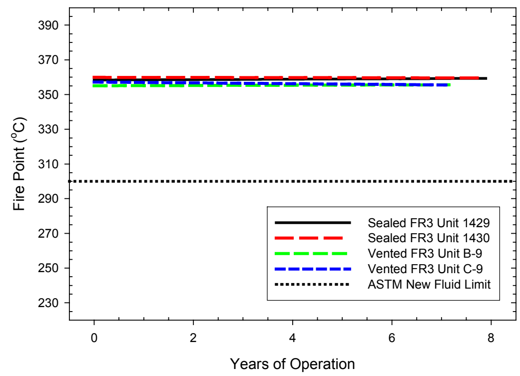
3.3. Flash and Fire Points

The highlight of the data below is the high fire protection that FR3 fluid affords and the fact that neither the flash nor the fire points have changed in nearly eight years for either design.

Flash Point



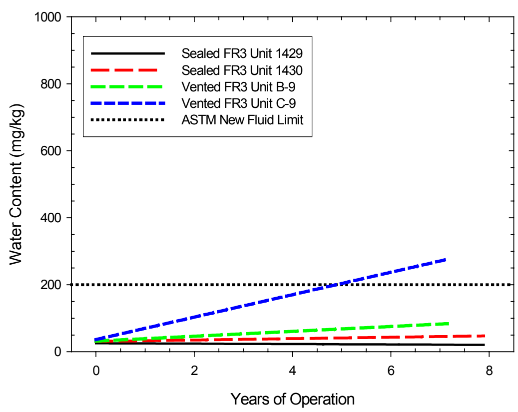
Fire Point



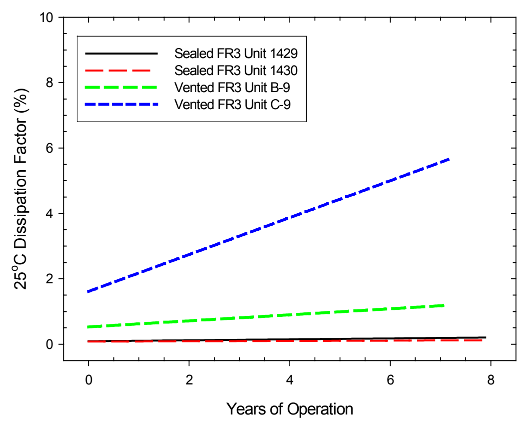
3.4. Water Content and Dissipation Factor

The following plots of the water content and dissipation factor highlight the difference between B9 and C9, but more importantly show the FR3 fluid stability in the sealed units. A free-breathing design promotes hydrolysis and oxidation of natural ester fluid, which leads to gradual increases in water content and dissipation factor.

Water Content

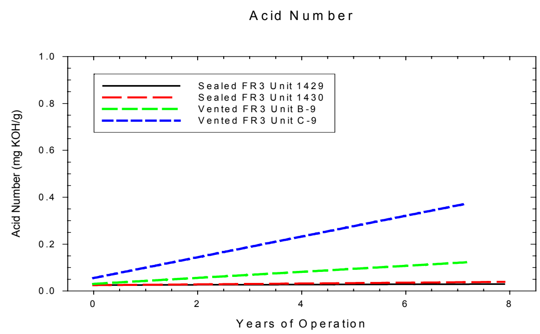


25°C Dissipation Factor



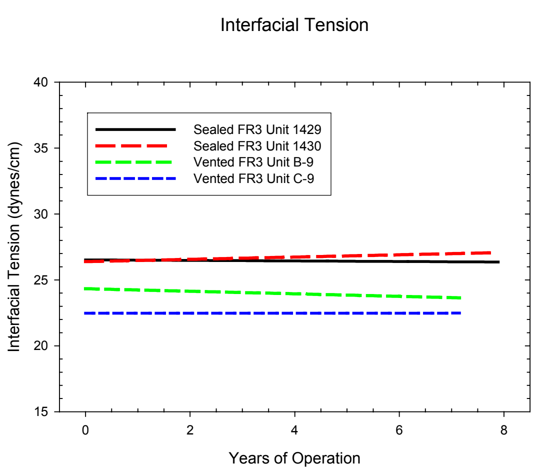
3.5. Neutralization Number

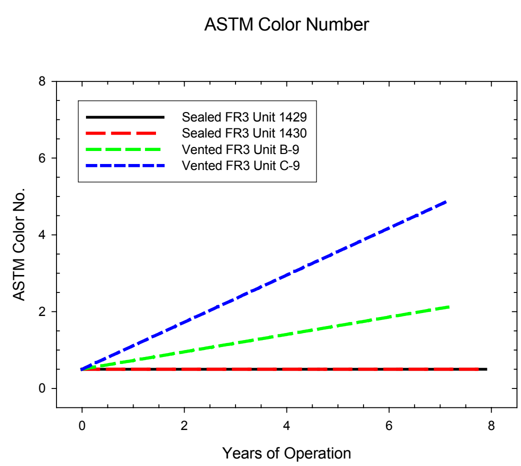
New natural esters have inherently higher neutralization number than mineral oil, compensated by the fact that the long-chain acids produced by the esters tend to be less aggressive. The neutralization number values show a gradual increase in FR3 fluid over the years of operation. The acid numbers of the free-breathing designs show the combined effect of higher water content and increased temperature that promotes mainly hydrolysis. Long-chain fatty acids are a by-product of natural ester fluid hydrolysis that cause increased neutralization number and dissipation factor. Acidic by-products are also formed from oxidation, especially at higher temperature, which cause similar effects. There was very little increase in the acid number of the sealed designed units over the seven-year time period.



3.6. Interfacial Tension and ASTM Color

The interfacial tension (IFT) analysis shows a difference in the FR3 fluid samples from sealed versus free-breathing units, however the difference was inherent in the fluid samples from the start of the test. Only a minor change in the IFT of FR3 fluid from the free-breathing units was noted after seven years. The by-products from oxidation and hydrolysis, as a result of free-breathing, darkened the FR3 fluid significantly after several years, while there was no darkening of the fluid from the sealed units. Changes in the ASTM color number correlate with changes in other diagnostic properties, such as dissipation factor and acid number. The results from the color change of the FR3 fluid from the free-breathing designs suggest the utility of the color test as an indictor of oxidation and hydrolysis.





3.7. Oxidation Inhibitor Content

A comparison of the antioxidant depletion in the FR3 fluid from sealed versus free-breathing designs also highlights the effect of free-breathing. Table 1 below shows the percent reduction in oxidation inhibitor after about five years of operation.

Table 1: Change in Oxidation Inhibitor After 5 Years of Operation

Transformer Description	**% Reduction in Antioxidant** (after ~ 5 years of operation)
Sealed FR3 Fluid 225 kVA Unit 1429	10
Sealed FR3 Fluid 225 kVA Unit 1430	3
Vented FR3 Fluid 25 kVA Unit B-9	61
Vented FR3 Fluid 25 kVA Unit C-9	81

4. Conclusions

Analysis of FR3 fluid from sealed and free-breathing transformers after seven-plus years of field operation show that gradual oxidation and hydrolysis occurs, detectable in several fluid properties in samples from the free-breathing units. Together, the results verify that changes in dissipation factor, neutralization number and viscosity offer ample early warning (in terms of years) that both excessive hydrolysis and oxidation are occurring in the FR3 fluid. ASTM color change of the FR3 fluid correlated with other diagnostic properties of the fluid and can be used as an indicator of degradation due to oxidation and hydrolysis.

Changes in the viscosity, which is a performance-related property, can be attributed to continuous exposure to oxygen. The change in viscosity occurred gradually over a lengthy period of time and most importantly, did not compromise the safe operation of the transformers. Because hydrolysis does not cause an increase in viscosity, measurable viscosity increases are a reliable indicator of excessive oxidation.

The FR3 fluid in the sealed designed transformers, in spite of their relatively high load demand, shows remarkable stability. Based on the significant difference in fluid stability, we continue to recommend that natural ester fluids be only used in sealed designed equipment. However, beyond the changes in the FR3 fluid properties in the free-breathing units, the transformer operation and performance have not been affected through seven years. Both of the free-breathing units have passed the IEEE C57.100 prescribed electrical end point stress tests and continue to operate. The functionality of Envirotemp FR3 fluid in these operating free-breathing transformers is currently verified out to seven years and remains on-line for future analysis.