Envirotemp™ FR3™ Fluid

Guide for Storage, Installation, Commissioning and Maintenance of FR3 Fluid Filled Transformers

G2300

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IMPORTANT:

This guide applies to Envirotemp™ FR3™ fluid filled transformers in general and is intended to provide information and guidance for the effective application of FR3 fluid in transformers. This guide does not replace original equipment manufacturer's Operation and Maintenance guide for a specific FR3 fluid filled transformer. Each FR3 fluid filled transformer and installation can have unique features that require additional or different steps and procedures not found in this guide.

In all cases, refer to and follow the specific steps, procedures and guidance in the original equipment manufacturer's Operation and Maintenance guide. Stricter, additional or different steps, procedures and risk mitigation actions may be required by the original equipment manufacturer to ensure its product warranties are not voided. Additional requirements may be dictated by standard industry operating and maintenance practices, site restrictions, by applicable legal, regulatory and local code requirements.

INTRODUCTION

Transformers are designed, manufactured and tested according high standards of practice, and it is an assumption of this document they meet the required levels of quality and reliability for proper operation and long term performance in service.

Due to some similarities between Envirotemp™ FR3™ fluid and conventional mineral oil, many of the traditional procedures are acceptable for FR3 fluid filled transformers.

This guide aims to support maintenance activities with focus on specific tests and evaluation procedures, as well as criteria and methods of maintenance for FR3 fluid filled transformers, which may be different from those traditionally applied in mineral oil or the ones applied for other natural ester fluids, and may require specific additional steps for specific transformers or local conditions.

Over 100 transformer manufacturers have successfully manufactured FR3 fluid filled transformers. FR3 fluid filled transformers are operating on six (6) continents, in over 35 countries.



Figure 1

Envirotemp™ FR3™ Fluid has been used in distribution and power transformers through 420kV.

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SAFETY INFORMATION

Cargill products meet or exceed all applicable industry standards relating to product safety. We actively promote safe practices in the use and maintenance of our products through our service literature, instructional training programs, and the continuous efforts of all Cargill employees involved in product design, manufacture, marketing and service.

This Guide does not cover procedures and actions needed to ensure worker safety in handling FR3 fluid. Readers should seek additional guidance to ensure all applicable legal, regulatory and industry safety practices and procedures are understood and followed.

This Guide is not a substitute for proper training or adequate experience. Only competent and experienced technicians, who are familiar with FR3 fluid and natural ester transformers should install, operate and service them. A competent and experienced technician has these minimum qualifications:

- Is thoroughly familiar with this Guide, the relevant (OEM) Operation and Maintenance guide and applicable legal, regulatory and local code requirements
- Is trained in industry-accepted high- and low-voltage safe operating practices and procedures.
- Is trained and authorized to energize, de-energize, clear, and ground power distribution equipment.
- Is trained in the care and use of protective equipment such as arc-flash clothing, safety glasses, face shield, hard hat, rubber gloves, hot stick etc. and other employee safety issues.

Special Attention Statement Definitions

This manual contains important statements:

IMPORTANT: Indicates information to help avoid unnecessary degradation of the product, equipment damage or application misuse, particularly if the practice differs from common practices in the storage and handling of convention transformer mineral oil.

ENVIROTEMP™ FR3™ FLUID OVERVIEW

FR3 fluid is a renewable, bio-based natural ester (vegetable oil) dielectric coolant for use in distribution and power class transformers where its unique fire safety, environmental, electrical, and chemical properties are advantageous. Recommended specification limits for new fluid according ASTM D6871 [1], IEEE C57.147 [2] and IEC 62770 [3] are shown in Table 1. Nearly twenty years of field experience, with over 1,000,000 transformers in service, confirms excellent performance.

FR3 fluid is formulated from seed oils and performance enhancing additives. It does not contain petroleum, halogens, silicones or corrosive sulfur. It quickly and thoroughly biodegrades [4] in the environment. The fluid is non-toxic in acute aquatic [5] and oral toxicity tests [6]. The Color Green tint is specific to FR3 branded fluid, reflects its favorable environmental profile (Table 2) and readily distinguishes it from petroleum based oils.

FR3 fluid has exceptionally high flash/fire points of approximately 330/360°C - the highest ignition resistance of any high fire point dielectric fluid currently available. It qualifies as a “high-fire-point”, “less-flammable”, “IEC Class K”, and “non-propagating” fluid. FR3 fluid is Approved [7] by FM Global and Classified [8] by Underwriters Laboratories as a Less-Flammable Dielectric Liquid for use in complying with the National Electric Code [9] (NEC) and insurance listing requirements [10].

Table 1
Envirotemp FR3 Fluid Recommended Specification Limits

	Standard Test Methods		Specification Limits	
Property	**ASTM**	**ISO/IEC**	**ASTM D6871 / IEEE C57.147**	**IEC 62770**
Electrical				
Dielectric Breakdown (kV)	D877		≥ 30	
1mm gap	D1816		≥ 20	
2mm gap	D1816		≥ 35	
2.5mm gap		IEC 60156		≥ 35
Dissipation Factor 25°C (%)	D924		≤ 0.20	
90°C (tan δ)		IEC 60247		≤ 0.05
100°C (%)	D924		≤ 4.0	
Gassing Tendency (mm/min)	D2300		≤ 0	
Physical				
Color	D1500	ISO 2211	≤ 1.0	
Visual Examination	D1524	IEC 62770 4.2.1	bright & clear	Clear, free from sediment and suspended matter
Viscosity (mm^2/sec) 100°C	D445	ISO 3104	≤ 15	≤ 15
40°C			≤ 50	≤ 50
-20°C			≤ 500	
Pour Point (°C)	D97	ISO 3016	≤ -10	≤ -10
Density at 20°C (g/cm^3)		ISO 3675		≤ 1.0
Relative Density 15°C/15°C	D1298		≤ 0.96	
Health, safety and environment				
Fire Point (°C)	D92	ISO 2592	≥ 300	> 300
Flash Point (°C)				
Cleveland Open Cup	D92	ISO 2592	≥ 275	
Pensky-Martens Closed Cup	D93	ISO 2719		≥ 250
Biodegradation		OECD 301	Readily biodegradable	Readily biodegradable
Chemical				
Water Content (mg/kg)	D1533	IEC 60814	≤200	≤ 200
Acid Number (mg KOH/g)	D974	IEC 62021.3	≤ 0.06	≤ 0.06
Corrosive Sulfur	D1275	IEC 62697	non-corrosive	non-corrosive
PCB Content (mg/kg)	D4059		non-detectable	free from PCBs
Total additives		IEC 60666		Max. weight fraction 5 %
Oxidation Stability (48 hrs, 120°C) [a]		**IEC 61125C**		
Total acidity (mg KOH/g)		IEC 62021.3		≤ 0.6
Viscosity at 40°C (mm^2/sec)		ISO 3104		≤ 30% increase over initial
Dissipation Factor at 90°C (tan δ)		IEC 60247		≤ 0.5

NOTE: a) See IEC 62770 Annex A for details of oxidation stability parameters of IEC 61125 modified method C for Natural Ester Based Fluids.

Environmental and Health

FR3 fluid is specifically formulated to help minimize health and environmental risks. The base oils come from renewable resources - commodity seeds - and can be recycled and reused.

The United States and California Environmental Protection Agencies published FR3 fluid's Environmental Technology Verification Report [11]. The verification process includes biodegradation and toxicity testing. Results from the aquatic biodegradation test confirmed that FR3 fluid's rate of biodegradation is the same as that of the standard reference material. FR3 fluid meets the aerobic aquatic biodegradation criteria (Figure 2) and the ready biodegradation (Table 2). When tested for acute oral toxicity, FR3 fluid is not toxic.

The Edible Oil Regulatory Reform Act (US Public Law 104-55, 1995) makes FR3 fluid eligible for current and future regulatory relief. The options of alternative spill response procedures, such as natural bio-remediation, are now more viable. The fluid's inherent viscosity and tendency to form thin layers to polymerize in the outside environment help prevent migration along the surface and into subsurface soils.

The US EPA [12], Occupational Safety & Health Administration (OSHA) [13], and the US Department of Transportation (DOT) [14] do not list FR3 fluid as hazardous. FR3 fluid's Hazardous Material Information System (HMIS) rating is 0 for both health and reactivity. FR3 fluid is not classified as bio-accumulating or mutagenic. It is not listed as a carcinogen by National Toxicology Program (NTP), in International Agency for Research on Cancer (IARC) monographs, or by OSHA Regulation. The products of complete combustion of FR3 fluid are essentially carbon dioxide and water.

Building for Environmental and Economic Sustainability (BEES) software [15], available from the National Institute of Standards and Technology, uses a life-cycle assessment approach, analyzing raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management, to determine a product's global warming potential.

Table 3 shows BEES amounts of greenhouse gas generated from raw materials through end of life for mineral oil and FR3 fluid. The cost of mineral oil, in terms of carbon emissions, is high. Meanwhile FR3 fluid is relatively low, about 0,98 ton/m^3 (equivalent to 8.2 lbs/gal) less greenhouse gas emitted to produce it. Additionally, the study reports that FR3 fluid's overall environmental impact score is one-fourth that reported for mineral oil (without consider the FR3 fluid's transformer insulation life extending performance properties). This cumulative score results from adding the impacts of water intake, smog, ozone depletion, indoor air, human health, habitat alteration, global warming, fossil fuel depletion, eutrophication, ecological toxicity, critical air pollutants, and acidification.

Table 2
FR3 Fluid's Environmental Attributes

Attributes	Results	Methods
Aquatic Biodegradation	>99%	EPA OPPTS 835.3100
Ready Biodegradation	>99%	EPA OPPTS 835.3110 or OECD 301B, C or F
Acute Aquatic Toxicity	Non-Toxic	OECD 203
Acute Oral Toxicity	Non-Toxic	OECD 420
Biobased Material Content	>95%	USDA Biopreferred program
Total Lifecycle Carbon Footprint	Carbon neutral	Department of Commerce NIST BEES V4.0
Overall Environmental Impact	1/4 impact of mineral oil	Department of Commerce NIST BEES V4.0

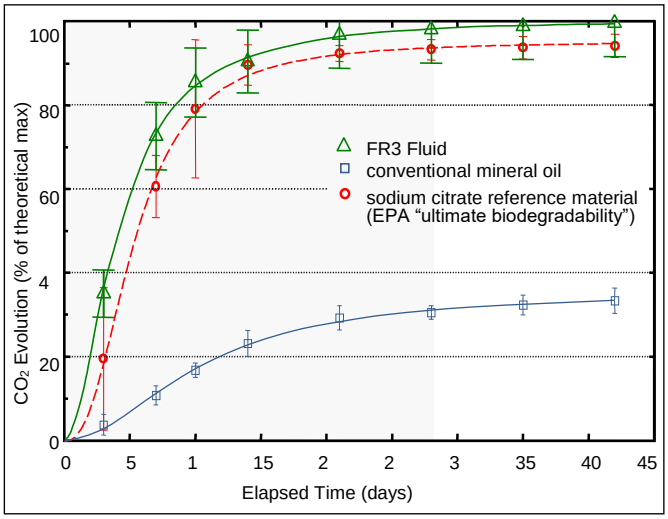


Figure 2
Aerobic Aquatic Biodegradation Graph EPA Test OPPTS 835.3100

Table 3
Greenhouse gases[a] attributed to transformer fluid for its complete life cycle.

	Grams per Unit[b]		Tons per 1000 Gallons	
Category	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 with 500 gallons of fluid

FR3 fluid and transformers filled with FR3 fluid are listed in the US Federal BioPreferred^{SM} Program [16], making them readily identifiable as BioPreferred to all applicable US Federal agencies. FR3 fluid is an excellent option for ISO 14000, Green Building, and other similar environmental programs that promote the use of alternative, environmentally preferable and sustainable materials and procedures.

Fire Safety

FR3 fluid has a typical fire point of approximately 360°C, well above the minimum of 300°C required for high fire point less-flammable fluid classifications. Its typical flash point (approximately 330°C) is higher than the fire point of most other less-flammable dielectric fluids in use today (Figure 3).

In laboratory and full-scale ignition tests, FR3 fluid has demonstrated greater fire resistance than other dielectric fluid types. Based on large-scale arc ignition testing, FM Global concluded that the probability of a pool fire evolving from FR3 fluid was so low that heat release rate need not be determined or considered for FM Global approval.

Based on large-scale arc ignition and hot metal ignition tests, FM Global recognizes FR3 fluid as an equivalent safeguard to space separation, fire barriers, and fire suppression systems for most installations.

FM Global recognizes FR3 fluid as a component of approved transformers per FM Global Standard 3990 [7].

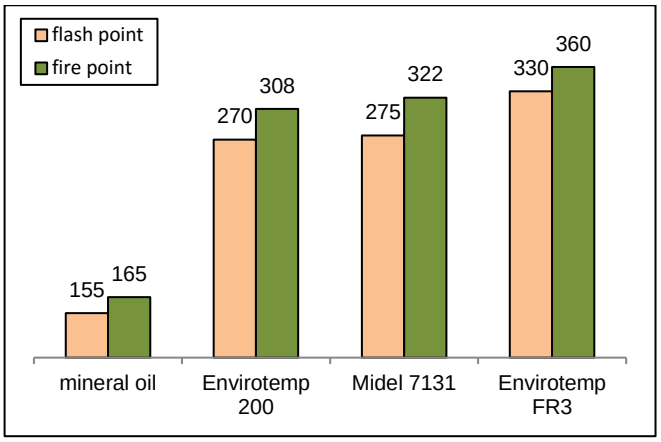


Figure 3
Flash & Fire Point of Dielectric Fluids (°C).

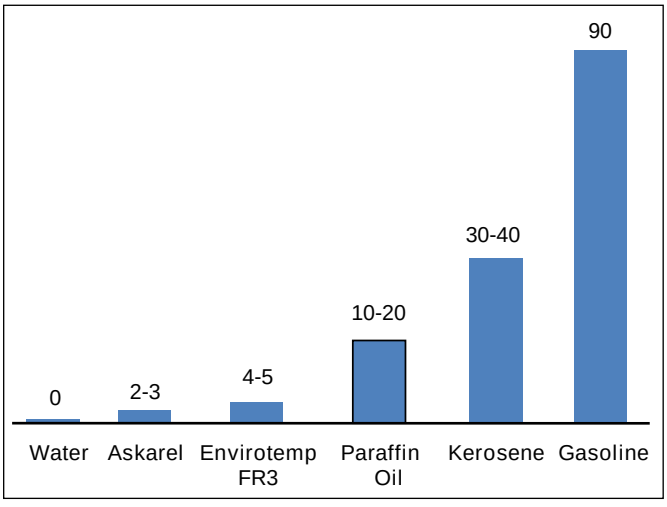


Figure 4
Fire Hazard Rating UL Standard 340.

When used in transformers containing 10,000 gallons of fluid or less, the transformer separation distance to buildings and other equipment may be up to one-tenth the distance required for mineral oil filled transformers, without fire walls or deluge systems.

OSHA recognizes this FM Global standard as fitting the definition of a Listed and Labeled Product per NEC Section 110-3(b). The standard permits FR3 fluid-filled transformers to be installed indoors, typically without sprinklers or vaults, with a minimum clearance to walls of just 0.9m (3 feet).

UL Standard 340 compares the fire hazard ratings of various fluids. Figure 4 shows the favorable rating assigned to FR3 fluid.

There are no known incidents of dielectric pool fires involving FR3 fluid filled transformers.

Fluid/Paper Insulation System

The unique chemical structure of FR3 fluid provides superior insulation system performance compared to other types of dielectric fluids. The thermal properties of FR3 fluid make it a more efficient coolant than higher molecular weight hydrocarbon and silicone dielectric coolants.

FR3 fluid has an exceptional ability to remove water generated by aging paper. This enables the fluid to reduce significantly the aging rate of transformer insulating paper. Per IEEE C57.100 [17], accelerated aging tests show that Thermally Upgraded Kraft (TUK) paper insulation aged in FR3 fluid takes 5-8 times longer to reach the same end-of-life points as TUK paper insulation aged in conventional mineral oil.

Table 4 compares the time to reach insulation end-of-life for TUK (Thermally Upgraded Kraft) paper aged in FR3 fluid and conventional mineral oil. The time to insulation end-of-life calculated using the IEEE C57.91 [18] loading guide is included for comparison. Accelerated aging tests show similar thermal aging improvement for non-thermally upgraded Kraft paper (plain Kraft paper).

Based on extensive studies evaluating the interaction between paper and FR3 fluid, two standards have been published for High Temperature Transformers, IEC 60076-14 [19] and IEEE C57.154 [20]. Both standards present an extensive material for supporting the adoption of higher thermal classes for cellulosic insulation materials immersed in natural ester fluids.

The temperature increment for Regular Kraft Paper is 15 degrees, upgrading its thermal class from 105 (in mineral oil) to 120 (in natural ester fluids), resulting in a hotspot temperature rise limit of 80°C for an average ambient temperature of 30°C (as assumed by IEEE C57.12.00 [21]) or 90°C if average ambient is 20°C (as assumed by IEC 60076-2 [22]).

Table 4
Transformer Insulating Paper End-of-Life (Hours)

End-of-Life Basis	150°C Mineral Oil	150°C FR3	150°C IEEE Basis	170°C Mineral Oil	170°C FR3	170°C IEEE Basis
Retained Tensile Strength 50%	3100	>4000*	1602	240	1300	323
25%	400	>4000*	3327	490	4000	671
Degree of Polymerization 200	3200	>4000*	3697	480	3400	746

* Paper did not reach end-of-life over the duration of the test. To be conservative, extrapolation was not employed.

Thermally Upgraded Kraft Paper (TUK or TUP) have their thermal class upgraded from 120 (in mineral oil) to 140 (in natural ester fluids), resulting in a hotspot temperature rise of 100°C for an average ambient temperature of 30°C (as per IEEE C57.12.00) or 110°C if average ambient is 20°C (as per IEC 60076-2). The complete set of new temperature rise limits for cellulosic insulation materials immersed in natural ester fluids can be found at the standards.

Applications

NOTE: The suitability of each application of FR3 fluid is the responsibility of the user.

Contact your local Cargill Dielectric Fluids group for application guidelines or email us at fr3fluid@cargill.com.

New Transformers

Distribution and Power class transformers filled with FR3 fluid for indoor, submersible and outdoor applications are available from manufacturers worldwide.

For indoor applications, FR3 fluid-filled transformers provide the proven technical and performance advantages of liquid-filled designs over dry types as well as a lower total life cycle cost when compared to all other transformer types. Advantages include:

- Lower noise
- Higher loading capability
- Contamination resistance
- Higher BIL
- Full diagnostic capability
- Lower temperature
- Higher efficiency
- Longer life
- Improved fire safety

Many types of FR3 fluid transformers are in service: pole-mounted, pad-mounted, networks, reactors, small, medium and large substations, transmission substations, and generator step-ups. FR3 fluid-filled transformers are accepted in both industry and government.

Contact your local Cargill Dielectric Fluids group for L10 FR3 Fluid User's List or email us at fr3fluid@cargill.com.

The higher temperature limits applicable for natural ester filled transformers using regular Kraft paper and/or thermally upgraded paper have enabled exciting possibilities in the design of new transformers. Higher temperature limits allow the optimization of the windings, saving considerable quantities of material. An optimized or compact winding result in a reduced core window and, consequently, in a decrease of the transformer height, length and width. The result is an overall reduction of the materials used for the transformer and potential savings in the transformer cost.

Retrofilling Transformers

FR3 fluid is especially suited for retrofilling as it improves fire safety, minimizes impact on the environment and helps slow the aging rate of mineral oil-filled transformers. It is miscible with conventional mineral oil, high molecular weight hydrocarbons, PCB (Askarel) and most PCB substitutes except silicone. FR3 fluid is not miscible with silicone and should not be applied in transformers previously containing silicone. However, this guide does not address requirements for the handling or disposal of PCB or other regulated hazardous materials.

Unlike most other fluid types, the residual transformer oil remaining in a properly retrofilled transformer should not reduce the fire point of FR3 fluid below the NEC minimum of 300°C (Figure 5) provided that the residual mineral oil remains below 7%. This is true even after full equilibrium has been achieved between the replacement fluid and the residual mineral oil in the paper.

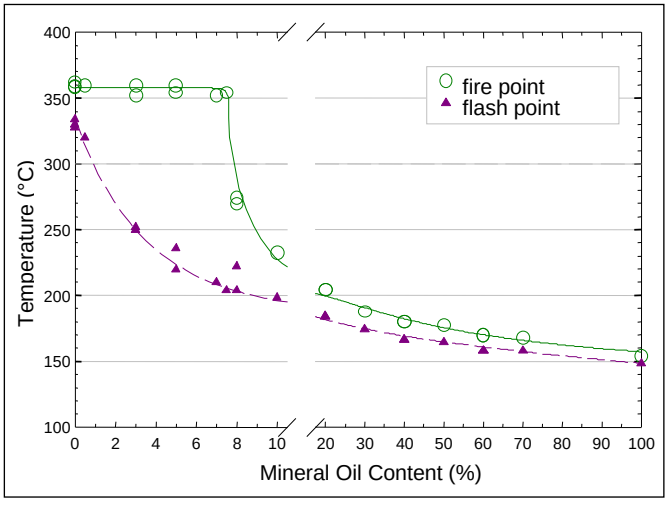


Figure 5
FR3 Fluid Flash & Fire Point Variation with Conventional Transformer Oil Content.

Additional advantages of retrofilling with FR3 fluid include high dielectric strength, better match of dielectric constant to Kraft paper insulation, excellent lubricity, material compatibility, and a coefficient of expansion similar to conventional mineral oil. FR3 fluid has superior resistance to coking and sludge formation when compared to conventional transformer oil. In addition to passing the Power Factor Valued Oxidation (PFVO) test, Doble Laboratories' Sludge-Free Life tests resulted [23] in no measurable sludge. The fluid also acts as a drying agent for transformer insulation that has become wet from aging, extending the useful life of the transformer insulation system.

Refer to Cargill Bulletin G2040, "Power Class Transformer Retrofill Guide > 7500KVA" and G2010, "Distribution Transformer Retrofill Guide ≤ 7500KVA".

TRANSFORMER DISPATCH PREPARATION AND TRANSPORTATION

Transformers designed for FR3 fluid should observe the following recommendations regarding the transportation and oil preservation system:

- FR3 fluid is not recommended for completely free breathing transformers, but is suitable for all non-free breathing transformer constructions (including but not limited to transformers with conservators when equipped with rubber bladders, gas head space designs, and corrugated tank designs). The continuous exposure of FR3 fluid to ambient air can reduce the life expectancy of the fluid. Despite limiting the application, lab and in-field testing have shown that reaching significant FR3 fluid oxidation is a long-term process (years) in a free-breathing transformer, taking years to affect the fluid performance. Eventual exposure to ambient air is not of concern.
- Minimize exposure of the FR3 fluid to the ambient air during processing and handling to maintain fluid properties as close to original as possible. During such short-term exposure, the rate of moisture absorption is more of concern than the oxidation, since moisture affects dielectric strength.
- Thin films of natural esters tend to polymerize much faster than conventional mineral oil, especially on non-porous surfaces. This is a cause of concern during transportation of transformers without fluid or with reduced fluid level. The use of an inert gas, such as Nitrogen, is recommended in both cases. For additional recommendations, see Cargill Bulletin R2080, "Thin Film Oxidation".

  NOTE: Thin film oxidation is not a concern for a transformer in service. The above steps pertain to the transportation, maintenance, processing and handling procedures of FR3.

Due to this, natural ester fluid-filled transformers are recommended to be transported using one of the following options:

- Fully filled with fluid and ready for service.
- Partially filled, with fluid covering core and windings. Remaining space should be filled with nitrogen or other inert gas at a small positive pressure. Dry air is also acceptable in some cases. Balance of fluid to be sent separately in drums.
- With no fluid in the tank. The entire transformer filled with nitrogen or other inert gas, at a small positive pressure. Dry air is also acceptable in some cases. All the volume of fluid to be sent separately.

When transporting a transformer with no fluid, the decision to apply dry air or nitrogen gas should be based on the total exposure time of the transformer assemblies. Typically, dry air can be applied in situations no longer than 14 days of drained fluid, at ambient temperature of 40ºC. Otherwise, nitrogen gas can be applied up to 6 months (eventually including some storage time). Both alternatives should consider keeping a slightly positive pressure inside the tank.

As an example, a recommended nitrogen gas has a water content ≤ 3 ppm, oxygen content ≤ 5 ppm per volume at ambient pressure and a purity level > 99.95%. The required pressure should be between 0.15 kgf/cm^2 and 0.30 kgf/cm^2, at 25°C.

External detachable components of large power transformers such as conservator, radiators, bushings, rollers, explosion vent, Buchholz Relay, etc., are typically removed and dispatched separately. In such cases, Cargill recommends removing remaining thin films of natural ester fluid, to avoid thin film polymerization in the situations where it can be not acceptable for the component.

RECEIVING THE TRANSFORMER

The receiving of a FR3 fluid filled transformer should follow the same procedures applied for conventional mineral oil units: overall visual inspection, verification of internal pressure, impact registers, complete documentation, etc.

A special attention to the pressure of the main tank is recommended. A positive pressure indicates the internal inert gas was preserved during the entire transportation period and maintained low moisture and low oxygen levels. Some manufacturers require the transportation company to register the pressure daily, which is an effective way to make sure no external air has been admitted to the tank.

When the transformer is transported partially filled or without any fluid, the inspection of fluid drums, totes or bulk containers is also recommended.

Fluid Inspection and Receiving Tests

The receiving inspection of FR3 fluid is done similarly to inspection of conventional mineral oil. Inspection and testing should be completed prior to unloading. Each FR3 fluid lot received should be inspected for container integrity. Verify that tamper seals are intact.

A Certificate of Analysis is included with every shipment of fluid. If independent receiving tests are required, samples should be taken from containers per IEC 60475 [24], IEC 60567 [25] or ASTM D923 [26] Standard Test Method.

When material is to be combined for production, samples may be mixed together to create a composite sample for testing.

Recommended tests and acceptance values are given in Table 1. Values shown in Table 1 are specified for all natural ester fluids as a class, in the original shipping containers and prior to filling equipment. Recommended receiving tests include dielectric strength, visual inspection, dissipation factor and water content.

If the as-received FR3 fluid does not meet the acceptance specifications shown in Table 1, contact your supplier immediately.

Fluid storage in the containers after sampling can be improved by applying an inert gas blanket to the headspace prior to resealing the container.

When the fluid analysis indicates significant changes in the fluid properties, the actions for the fluid must be followed as described in the Fluid Treatment section.

Although laboratory testing of FR3 fluid is done in much the same way as mineral oil, minor modifications to certain test procedures are needed to obtain repeatable and reliable results. Refer to the section Fluid Testing and additional information in Cargill Bulletin G2090 “FR3 Testing Guide”.

If your laboratory does not have experience testing FR3 fluid, please contact your local Cargill Dielectric Fluids group for detailed test recommendations or email us at fr3fluid@cargill.com.

Container Handling

Storage

Similar meticulous procedures for storing and handling conventional transformer mineral oil should be followed with FR3 fluid.

Drums and totes of FR3 fluid are sealed at the factory to protect against ingress of foreign material and moisture contamination during shipping. Tamper-resistant seals verify that the container has not been opened. To help maintain the extremely low percent moisture saturation at time of fluid manufacture, exposure time to moist air should be minimized.

IMPORTANT: Avoid extremes of temperature in storage. Store FR3 fluid in labeled, tightly closed containers at 10-40°C, in dry, isolated and well-ventilated areas, away from sources of ignition or heat.

Cargill recommends storing drum and totes indoors, in a dry location, out of direct sunlight, and with ambient temperature above 10°C. If long-term outside storage cannot be avoided, drums stored horizontally with the bungs of the drum below fluid level are acceptable. Containers should be placed in protected areas to avoid exposure to sun and rain. Refer to the Cargill Bulletin S10 “FR3 fluid Storage and Handling Guide”.

Totes are designed to be stacked during storage. However, totes are not designed to, and should not be stacked during transportation.

For drum and tote storage, drip pans or basins are always recommended, and may be required by local codes. Please refer to your local authority having jurisdiction for definitive rulings.

IMPORTANT: Prolonged low temperature storage will cause the viscosity of FR3 fluid to significantly increase. Warm fluid to >10°C for efficient transfer by pump.

Heating

In the event the drums and totes have been stored in a very cold environment, or it is necessary to use cold FR3 fluid as soon as it is received, heating the containers may be necessary to reduce viscosity. If heating in a brief period is necessary, heating ovens can be used.

Cargill recommends opening the vent to provide pressure relief during heating cycle. For drums, electric drum heaters may be used.

Fluid Removal from Containers

Pumps with a positive suction capability are recommended to remove FR3 fluid from drums and totes. Positive displacement pumps, diaphragm, or air-operated drum pumps are satisfactory. Centrifugal pumps can be used if the fluid is heated to obtain a suitable viscosity. This temperature will vary with the size and brand of pump. Contact your pump supplier to make sure that a centrifugal pump is correctly sized for a given viscosity (temperature) of fluid.

Totes have drain valves that permit gravity feed. The totes accept forklifts from 4 sides, and may be raised to a desired height with suitable forklifts. Gravity feed from drums can be done when properly rigged.

IMPORTANT: Dedicated equipment is recommended for storing, handling and processing FR3™ fluid. However, if existing equipment is used for both mineral oil and FR3 fluid, it should be drained of mineral oil and flushed with FR3 fluid to minimize mineral oil content. After use, the equipment should be drained of FR3 fluid and flushed with mineral oil.

Bulk Unloading

When received in bulk, FR3 fluid can be unloaded using a pump or gravity feed. Particle filtration is recommended during the process of unloading into bulk storage.

Hoses and Fittings

The unloading hose should be a quality oil resistant hose designed for suction service. The hose length should be kept to a minimum. Dedicated hoses are recommended for use with FR3 fluid to minimize the possibility of contamination. Hoses previously used for electrical grade mineral oil can be used for FR3 fluid if first flushed with FR3 fluid. The minimum recommended hose size is 3 inches (7.62 cm) in internal diameter. Hose fittings should be aluminum or brass, and firmly attached to the hose.

Dry break type quick connector fittings are recommended to reduce spillage and contamination of FR3 fluid. Dust caps and plugs should be used whenever the hoses are not being used.

If the viscosity of cold fluid hampers unloading, hoses and transfer lines should be heat traced.

Pumps

Capacity

FR3 fluid is more viscous than conventional mineral oil. Select the proper pump size based on the required flow rate, head pressure, and fluid temperature (viscosity) (see Figure 6) Determine the maximum flow rate required. Select a pump and motor for use at the lowest temperature (highest viscosity) that will be encountered.

Type

Positive-displacement pumps are commonly used to pump FR3 fluid. A standard iron pump with either a mechanical seal or stuffing box is satisfactory. When specifying the correct size pump and motor, pump supplier should be made aware of the viscosity, pumping rate required, suction lift, and discharge head. Capacities up to 76 LPM (20 GPM), direct driven pumps have proved to be satisfactory. A reduction gear or belt driven pump may be required for higher pumping rates. Other pump types used successfully are air-operated diaphragm pump, progressive cavity pump and flexible impeller pump.

Horsepower

If pumps used for conventional mineral oil are used in an FR3 fluid system, it is necessary to check the motor horsepower to make sure it has sufficient capacity. Many times, the existing pump will be entirely satisfactory, or may be made satisfactory by a change in the motor horsepower or using a slower pump speed.

NOTE: If a larger motor is used, ensure that the pump and drive coupling will withstand the increased horsepower. If a change to a lower RPM is made, ensure that the required pumping rate will be obtained at the lower RPM.

Valves

Valves suitable for use with conventional mineral oil have been successfully used with FR3 fluid.

NOTE: A vacuum degassing and dehydration system requires temperatures of 60-80°C (140-180°F). Be sure to select components compatible with the fluid and process temperatures. Consult with the component manufacturer for the proper selection.

Filters Types

Most types of filters used for conventional mineral oil service can be used with FR3 fluid. The cartridge-type filter is best suited for this service, consult the filter manufacturer for the appropriate flow rates. It is offered in various micron ranges and sizes for either low or high flow rates. Adsorption filters such as activated clay (Fuller's earth) can be used, up to process temperatures of 75-80°C, but it may remove the additives.

Contact your local Cargill Dielectric Fluids group for advice on reclaiming aged FR3 fluid or email us at fr3fluid@cargill.com.

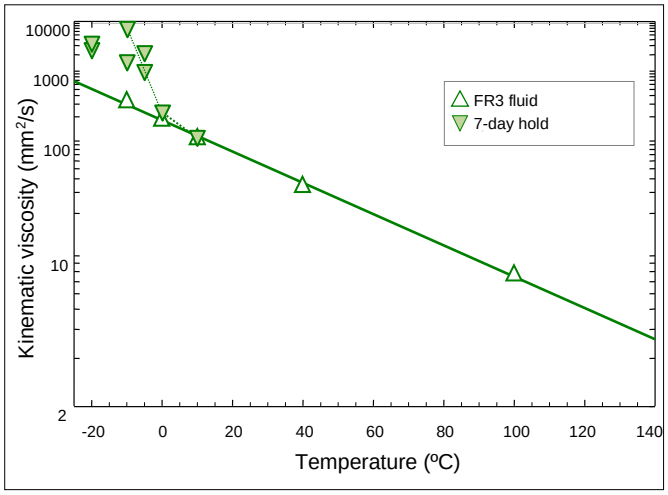


Figure 6
Kinematic viscosity of FR3 fluid as measured using ISO 3104 [17] or ASTM D445 [18].

Types of heaters

Recommended types of heating systems are:

- Indirect heating, such as a steam-jacketed storage tank, is preferred. The watt-density of the heating systems should be 1.55 W/cm^2 (10 W/in^2) or less.
- An in-line heater can be used as long as the watt density is less than 1.55 W/cm^2 (10 W/in^2). This limits the overheating of the layer of liquid in direct contact with the heater.

Degree of Filtration

For maximum dielectric strength, filter FR3 fluid just prior to introduction into the electrical apparatus. A particulate filter with a nominal pore size of 0.5 microns is recommended.

Moisture Removal Filters

FR3 fluid can tolerate much more water than conventional mineral oil before compromising its electrical characteristics.

If moisture content of FR3 fluid increases above acceptable limits, additional treatment is required. Moisture can present itself in two forms in the oil: free water and dissolved moisture.

Free Water Removal

- If the moisture is in the form of free water, filter units such as zeolite cartridges, AMF CUNO Zeta-Plus™ and HILCO™ blotter paper cartridge filters can be used effectively. Desiccant packaged filter cartridges should be specified to ensure dryness of the filter media
- Free water pooled on the bottom of the container must be removed and the FR3 fluid should be dried. See Dissolved Moisture Reduction section for additional requirements.

Dissolved Moisture Reduction

- If the dissolved moisture content must be lowered, a high vacuum dehydration system may be required. An advantage of vacuum dehydration is that dissolved gases are also removed. (See the Vacuum Filling section).
- Molecular sieve filters are also satisfactory if the quantity of moisture to be removed is not excessive. Activated grade 3A or 4A molecular sieves are recommended for moisture removal from FR3 fluid, and are effective over a broad temperature range, provided adequate care is taken in filter selection to ensure sufficient residence time in the filter.

Moisture removal filters should be located upstream of the final particulate filter in the fluid handling system.

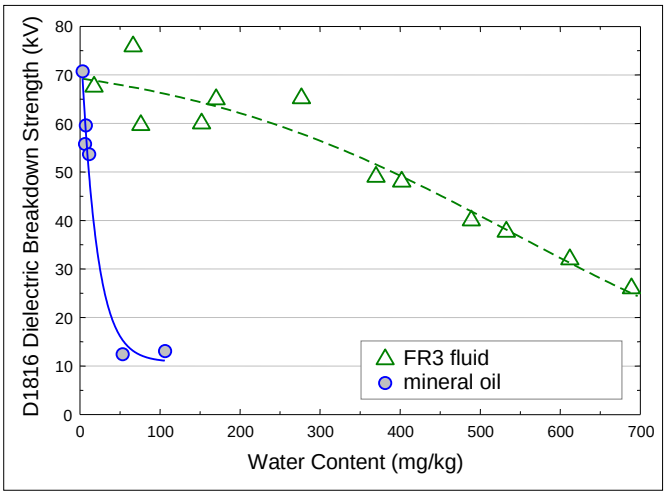


Figure 7
Dielectric breakdown strength versus absolute water content for mineral oil and FR3 fluid.

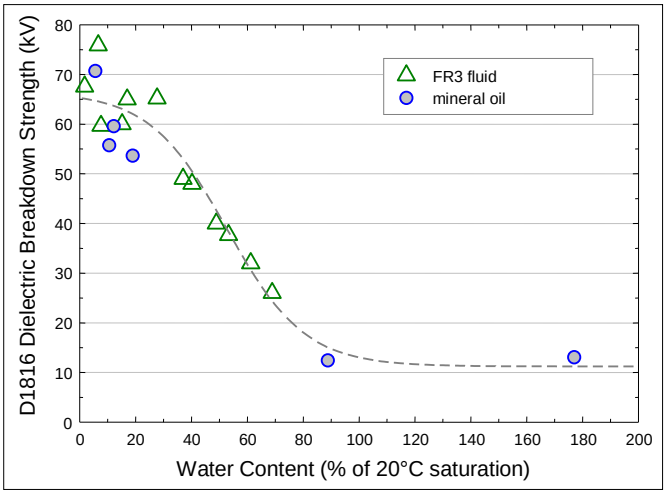


Figure 8
Dielectric breakdown strength versus relative water content for mineral oil and FR3 fluid.

Thermo-Vacuum/Degassing Machines

During the fluid processing in field, prior to transformer filling, or even as maintenance step, the thermo-vacuum / degassing machines are frequently applied. It is typically performed using same equipment of mineral oil, just performing decontamination prior to use (internal flush and filter replacement).

Tests have been performed showing that FR3 fluid may be processed at temperatures in the range of 60-80°C (140-180°F) under vacuum, if the maximum watt density of the heater is limited to 1.55 W/cm^2 (10W/in^2). It covers, in general, three different treatments:

- Filtering;
- Moisture content reduction;
- Degassing

FLUID TESTING

Differences in Fluid Properties

Physical, chemical, and electrical properties are used to specify and evaluate new electrical insulating fluids and monitor in-service fluids. Some traditionally acceptable indicators of mineral oil performance may not apply or may have different values for FR3 fluid.

The chemical composition of FR3 fluid is a mixture of relatively polar triglycerides (long-chain fatty acid ester molecules) having some unsaturation and the ability to form hydrogen bonds. Conventional mineral oil consists of cyclic naphthenes, branched alkanes, and aromatic molecules. These relatively low boiling point compounds are non-polar and hydrophobic. The difference in basic chemistry between vegetable oil and mineral oil accounts for disparate values in several tests assessing fluid characteristics. Table 1 shows the specification limits for FR3 fluid and other natural ester fluids.

Performance Tests

Insulating fluids provide both electrical insulation and cooling capability, then two key properties that affect the function and performance of an insulating fluid are dielectric breakdown voltage and viscosity. The dielectric breakdown measures the effectiveness as electrical insulation. The viscosity influences the cooling performance.

Viscosity

The kinematic viscosity of FR3 fluid is slightly higher than that of mineral oil. Use ISO 3104 [27] or ASTM D445 [28] without modification.

Dielectric Breakdown Voltage

IEC 60156 [29] or ASTM D1816 [30]: The only modification is the stand time before test. The method calls for a stand time of 3-5 minutes. Because the viscosity of FR3 fluid is higher than conventional mineral oil, a 30-minute stand time is recommended between pouring the room temperature equilibrated fluid sample and starting the test. This gives entrapped air sufficient time to escape after pouring the sample.

ASTM D877 [31]: The stand time specified in this method is 2-3 minutes. As stated, a 30-minute stand time is recommended for FR3 fluid. Despite also working for measuring BDV with FR3 fluid, IEC 60156 or ASTM D1816 are preferential for all fluids. The method ASTM D877 is less sensitive to dissolved gases, moisture and particles.

Effect of Water Content

The breakdown strength of any dielectric fluid starts to decrease as the water content increases to about 40% relative saturation. At room temperature, 40% relative saturation in mineral oil occurs at an absolute water content of approximately 25 mg/kg (or ppm), and about 400 mg/kg in FR3 fluid. To get a meaningful comparison of water content in diverse types of dielectric fluids, we should use relative saturation rather than the absolute water content in mg/kg. Figure 7 and Figure 8 compares the D1816 dielectric strength versus absolute and relative water content for FR3 fluid and mineral oil.

WARNING: All activities must comply with the local regulations regarding working and safety conditions. This document does not replace or overtake manufacturer manual instructions. Only qualified professionals, with proper equipment and protections should be allowed to perform these activities.

TRANSFORMER INSTALLATION

The following measures should be verified for the transformer installation:

- To confirm ID nameplate ID of the equipment.
- Visual inspection of the installation area, especially regarding land site preparation, flatness, basis alignment and equipment positioning.
- Visual inspection of the equipment, searching for damage caused during the transportation.
- To check the installation for compliance with applicable local regulations, such as electrical and fire safety codes.

The equipment temperature should be equal or higher than ambient temperature. When lower than ambient, any eventual penetration of moisture can result in moisture condensation.

The following actions are strongly recommended before starting transformer assembly:

- Install and verify all grounding connections of the transformer to the substation.
- Verify internal pressure of the transformers transported or stored without insulating liquid. If positive pressure is lost, search for possible leakage and measurement of the insulation surface relative moisture is recommended.
- Fluid sample should be taken for laboratory analysis for transformers transported or stored with insulating fluid.

General Important Practices

- Extreme care should be taken to prevent any foreign material being dropped into the transformer. Any spanners or other working tools should be securely tied so that they can be recovered easily in case of an accidental drop.
- Fibrous cleaning materials should not be used. The presence of loose fibers in suspension on insulating liquid can reduce its dielectric strength properties.
- All components dispatched separately should be cleaned inside and outside before fitted.

Transformer Assembly

Usually, large transformers are partially disassembled for transportation, then, the following procedures are recommended for FR3 fluid filled units:

- To verify accessories and bill of materials;
- For capacitive bushings, measure its power factor and capacitances;
- To verify accessing points, inspection windows, available valves and its connections;
- To check oil preservation system, especially vacuum equalization piping for transformers with rubber bag or membrane (atmoseal type);
- To prevent opening more than one point in the main tank, to minimize air flow through the tank.

Transformer Filling

For transformer partially filled, the oil preservation system and transformer type will define whether filling operation should be done under vacuum or at ambient pressure. For the transformers shipped without insulation liquid, vacuum filling is recommended.

Vacuum Filling

When possible, fill the tank with hot degassed fluid at a rate that maintains the required (partial) vacuum. If foaming occurs when filling under vacuum conditions, degas the FR3 fluid.

Degassing should be carried out at 80°C, at a pressure as low as practical, typically less than 100 Pa prior to introduction into the equipment. Degassing and dehydration units are available for processing oils to acceptable levels of dissolved moisture and dissolved air.

After FR3 fluid is degassed, it should be introduced directly into the tank under vacuum. If this is not possible, a storage tank that can be maintained under a vacuum at least equal to, or greater than, the vacuum maintained in the transformer, is recommended. Otherwise, the FR3 fluid may absorb gases and foam during filling.

Dedicated equipment is recommended for processing FR3 fluid, but not required. If existing equipment is used for both mineral oil and FR3 fluid, it should be drained of mineral oil and flushed with FR3 fluid to minimize mineral oil content. After processing FR3 fluid, the equipment should be drained and flushed with mineral oil.

Atmospheric Filling

Vacuum filling, even with only a partial vacuum, is preferable to atmospheric filling. When filling units with

IMPORTANT: In order to avoid moisture absorption, the ‘transformer main tank should not be opened whether ambient relative moisture is higher than 70%, ambient temperature lower than 0°C or with strong wind.

IMPORTANT: If ambient temperature is lower than -10°C, it is strongly recommended to keep the transformer under no load condition, just energized with voltage, until the no load losses heat up fluid to positive temperatures. Operation of tap changers can result in damage, since the fluid viscosity is high at such condition.

FR3 fluid at atmospheric pressure, heating and degassing the fluid are strongly recommended to maximize performance.

If a new transformer must be filled under atmospheric conditions, it is recommended to heat both the transformer and the FR3 fluid to 75-80°C while under a nitrogen gas blanket to promote more complete impregnation. The impregnation rate is much slower than mineral oil. Higher voltage rated units will require longer impregnation times. The thicker the pressboard, the longer the impregnation time required.

Also, when retrofilling transformers under atmospheric conditions, FR3 fluid should be filtered and heated to 75-80°C while under nitrogen gas blanket to protect against oxidation of both solid and liquid insulations.

NOTE: Insure no residual FR3 fluid is on the surface of insulators after filling the equipment. Wipe the insulators with a suitable cleaner.

Transformer Storage Procedures

Transformers that are required to be kept in storage for prolonged periods should preferably be stored partially filled with a headspace of approximately 5% of the transformer tank height filled with dry nitrogen under slight positive pressure.

FR3 fluid filled transformer can be stored without the fluid and under dry air for periods up to two weeks (taking an ambient temperature of 40ºC as reference).

For periods no longer than six months the equipment can be stored using nitrogen or other inert gas, or be partially filled keeping a minimum fluid level covering core and coils (windings) and keeping a nitrogen headspace. For periods longer than six months, storage without the insulation liquid is not recommended.

The storage of accessories must follow same procedures applied for mineral oil transformers. Special attention must be taken to the accessories coated with residual films of FR3 fluid. Thin films of natural esters tend to polymerize when exposed to air for periods greater than two weeks at 40°C. In most cases the polymerization of a thin film is not an issue, as it looks like a few microns varnish layer, however, it must be evaluated to decide if cleaning is required. For example, the effect on the Buchholz Relay is critical, as the movement of floating device lever can be blocked by adherence to the varnish.

TESTING / COMMISSIONING

Pre-Commissioning Tests

For power transformers or according customer procedures, the following tests can be carried out:

- Fluid Analysis:

  Fluid analysis prior to energization is commonly required. The properties of the sampled FR3 fluid from the transformer after tank filling, when the fluid has contacted core and coils, are no longer the same as the limits applied for new FR3 fluid. Acceptance values for relevant fluid properties are listed in Table 5, based on the values from IEEE C57.147 and work group of IEC PT 62975 [32].

- Transformation Ratio, Polarity and Phase Relation tests:

  Using a turn's ratio meter, the transformer ratio should be checked on all taps and windings. Results should be compared with the values indicated in the original equipment manufacturer factory test report. The polarity and phase should also be checked to the guaranteed and specified values.

- Measurement of Winding Resistance:

  Tapped winding resistance should be measured at all taps using a Kelvin Bridge meter. Results should be compared with the values obtained in the original equipment manufacturer factory tests.

- Measurement of Winding Power Factor:

  Windings power factor should be measured according to local standards. Results should be corrected to 20°C and compared with the values from original equipment manufacturer factory tests. A tolerance of 50% is typically accepted.

- Measurement of Winding Capacitance:

  Windings capacitance should be measured according to local standards. Results should be compared with the values from original equipment manufacturer factory tests. A tolerance of 20% is typically accepted.

- Insulation Resistance:

  IR values between windings and between windings to earth should be checked. While checking IR values, no external lines, lighting arresters, etc., should be connected in the circuit. Before IR measurement, bushings contacts should be thoroughly cleaned using preferably dielectric solvent or isopropyl alcohol. Instruments of 2500V or 1000V (use same factory test voltage to minimize deviations), preferably motor operated, should be used for IR measurement. Be sure to securely install lead wires. See Commissioning section for differences on IR measurements between natural ester and mineral oil.

- Tap Changers Operation:

  Transformers with de-energized tap changer must be isolated from supply on all windings before operation of the tap changer. Tap position must not be changed if the fluid temperature is below 0ºC. The tap switch should be padlocked in the "working position" ensuring contacts are correctly and fully engaged. To avoid severe damage to the transformer, tap switch handle cannot be left in any way half way or unlocked.

  Transformer with load tap changer should have OLTC operation verified from minimum to maximum tap. Make sure OLTC is filled at required level with proper insulation fluid, also meeting standard requirements.

Table 5
FR3 Fluid and other Natural Ester Fluid Acceptance Values After Contact and Prior to Energization

	Standard Test Methods		Voltage Class			
Property	**ASTM**	**ISO/IEC**	**≤36kV**	**>36kV ≤ 69kV**	**> 69kV ≤ 230kV**	**> 230kV**
Electrical						
Dielectric Breakdown (kV) 1mm gap	D1816		≥ 20	≥ 25	≥ 30	≥ 32
2mm gap	D1816		≥ 30	≥ 45	≥ 52	≥ 55
2.5mm gap		IEC 60156	≥ 32	≥ 47	≥ 55	≥ 60
Dissipation Factor 25°C (%)	D924		≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.5
90°C (tan δ)		IEC 60247	≤ 0.072	≤ 0.072	≤ 0.072	≤ 0.072
Physical						
Visual Examination	D1524	IEC 62770 4.2.1	Clear, free from sediment and suspended matter			
Viscosity at 40°C (mm^2/sec)	D445	ISO 3104	≤ 50	≤ 50	≤ 50	≤ 50
Health, safety and environment						
Fire Point (°C)	D92	ISO 2592	≥ 300	> 300	> 300	> 300
Flash Point (°C)						
Cleveland Open Cup	D92	ISO 2592	≥ 275	≥ 275	≥ 275	≥ 275
Pensky-Martens Closed Cup	D93	ISO 2719	≥ 250	≥ 250	≥ 250	≥ 250
Chemical						
Water Content (mg/kg)	D1533	IEC 60814	≤ 350	≤ 300	≤ 150	≤ 100
Acid Number (mg KOH/g)	D974	IEC 62021.3	≤ 0.06	≤ 0.06	≤ 0.06	≤ 0.06

General Verifications

- Confirm all valves are in correct position, closed or opened as required.
- Confirm the purge of all tank compartments and accessories.
- Check that all thermometer wells are filled with oil.
- Verify oil level in the conservator, on load tap changer tank, bushings etc.
- Verify all grounding connections.
- Check the proper operation of all supervisory equipment, fans, heaters, pumps etc.

Commissioning

If approved in all pre-commissioning tests/checks, allow a settling time of at least 24 hours for power transformers or to double the typical time of mineral oil transformer, to ensure that all possible micro gas bubbles can dissipate from core and coil assembly. After setting up all supervisory and protection systems, such as overcurrent relays or differential relays, the transformer is prepared to be energized at no load with the tap changer at normal position. The voltage should be built up in steps wherever possible. Check whether the primary voltages and currents are balanced. Also, check if there is any undue noise or vibration during commissioning.

If possible, observe operation for a while. If operation is satisfactory, keep transformer on load and check voltages and currents readings on all phases of both HV and LV sides. Check top oil temperature at regular intervals and take oil samples are per standard procedures.

Insulation Resistance

The traditional procedure for insulation resistance (IR) measurement in conventional mineral oil filled transformers can also be applied in natural ester filled transformers. It is important to note that usual IR values in natural ester filled transformers are lower than mineral oil filled units. However, the IR measurement is still applicable as comparison with:

- original equipment manufacturer factory measurements, as a quality gate for manufacturing deviations prior to dielectric tests;
- measurement between phases, for tracking eventual insulation degradation;
- a typical (but not an acceptance criteria) minimum value of 500MΩ, measured with a $1000V_{DC}$/10GΩ instrument).

If these criteria are not reached, the original transformer manufacturer should be contacted regarding possible additional procedures requirements.

Power Factor Measurements

The power factors of transformers filled with FR3 fluid are usually higher than similar transformers filled with mineral oil. Cargill recommends User Specification acceptance limits to be doubled for FR3 fluid filled transformers.

Power factor testing is more common for power than distribution class transformers (IEC 60076-1 [33] and IEEE C57.12.00 [21] do not establish an acceptance criteria for power factor test). Some customers request the measurement for both factory quality assurance criteria and for establishing a baseline for preventive maintenance analysis.

Power factor is the ratio of resistance current to capacitance current in an insulation system. The power factor value depends on, among other things, the level of insulation dryness in new transformers. For operating transformers, changes in power factor can indicate increased levels of moisture or other contaminates in the insulation system. Power factor is a diagnostic property most effectively used to monitor trends over time.

There are several variables that impact power factor measurements, even for new, essentially dry uncontaminated units.

For liquid filled transformers, the insulation system is comprised of cellulose based solid insulation and a liquid dielectric coolant. The ratio of solid to liquid insulation varies with transformer design. Solid and liquid insulation differ in their dielectric properties. Distinct types of insulating coolants will also differ in their dielectric properties. Finally, as temperature varies, the power factor will also vary.

To properly evaluate power factor measurements, it is important to understand the variables and their relative impact. Correct fluid properties with measured values higher than expected are an indication of moisture in the solid insulation. A dry out procedure is recommended.

Insulation Systems Component Differences: FR3 Fluid and Mineral Oil Dielectric Loss Differences

The chemical makeup of natural esters has a slightly more polar character compared to mineral oil. This translates into a higher dissipation factor, all other variables equal. The dissipation factors of fluids and solid insulation also increase with temperature. Thus, the transformer power factor increases with temperature. Temperature correction factors convert power factors to their equivalent at 20°C so that values can be compared. The corrections to 20°C are not precise, and can vary even between the different measurements within the same transformer.

Figure 9 shows the approximate range of dissipation factor versus temperature of mineral oil and FR3 fluid.

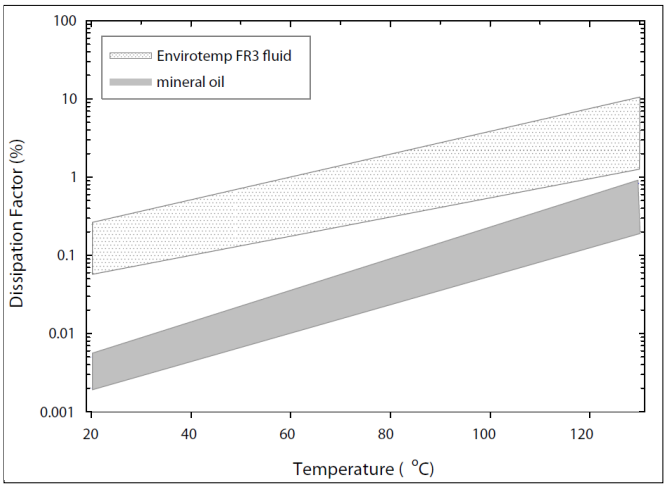


Figure 9
Dissipation factor versus temperature of mineral oil and FR3 fluid.

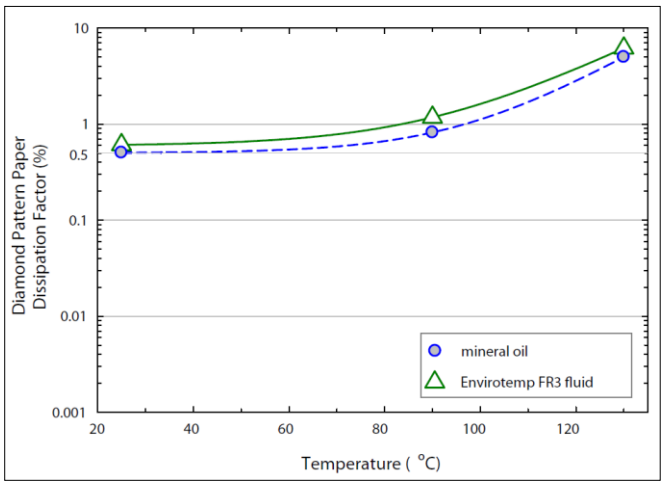


Figure 10
Dissipation factor vs. temperature of diamond patter paper impregnated with mineral oil and FR3 fluid.

Solid Insulation Impregnated with FR3 fluid or Mineral Oil

Impregnated solid insulation shows a higher dissipation factor with FR3 fluid compared to mineral oil. EHV Weidmann [34] evaluated the dissipation factors of three types of solid insulation impregnated with mineral oil or FR3 fluid.

Diamond epoxy coated insulating TUK insulating paper, medium density pressboard, and high-density pressboard all have similar relative difference in PF, approximately 50% increase, if impregnated with FR3 fluid rather than mineral oil. Figure 10 shows the relative dissipation factor differences vs. temperature.

Insulation Systems using FR3 fluid or Mineral Oil

Insulation system models were constructed using relative proportions of fluid and solid insulation to simulate the high to low winding insulation space of distribution and power transformers. The distribution models had impregnated solid insulation between the windings and the power transformer models had approximately 85% fluid between the paper wrapped windings.

The power factor measurements of the distribution system models using FR3 fluid were approximately 50% higher the same models using mineral oil. These measurements, in conjunction with distribution production data, indicate that a typical new distribution transformer impregnated with FR3 fluid would have a power factor measurement around 0.75% vs. an identical unit impregnated with mineral oil of approximately 0.50%.

The power factor measurements of the power system models using FR3 fluid were approximately 100% higher than the same models using mineral oil. This higher relative value for the power models is due to the higher ratio of oil to paper in the insulation system being measured. These measurements, in conjunction with power original equipment manufacturer production data, indicate that a typical new power transformer impregnated with FR3 fluid would have a power factor measurement around 0.40% vs. an identical unit impregnated with mineral oil of approximately 0.20% (see Figure 9).

The above relative differences also apply to retrofilled transformers initially impregnated and filled with mineral oil. However, the initial change in power factor will be less than that of the new FR3 fluid system due to the time it takes for the mineral oil in the solid insulation to exchange and equalize with the FR3 fluid. In general, the time to reach power factor equilibrium will be slower for retrofilled distribution transformers, again due to the much higher paper to oil insulation system ratio.

Moisture Measuring in Solid Insulation

Also known as estimation of moisture content at solid insulation surface, the procedure of evaluating the dew point of an initially dry air inserted in the drained tank, after it reaches an equilibrium condition with the solid insulation can also be applied in FR3 fluid filled units. The process starts by keeping transformer under vacuum for a certain period, filling then with dry air to reach a very low dew point (typically around -60ºC). After 12h or 24h there will be equilibrium between the dry air inside the tank and the solid insulation surface. The dew point change of the air inside the tank is used to estimate the insulation moisture content.

The estimation of the solid insulation moisture content based on the moisture content of the fluid is also an alternative, using the data from chart Figure 11.

The value measured can be compared with the factory measurement before dispatch. The original transformer manufacturer should be contacted for acceptance criteria.

IMPORTANT: Unlike assemblies impregnated with mineral oil, hot air drying is an unacceptable process for reducing power factor of assemblies already impregnated with natural ester fluid. For additional drying of natural ester impregnated assemblies, a method that does not expose the impregnated insulation to air is required to avoid polymerization of the dielectric fluid.

Drying Impregnated Insulation

Drying impregnated insulation by exposure to hot FR3 fluid, kerosene vapors, or nitrogen is acceptable.

Hot FR3 fluid dry out of insulation impregnated with FR3 fluid:

- Lower the fluid level well below the radiator inlet, but above all current carrying parts, to disable radiator cooling.
- Seal the tank with a nitrogen atmosphere over the fluid. Use a pressure relief device to protect against over-pressure.
- Heat the transformer until the top fluid temperature is about 110°C by means of a fluid heater or by using the heat run power supply.
- Using a nitrogen backfill, drain the fluid from the tank. Place the tank under vacuum to dry the insulation. Do not exceed the vacuum rating of the tank. Cold traps (water vapor condenser) will make the system more effective.
- Vacuum fill with dry FR3 fluid or break vacuum with dry nitrogen if the unit must be stored prior to vacuum filling.

Repeat as needed to obtain the required insulation dryness. Vapor phase drying of FR3 fluid impregnated assemblies can be used. Remove the residual FR3 fluid from the vapor condensation chamber. The user is responsible for developing a procedure compatible with their manufacturing or repair process.

MAINTENANCE

A rigorous system of inspection and preventive maintenance will ensure long life, trouble-free service and minimize maintenance costs. Maintenance includes regular inspections, testing and reconditioning. Records of the transformer, written details of all inspections, tests performed and unusual occurrences, if any, should be kept. Main target of maintenance is keep insulation in good conditions. Moisture, dirty particles and excessive heating are common causes of insulation deterioration and avoiding them will keep the insulation in good condition.

General Safety Precautions

Good preparation is essential before performing any intervention in transformers. Good planning includes evaluation of required facilities, tools and equipment to ensure a safe work environment. Only qualified personal can be assigned to these activities, following all local regulations and standards.

IMPORTANT: To prevent moisture ingress, and maintain the optimal fluid properties for its intended use as an electrical insulating fluid, exposure to oxygen, moisture and other contaminants should be minimized.

Before starting any maintenance work the transformer should be isolated from the supply and the terminals grounded. The level of insulation fluid in the transformer should be considered before undoing nuts and bolts and before unsealing the tank.

General Procedure

Fluid analysis is the most important predictive maintenance procedure for power transformers. As getting a “blood test” for human being, the fluid provides information about what is happening inside the transformer. Every company should decide on sampling interval according to transformer ratings. Usual timing is:

- Dissolved Gas Analysis: every 6 months
- Fluid physical-chemical analysis: every 1 year

Importance of Sealing System

Transformer sealing system is responsible to form a separation barrier between the external environment and transformer insulation system, formed by solid and liquid insulation materials.

Free-breathing transformers have been widely used. In the 60’s, several studies such as Fabre and Pichon [35] revealed that, when the fluid is rich in dissolved oxygen gas, the degradation of the solid cellulosic insulation due to oxidation is much higher than thermo-hydrolytic degradation. The moisture absorption from ambient is also a concern, impacting paper degradation and requiring fluid treatment, especially in wet regions.

These tests have been performed using mineral oil and encouraged the use of sealing systems. Paper aging reduction is the main expected advantages of sealed and “non-free breathing” construction design.

Free-breathing construction design is not recommended for FR3 fluid filled transformers. In addition to the recognized benefits for paper degradation, a sealing systems or non-free-breathing construction design will prevent the dielectric fluid from coming in contact with replenishing air. This will help ensure long term stability of the natural ester fluid.

A large quantity of tests has been performed assuring FR3 fluid is a robust product for all application except free-breathing transformers. FR3 fluid has service proven stability in sealed transformers and some

eventual exposure to ambient is not a concern for the FR3 fluid oxidation stability.

For example, a large test tank filled with FR3 fluid was left without cover during 5 years in a warehouse. The fluid presented elevated dissipation factor, elevated water content and slight increase in viscosity, but maintained a relatively good condition. There was no polymerized layer on fluid surface caused by the free oxidation. Another test, with completely free breathing construction transformers, was performed during 11 years, under cyclic loading operation to force transformers to the "breathing effect". Twice a year the transformers were dielectrically tested (applied voltage, induced voltage and 3x impulse, all at nominal level), without present any failures. After 7 years, the viscosities had increased about 10%, which is the acceptance limit for triggering an investigation according IEEE C57.147

Oil Deterioration

In general, insulating oils are subject to deterioration or contamination during storage, handling or service. As a result, periodic treatment to maintain the fluid in as-new condition is indicated. Insulating oils are subject to normal deterioration due to normal operating conditions. Oxidation is a long-term process and the most common deterioration of a fluid. Kinematic viscosity increase is the main property to indicate significant oxidation of FR3 fluid and other natural ester fluids.

Like conventional mineral oil, FR3 fluid thermal degradation occurs along the years of transformer life. The insulating fluid is submitted to a slow process of thermal degradation due to some content of dissolved oxygen always presented in the fluid, and reactions accelerated by temperature with the presence of metal catalysts such as iron, copper, and other dissolved metallic compounds. Thus, the oil darkens in color, acidity increases simultaneously with changes in electrical characteristics such as reduction in the dielectric breakdown voltage and/or increase in dissipation factor and, as a late effect, increasing the viscosity. Main difference to mineral oil lays on the absence of sludge.

Insulating liquid in a transformer operating under normal load conditions, adequately sealed and away from moisture and particles, will present very little deterioration after several years of service. Periodic testing for FR3 fluid is recommended according the customer procedures for mineral oil or, if not defined, at 12 monthly intervals for moisture content, dielectric breakdown, acidity, viscosity, flash point and dissipation factor. Dissolved gas analysis can also be applied similarly to mineral oil filled transformers.

Records of all tests should be kept together with records of load and operating conditions. Excessive and increasingly deterioration can be assessed, preventing fluid damage and keeping transformer performance.

Guidelines for key properties acceptance values for triggering prompt investigation of service-aged FR3 fluid and other natural ester filled transformers are presented in Table 6 and Table 7. Since in-service transformers filled with natural ester fluids are relatively recent, data collection is still undergoing refinements in the parameter.

Effects of Oxygen and Moisture in Solid and Liquid Insulation

The main concern during a short-term exposure of the internal components of a transformer to the ambient is moisture ingress. Depending on the ambient moisture content and transformer loading there is a possibility to have some moisture migration to the solid insulation. Increased oxygen and water content in the solid insulation is not desired as it accelerates solid insulation aging rate (oxidation and thermo-hydrolytic degradation) and can affect dielectric strength.

Water solubility of FR3 fluid is higher than mineral oil, shifting solid-liquid equilibrium and causing significantly water migration from paper into FR3 fluid. Figure 11 shows the effect of the equilibrium shift and the water drying out process on solid insulation. The influence of the water shift is discussed in references [36] [37].

Field experiences confirmed that the moisture, eventually absorbed by fluid from the contact with ambient air, can also be consumed by fluid hydrolysis, preventing moisture migration to the solid insulation.

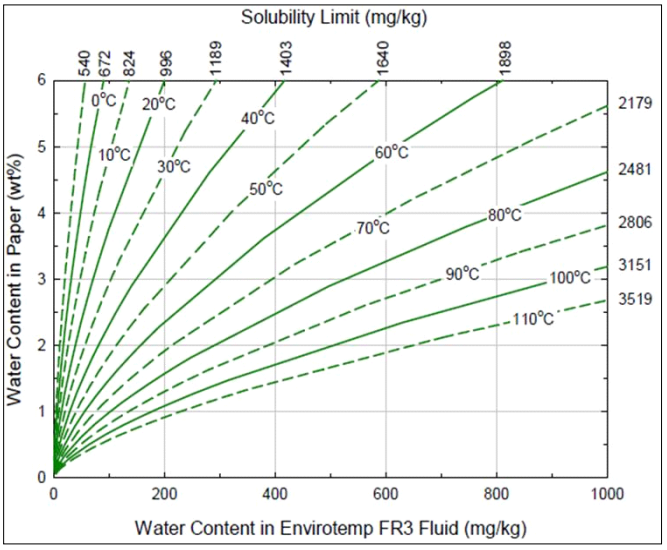


Figure 11
Water content in FR3 fluid in equilibrium with water content in thermally upgraded Kraft paper based on vapor pressure of water ("Piper" chart).

Table 6
Guidelines for Key Properties Acceptance Values of Service-Aged Envirotemp FR3 Fluid and other Natural Ester Fluid for Triggering Prompt Investigation of the Transformer

	Standard Test Methods		Voltage Class			
Property [a]	**ASTM**	**ISO/IEC**	**≤36kV**	**> 36kV ≤ 69kV**	**> 69kV ≤ 230kV**	**> 230 kV**
Electrical						
Dielectric Breakdown (kV)						
1mm gap	D1816		< 23	< 23	< 28	< 30
2mm gap	D1816		< 40	< 40	< 47	< 50
2.5mm gap		IEC 60156	< 40	< 40	< 50	< 60
Dissipation Factor						
25°C (%)	D924	IEC 60247	> 3%	> 3%	> 3%	> 3%
90°C (tan δ)			b	b	b	b
Physical						
Color	D1500	ISO 2211	> 1.5	> 1.5	> 1.5	> 1.5
Percentage increase in Viscosity at 40°C (%) [a]	D445	ISO 3104	> 15%	> 15%	> 15%	> 15%
Safety and Environment						
Flash Point (°C)						
Cleveland Open Cup	D92	ISO 2592	< 275	< 275	< 275	< 275
Pensky-Martens Closed Cup	D93	ISO 2719	< 250	< 250	< 250	< 250
Chemical						
Relative Moisture (%)	D1298		> 45%	> 40%	> 25%	> 20%
Water Content (mg/kg)	D1533	IEC 60814	> 435	> 385	> 240	> 200
Acid Number (mg KOH/g)	D974	IEC 62021.3	> 0.3	> 0.3	> 0.3	> 0.3

NOTE: a) The trend along time is more relevant, especially due to the fact the values are still considered as provisional.
b) These values are not yet available. Further investigation is required.

Table 7
Decision table with recommended actions for FR3 fluid out of service limits or according to one specific analysis.

Viscosity	Tgδ (%) or DDF (%)	BDV	Moisture Content	Neutralization Index	Recommendation
OK	OK	OK	OK	OK	No action
				Not OK	Reclaiming of the insulating liquid
		Not Ok	OK	OK	Reconditioning of the insulating liquid
				Not OK	Reclaiming or replacement of the insulating liquid
			Not OK	OK	Reconditioning of the insulating liquid. If transformer power factor is changed, consider a dry out of core and coil
				Not OK	Reclaiming and recuperation of the insulating liquid or replacement
	Not OK				Reclaiming and recuperation of the insulating liquid or replacement
Not OK					Consider replacement of the insulating liquid

NOTE: a) Reclaiming of the insulating liquid = treatment using bauxite or Fuller's earth
b) Reconditioning of the insulating liquid = treatment using thermo vacuum and filtering (degassing machine)
c) Core and Coil Dry Out = core and coil treatment to extract moisture from solid insulation material.
d) OK or Not OK refers to the suggested limits of Table 6 or according to criteria of each user.

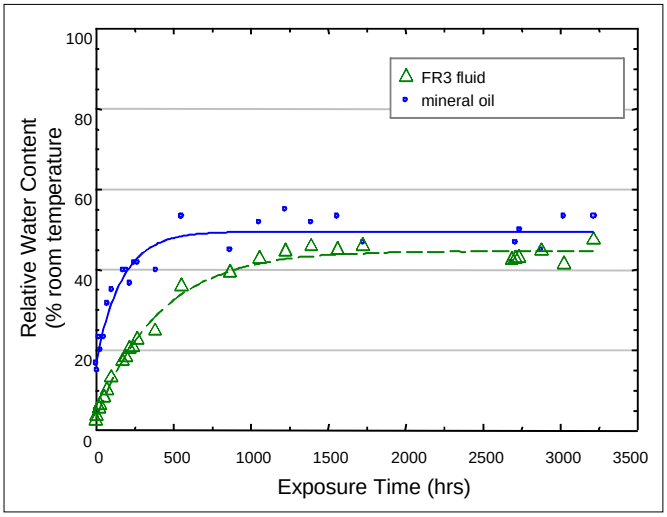


Figure 12
Water absorption of mineral oil and FR3 fluid exposed to ambient air, show as relative water content

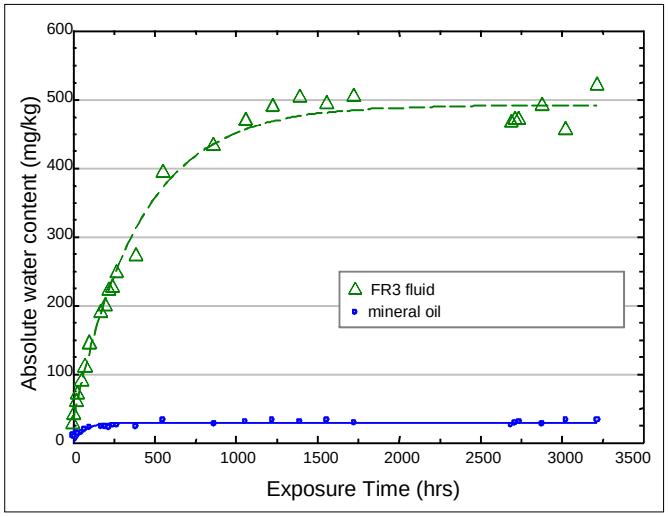


Figure 13
Water absorption of mineral oil and FR3 fluid exposed to ambient air, shown as absolute water content.

Water Absorption During Maintenance and On-Site Drying

Water absorption from the atmosphere is shown in Figure 12 and Figure 13. In terms of absolute water content, FR3 fluid absorbs water at a faster rate than mineral oil. In terms of relative water content, mineral oil absorbs water at a faster rate. The same precautions taken to minimize water absorption by mineral oil during maintenance should be taken for FR3 fluid.

The water content of FR3 fluid is reduced through treatment/filtering process in the same way as mineral oil. Water contents below 50 mg/kg are easily achieved.

Measures to Avoid Polymerization During Maintenance

Natural esters oxidation leads to the formation of oligomers, increasing its viscosity and eventually forms polymers (thin film polymerization).

Increase in viscosity is the definitive indication that oxidation is occurring. Polymerization is most likely to occur when thin films of FR3 fluid on metal surfaces are exposed to air and sunlight (UV radiation).

FR3 fluid in a transformer under an unintentional free-breathing condition will take years to show an increase in viscosity. However, long before the viscosity increases, the dissipation factor of the fluid increases greatly, anticipating ample warning to the user if transformers fluid is routinely sampled.

Transformer maintenance and repair tasks are most likely to expose FR3 fluid to the atmosphere and potentially cause thin film polymerization. Components impregnated with FR3 fluid and susceptible to the thin film polymerization should be immersed in FR3 fluid. If immersion is not a possibility, the components can be rinsed preferably with dielectric solvent or isopropyl alcohol and stored in plastic bags of low oxygen permeability. Do not dry components in hot air ovens. For additional recommendations, see Cargill's Bulletin R2080, "Thin Film Oxidation".

DIAGNOSTIC TESTS

The properties in this category do not directly affect transformer performance, but rather are used as indicators of changes in the fluid over time due to transformer operation. The trends are at least as useful as the values themselves. The quality of FR3 fluid is measured using the same standard test methods used for conventional mineral oil. However, due to the differences in their chemistry, the normal base line values will be different for certain properties.

The polarity and molecular structure of esters influence the values obtained from the standard tests. Water content, dissipation factor, pour point, and acid number are typically higher than those of conventional transformer oil. Interfacial tension, gassing tendency and resistivity are normally lower than mineral oil. Other tests, such as furanic compound content, require specific test methods to obtain reliable results.

Water Content

Use IEC 60814 [38] or ASTM D1533 [39] without modification. Water saturation versus temperature is shown in Figure 14. The room temperature water saturation of FR3 fluid is about 1000 mg/kg, and about 55 mg/kg for mineral oil. This high capacity for water is one of the important attributes of FR3 fluid, and is a major factor in the longer life of Kraft paper insulation compared to its life in mineral oil.

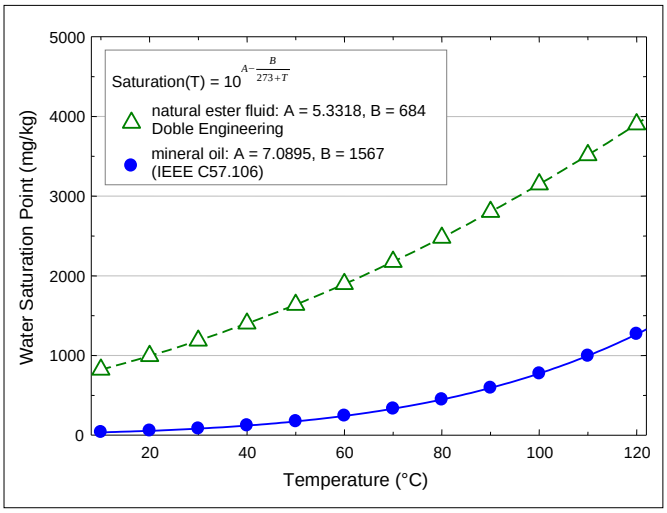


Figure 14
Water saturation versus temperature for mineral oil and FR3 fluid.

New processed FR3 fluid typically contains 20-50 mg/kg of water. IEC 62770 and ASTM D6871, reference standards for Unused Natural Ester Fluids, allow a maximum of 200 mg/kg.

Dissipation Factor

Use IEC 60247 [40] or ASTM D924 [41] without modification. When using a single test cell for both mineral oil and FR3 fluid dissipation measurements, the cell must be meticulously cleaned when changing from one type of fluid to another. This is especially true when measuring FR3 fluid after mineral oil. Artificially high values may be seen if the cell is not sufficiently clean. The dissipation factor of new FR3 fluid is naturally higher than new mineral oil. The chemical makeup of ester fluid is relatively polar compared to mineral oil. This characteristic, along with the higher acid number, explains the higher dissipation factors.

Acid Number

Use IEC 62021-3 [42] or ASTM D974 [43] without modification. New FR3 fluid naturally contains small amounts of free fatty acids that result in acid numbers higher than those typically seen in mineral oil. As the FR3 fluid ages, it reacts with water (hydrolysis), generating additional long-chain fatty acids. The long-chain fatty acids are mild and non-corrosive compared to the short chain organic acids found in mineral oil. Although the acid number method determines the amount of acidic components present, it does not indicate the type or reactivity of the acid.

Interfacial Tension

Use ISO 6295 [44] or ASTM D971 [45] without modification. Due to the slightly polar characteristic of FR3 fluid, interfacial tension, typically, is not affected by fluid deterioration, bringing no useful information on this regard. However, more service history data is required to establish limits. New FR3 fluid has an inherently lower IFT value compared to mineral oil.

Resistivity

Use IEC 60247 or ASTM D1169 [46] without modification. For the same reasons that the dissipation factor of FR3 fluid is higher than mineral oil, the resistivity is lower.

Pour Point

The pour point of FR3 fluid is typically in the range -24°C to -21°C, and is higher than that of mineral oil. Carefully follow ISO 3016 [47] or ASTM D97 [48] to obtain accurate results. Heat fluid samples to 130°C and cool to room temperature before starting a pour point determination. Cooling ramp rates and pour point monitoring intervals need to conform exactly to the test method to obtain accurate pour point values.

ASTM D5950 [49] can also be used to determine the pour point of FR3 fluid. Note that D5950 consistently gives a pour point about 3°C lower than D97. The main reason is the difference in optical sensitivity of the detector versus the human eye to the refracted light.

NOTE: Pour point is simply a diagnostic test that compares relative cold flow properties of different oils but does not determine fluid performance below its pour point.

Gassing Tendency

The IEC 60628 [50] or ASTM D2300 [51] can be used. Per ASTM D2300 gassing tendency for FR3 fluid is -79 µl/min, significantly lower than that of mineral oil. The high degree of polyunsaturation has a greater tendency and capacity to absorb hydrogen under partial discharge conditions.

Oxidation Inhibitor

The oxidation inhibitor content can be measured using the general conditions for additive types found in IEC 60666 [52] and ASTM D4768 [53] test methods. The GC or HPLC methods are more specific and preferred over the infrared (IR) technique because esters and ester by-products absorb IR in the same region(s) as the inhibitor additives.

Consider replenishing the inhibitor if the inhibitor content falls below 0.12%. Note that mineral oil oxidation stability tests are not suitable for use with natural ester fluids. Cargill recommends using an oxidation induction time method employing a differential scanning calorimeter (DSC) using oxygen gas to compare natural ester fluids and evaluate inhibitor additives.

Oxidation Stability

IEC 62770, has published an oxidation stability method for natural ester fluids. After several rounds of

laboratorial comparison around the world, a modified version of IEC 61125C has been developed and the acceptance criteria defined. This method is an acceptance test and not intended for comparison between different natural ester fluids. Cargill recommends the use of this method for qualifying natural ester based fluids.

As of this writing, ASTM has not published an oxidation stability method applicable to natural ester fluids. However, a new ASTM work group WK21616 - Standard Test Method for Oxidation Induction Time of Natural Ester Insulating Fluids by Differential Scanning Calorimetric (PDSC) has been initiated in Subcommittee D27.06 as of May 2014. Cargill recommends the use of differential scanning calorimetric (DSC) method [54] for comparison between different fluids and determine the oxidation induction time.

Contact your local Cargill Dielectric Fluids group to obtain detailed procedures or email us at fr3fluid@cargill.com.

PCB Content

New FR3 fluid contains no detectable polychlorinated biphenyls (PCB). PCB content is measured in accordance with IEC 61619 [55] or ASTM D4059 [56] using a packed column. Accurate results can be obtained using the sulfuric acid treatment to remove interferences.

Adsorbent treatment to remove interferences is not recommended. PCB contents of spiked lab samples prepared using the adsorbent treatment were consistently low.

Flash and Fire Points

Use ISO 2592 [57] or ASTM D92 [58] without modification for open cup flash and fire points. Use ISO 2719 [59] or ASTM D93-16a [60] Flash Point for closed cup flash point measurements.

Contamination by more volatile fluids lowers the flash point, and may lower the fire point. Flash point values can be used to estimate the residual amount of mineral oil in a transformer retrofilled with FR3 fluid. Figure 5 shows the flash and fire points as a function of mineral oil content in FR3 fluid.

Corrosive Sulfur

The ASTM D1275 [61] and/or IEC 62535 [62] and/or IEC 62697-1 [63] methods can be used for detecting corrosive sulfur in FR3 fluid without modifications to the methods. Note that the ASTM D1275 method uses the intensity of discoloration observed on a copper strip to determine the presence of corrosive sulfur. The discoloration of a strip, especially at higher temperatures or longer aging times, can also be due to non-sulfur sources that act as false positives. Semi-quantitative elemental surface analysis using energy dispersive x-ray spectroscopy (EDS or EDX) provides the needed source discrimination. IEC 62535 uses a copper strip covered with Kraft insulating paper for detection. IEC 62697-1 is a method to detect DBDS in insulating liquids using various methods.

Furanic Compounds

Both IEC 61198 [64] and ASTM D5837 [65] method for determining furanic content in mineral oils was applied to FR3 fluid although the method does not specifically include natural ester fluids in its scope. The technique works very well for both new mineral oil and new FR3 fluid. However, as the FR3 fluid becomes degraded, the method begins to suffer from interferences from other degradation products being extracted and concentrated along with the furans. These interferences raise the lower detection limit and increase the error of the method.

Particle Count

The IEC 60970 [66] and ASTM D6786 [67] method for determining the number of particles in a fluid can be used if the sample is diluted with a clean lab solvent. The viscosity of FR3 fluid may not allow the air bubbles entrapped in the fluid to dissipate in the time allotted to make the measurement. The air bubbles are detected as particles.

Dilute the FR3 fluid about 75% with pre-filtered heptane or hexane. Filter the solvent using a 0.2µm membrane filter. Use the filtered solvent to obtain a blank value for particles. This works effectively unless the particle count in the fluid is low. In that case, less dilution and some trial and error are required. Note that the applied pressure should be limited to 80 psi to minimize the pressure drop across the cell.

A high particle count can be the result of crystallites in fluid recently below the cloud point temperature. If this is the case, warm the fluid to re-dissolve the crystallites.

DISSOLVED GAS ANALYSIS (DGA)

Dissolved gas analysis (DGA) is a diagnostic technique useful in preventive maintenance, condition assessment, and fault identification of liquid-filled transformers (the transformer equivalent of getting a blood test as part of a routine physical examination). The analysis determines the amounts of gases dissolved in the oil: hydrogen, hydrocarbon gases (methane, ethane, ethylene and acetylene), carbon oxides (carbon monoxide and carbon dioxide), oxygen, and nitrogen.

IMPORTANT: Samples of FR3 fluid for dissolved gas determinations are taken and analyzed using the same procedures and techniques as those used for mineral oil. The data are interpreted in much the same way as for gases in mineral oil.

The types of gases dissolved in the oil, along with their amounts, relative proportions, and changes over time provide clues about what's happening in the transformer. Gases are formed during normal aging processes, thermal breakdown, operation of fuses or switches, by electrical defects, or during abnormal events.

- The gases formed during oil decomposition are typically hydrogen and hydrocarbon gases.
- The gases formed from paper insulation (cellulose) decomposition are typically carbon oxides.
- Different types of faults generate gases with their own characteristic "signature" gas proportions.

The gas analysis tells us the amounts of gases dissolved in the oil. Although all the gas data are informative, the dissolved combustible gases are the most useful for fault diagnosis. Guides to aid in the interpretation of dissolved gases use several methods to extract information about transformer condition. The amounts, proportions, and rates of gas generation are used to help determine if a fault exists and identify the type of fault.

More important than data from a single gas sample are the rates of gas generation (how the gases change over time). The effort expended in interpreting and acting on the gas data is almost always in direct proportion to the generation rate.

Although some faults can be consistently diagnosed using DGA (active arcing faults, for example), many times evaluating the data requires the operational, maintenance, and test histories of the transformer. Even then, the interpretation may not be clear-cut.

Excellent discussions of dissolved gas theory and its practical application can be found in the Facilities Instructions, Standards, and Techniques manuals published by the U.S. Bureau of Reclamation [70] [69].

Gas Solubility

The solubility of gases in FR3 fluid differs slightly from their solubility in mineral oil (Table 8). The volume of gases generated by some faults, most notably arcing faults, can also be different. Low current arcing faults in FR3 fluid generate smaller volumes of gas (tests yield gas volumes of about 75% the volume generated in mineral oil). These differences might affect the utility of some ratio analysis methods and estimates of combustible gas content in the headspace.

Table 8
Gas Solubility (Ostwald) Coefficients for FR3 Fluid and Mineral Oil

	25°C		70°C	
Gas	**FR3 fluid** [68]	**Mineral oil** [69]	**FR3 fluid** [68]	**Mineral oil** [69]
Hydrogen H_2	0.05	0.05	0.097	0.092
Oxygen O_2	0.15	0.17	0.255	0.208
Nitrogen N_2	0.07	0.09	0.141	0.127
Carbon Monoxide CO	0.09	0.12	0.148	0.143
Carbon Dioxide CO_2	1.33	1.08	1.187	0.921
Methane CH_4	0.30	0.43	0.387	0.432
Ethane C_2H_6	1.45	2.40	1.677	2.022
Ethylene C_2H_4	1.19	1.70	1.389	1.419
Acetylene C_2H_2	1.63	1.20	1.763	0.992
Propane C_3H_8	-	-	4.041	6.844
Propylene C_3H_6	-	-	4.078	5.369

Methodology and Comparison to Mineral Oil

Dissolved gas data from thousands of normally operating and faulted mineral oil transformers, collected, examined, and pondered over the course of decades, form the empirical basis of a means to help assess the condition of a particular transformer.

The IEC, IEEE, Cargill and U.S. Bureau of Reclamation publish guides to aid in interpreting dissolved gas data for fault diagnosis [25] [69] [70] [71] [72] [73] [74] [75] [76] [77]. Because transformers using natural esters such as FR3 fluid are a recent development with practically no failures in the field, the opportunities to evaluate actual faulted transformers are very few. The few available to us, together with data from normally operating transformers and a variety of laboratory studies, have helped to validate the application of DGA to FR3 fluid.

The data are interpreted in much the same way as for gases in mineral oil. The combustible gases generated by faults in FR3 fluid are similar to those in mineral oil: high levels of hydrogen may be an indication that partial discharge is occurring; carbon oxides in certain ratios suggest overheated paper; hydrocarbon gases could result from a thermal fault in oil; acetylene points to arcing.

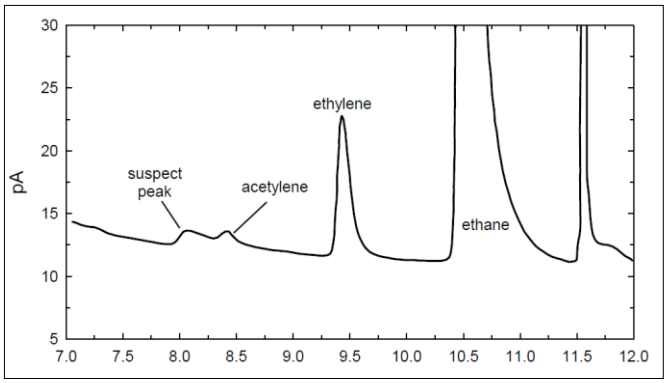


Figure 15
Chromatogram showing a small "false acetylene" peak eluting just prior to acetylene.

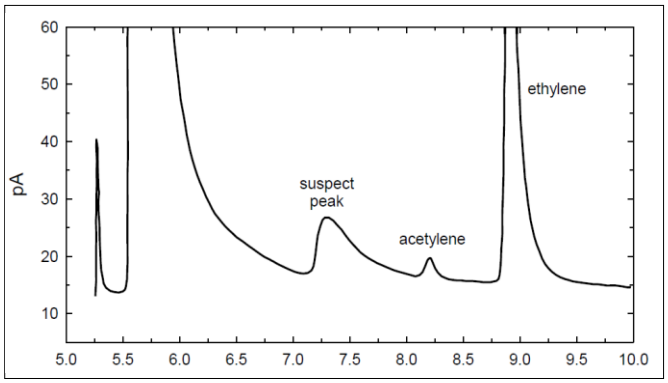


Figure 16
Chromatogram showing a larger "false acetylene" peak that could be mistaken for acetylene.

Always, the first step is to determine if a fault exists using the amounts and generation rates of dissolved gases before trying to further interpret the gas data. The most useful approaches to dissolved gases in FR3 fluid use the gas generation rates combined with the IEEE Key Gases method or the IEC Duval method [74].

Ethane and Hydrogen

Many (but not all) otherwise normal operating transformers using FR3 fluid have higher ethane content compared to mineral oil units. Other hydrocarbon gases remain low – only ethane can be elevated. Occasionally, a slightly elevated level of hydrogen is also found. This may incorrectly indicate a partial discharge fault.

The presence of an elevated level of ethane and sometimes a slight amount of hydrogen from FR3 fluid and other natural esters has been studied and described as resulting from stray gassing [78]. Stray gassing is due to oxidation of the unsaturated fatty acid compounds of natural ester fluids under service conditions. Even degassed fluid contains some dissolved oxygen that can react with the oleic, linoleic and linolenic acid portions of the fluid.

Ethane gas predominates from linolenic acid that is higher in FR3 fluid than other natural ester fluids. Fluids that contain higher amounts of oleic and linoleic acids, and little to zero linolenic acid can produce higher levels of octane and pentane respectively, but little to zero ethane.

Acetylene

Throughout the adaptation of gas chromatography and analysis for FR3 fluid, we often see a peak (identity unknown) with an elution time close to the elution time of acetylene. At times this peak is no more than a baseline rise that quickly levels off and can easily be distinguished from acetylene (Figure 15).

In other cases, the peak appears to be genuine (more than a baseline rise) and elutes so closely to acetylene that it can be mistaken for acetylene (Figure 16).

Because the presence of small quantities of acetylene prompts additional transformer scrutiny, the chromatographer should be aware of the possible occurrence of the misleading peak.

More work should be done to identify this substance and develop criteria to reliably distinguish it from acetylene.

IEC Methods of Interpretation

The IEC 60567 [25] gas guide basic ratio and simplified ratio methods use various ratios of hydrogen and hydrocarbon gases to help identify fault types. The IEC Duval method looks at the relative proportions of methane, ethylene, and acetylene to identify the type of fault, assuming one is present. The Duval method plots the data on a ternary graph divided into areas of fault types. This has so far been the most reliable fault identification method for FR3 fluid. Refer also to the recent publication from CIGRE D1 Working Group about DGA in non-mineral dielectric fluids [79].

The user should determine if a fault condition exists for the interpretation methods to be meaningful. The user establishes the presence of a fault using the gas generation rate and typical gas levels of normally operating transformers. Duval reviews the IEC methods development and application [74] [75] [79].

Rates of Gas Increase

According to the IEC guide, an increase in gas concentrations of more than 10% per month above typical concentration values is generally considered a prerequisite for pronouncing the fault as active, provided the precision of DGA values is better than 10% after one month.

Much higher rates of gas increase, such as 50% per week, and/or evolving towards faults of higher energy (e.g. D2 or T3), are generally considered very serious, especially if they exceed alarm concentration values. In the case of power transformers, typical rates of gas productions in milliliters per day are also reported. Special attention should be given to cases where there is acceleration in the rate of gas increase.

Table 9
Methods of Analysis from IEC Gas Guide

Method	Analysis	Application to FR3 fluid
Duval	proportions of methane, ethylene, and acetylene	applicable (most reliable method overall)
Basic Ratios	combinations of methane/hydrogen, ethylene/ethane, and acetylene/ethylene ratios	applicable
Simplified Ratios	ratios of methane/hydrogen, ethylene/ethane, and acetylene/ethylene	applicable
CO2/CO	carbon oxides ratio	applicable

IEC uses broad classes of detectable faults: partial discharge, low or high-energy discharges, and thermal faults in oil and/or paper (Table 9). The basic and Duval methods subdivide these into more specific types. The simplified method identifies only the main fault type.

Duval Triangle

A modified Duval triangle for FR3 fluid has been published recently. The modifications are very small with slight changes in the percentages for T1-T2 and T2-T3 transitions. Figure 17 and Figure 18 shows Duval triangles [75] for FR3 fluid and mineral oil.

The comparison of both triangles allows a clear understanding about the similarity for the analysis, since the modifications are very small. This is a continuous improvement active, which is supposed to receive updates along the time, when more and more power transformers using FR3 fluid will be in operation and the repertory of DGA grows.

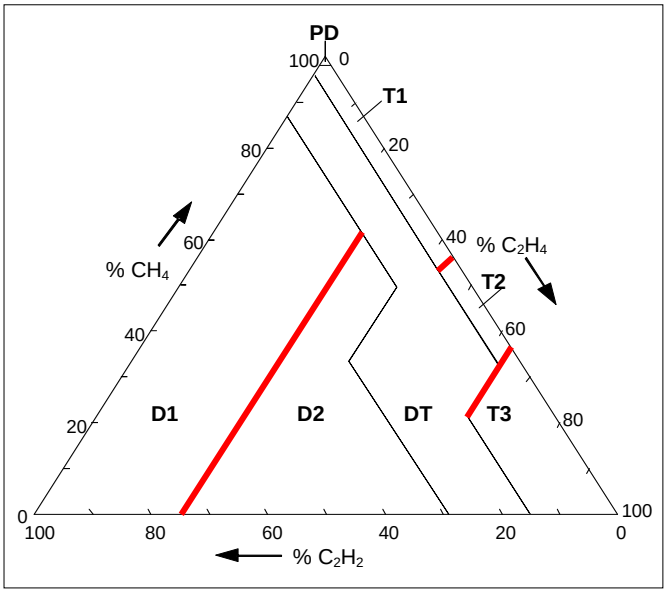


Figure 17
Duval Triangle for FR3 fluid. Zone boundaries in red color are specific for FR3 fluid.

IEEE Methods of Interpretation

The IEEE C57.155 [77] focus on the dissolved gas analysis of non-mineral dielectric fluids and presents an important collection of stray gassing data. Stray gassing refers to the gases produced from the dielectric fluid of a transformer under normal service operating conditions and is therefore not an indication of failure or abnormal behavior.

Stray gassing classification or fault indication is the main difference of dissolved gases analysis for mineral oil filled transformers to the ones filled in FR3 fluid.

Table 10 shows the gases and volumes characteristic of stray gassing for FR3 fluid. An initial sample from transformer with no previous sample history that exceeds the values given in Table 10 should have a confirmation DGA sample. Subsequent results of samples should be trended and, if necessary, diagnostic methods applied to the results.

Table 10
Threshold Value [µL/L (ppm)] for Transformers with no Previous Sample History

	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
90th Percentile	112	20	232	18	1	161
95% Confidence Interval	(105-118)	(19-22)	(219-247)	(17-20)	(1-1)	(150-179)

Applying the IEEE methods to distribution transformers can require some deviation from the guide: switches and fuses generate gases during their normal operation; the proportions and amounts of paper and oil differ from large transformers; smaller volumes of oil result in higher concentrations of gas; the lower voltages used in distribution are less likely to cause partial discharge.

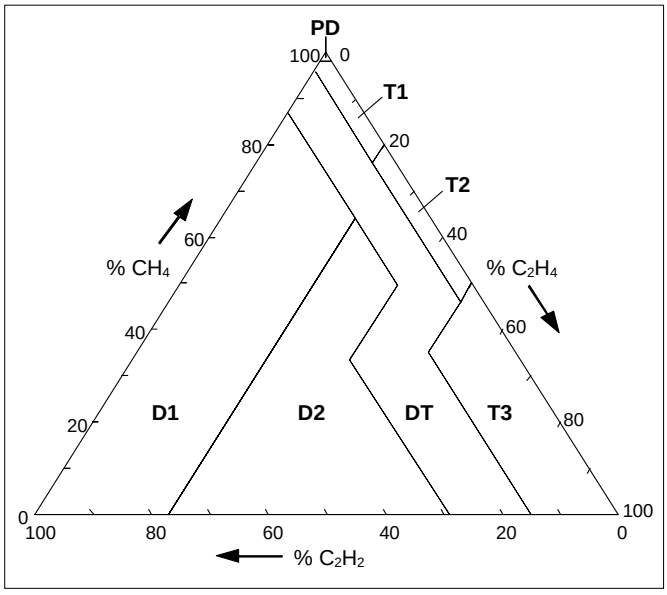


Figure 18
Duval Triangle for Mineral Oil.

Table 11
Gases by Fault Type from IEEE Gas Guide

Fault Type		Gases Created
Thermal	mineral oil:	
	low temperature	hydrogen, methane; trace levels of ethane, ethylene
	modest temperature	hydrogen > methane; ethane, ethylene
	high temperature	hydrogen, ethylene; trace levels of acetylene
Electrical	paper	carbon monoxide, carbon dioxide
	low intensity discharges	hydrogen, decreasing quantity of methane, trace acetylene
	high intensity arcing	Acetylene

Table 11 shows the gases generated by fault type from IEEE C57.104 [72] gas guide for mineral oil. A prerequisite to applying the interpretation methods should be to determine if a fault exists using the amounts and generation rates. IEEE divides the gas generation rate into three ranges: <10 ppm/day, 10-30 ppm/day, and >30 ppm/day. The gassing rate is used in conjunction with the amount of gas present (condition method) to advise actions.

FLUID TREATMENT

Degassing

Degassing of FR3 fluid is done the same way, and using the same equipment, as for mineral oil. Due to the higher thermal stability FR3 fluid, it may be possible to perform the degassing at a slightly higher temperature, up to 80°C. This can bring advantages regarding the total time of the process and will not affect the fluid long term performance (no extraction of additives). However, since most of modern machines have automatic control of the flow, no differences of performance are expected when processing FR3.

Fluid Reconditioning

The reconditioning processes applied for mineral oil can also be applied for FR3 fluid. The reconditioning is, typically, performed using a degassing machine associated with a filtering unit, a machine also named as “Thermo-vacuum”. More details can be found at the section Thermo-Vacuum/Degassing Machines.

Fluid Reclaiming (Regeneration)

The processes for fluid reclamation applied for mineral oil can also be applied for FR3 fluid. Typically, the applied processes are percolations using Fuller Earth or Bauxite (alumina).

Both options are effective for reclaiming dissipation factor and neutralization number. Essential difference is the color recovering, since the color change in FR3 fluid is not caused by sludge or other contaminants. Vegetable oils have a “color fixation” characteristic condition, well known for the refining process. Differently than mineral oil, color cannot be used as a control parameter for fluid reclamation process.

MATERIAL COMPATIBILITY

Material compatibility with FR3 fluid is a recurring requirement for customers using it as a dielectric insulating fluid alternative to petroleum-based mineral oil. The FR3 fluid compatibility data and results supplied in this document were summarized from sixty seven separate studies on FR3 fluid and materials that date back to 1995. This report reflects the most current information available. Table 12 presents a list of tested and approved materials. Materials not listed may have not yet been tested.

In general, results show that FR3 fluid is compatible with the majority of elastomers, polymers and materials commonly used in electrical equipment manufacturing. These same materials are also, in general, compatible with mineral oil and synthetic ester fluid. Of course, electrical equipment manufacturers should test their specific materials for compatibility with FR3 fluid. The compatibilities stated here are based on new unused materials. Materials aged in other dielectric fluids, such as from a retrofilled transformer, may reach different results.

Compatibility Testing Methods

Elastomeric and polymeric materials were tested in accordance with the following methods:

- ASTM D395 Standard Test Methods for Rubber Property Compression Set
- ASTM D412 Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers Tension
- ASTM D471 Standard Test Method for Rubber Property Effect of Liquids
- ASTM D573 Standard Test Method for Rubber Deterioration in an Air Oven
- ASTM D624 Standard Test Method for Tear Strength of Conventional Vulcanized Rubber and Thermoplastic Elastomers
- ASTM D2240 Standard Test Method for Rubber Property Durometer Hardness
- ASTM D149 Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies
- ASTM C961 Standard Test Method for Lap Shear Strength of Sealants

The insulating fluids were tested in accordance with the following test methods:

- ASTM D924 Standard Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids

Table 12
Materials Tested and Approved for Use in Contact with FR3 Fluid.

Core & Coil Materials	polyphthalimide	**Elastomers**	**Tapes**
core steel	Mylar film (PET)	Buna-N	polyester/glass with thermoset
bare copper	Masonite	Nitrile NBR	rubber adhesive
bare aluminum	Porcelain – radio glaze	Nitrile HNBR	thermosetting acrylic adhesive
polyvinyl Formvar	Nylon tie wrap	Epichlorohydrin ECO	kraft paper w/ wheat gum
copper magnetic wire	Carri-strap	Viton (FKM)	adhesive
aluminum magnetic wire	**Group B Materials**	Neoprene (used)	
conical mandrel	Rosite 3250	Cork/neoprene (used)	**Miscellaneous**
Thermally Upgraded Paper	PVC wire jacket		Polyethylene naphthalate
Kraft paper	Storm Trapper epoxy	**Sealant**	(PEN)
pressboard	coating & wire pine block	Locktite PST592 pipe sealant	Rynite 350
diamond paper	**Switchgear Components**	Locktite Vibra-Seal	HTN primary bushing
plain paper	tin-plated but bas	Permatex 51D pipe joint	tap changer
tubing	silver-plated bus bar	compound	bay-o-net fuse
crepe tubing	Nylon tie wraps		Epoxy Paint (two part)
vulcanized fiber sheet	fiberglass string	**Core Banding**	Core Epoxy
polyamide blas tape	bottle bushing	Glass / Polyester	Phenolic (DETC)
polyvinyl acetate adhesive	CT protector	Dacron / Epoxy	Heat Shrink (polyester)
Group A Materials	cover gasket	Green Polyester Bands	Laminated wood
thermo set epoxy	bushing gasket	Black Nylon Bands	TX Block material (HDLP)
Rynite 530 (PET)	GPO3 polyester		Nylon (6/6) Ty-wraps Banding
High temperature Nylon	Semaphore window	**Adhesives**	Yoke band insulation
Rostone thermoset polyester	Auxiliary switches	PVA	CTC (Bonded)
fiberglass / epoxy	shaft seal o-ring	Casein	
Amodel 1133	semaphore gasket	Epoxy	
GPO3 polyester / glass	bottle disc	Cyanoacrylate	
laminate	tank connector	Anaerobic thread lockers	
	tank connector gasket	Acrylics (tapes)	
	CT with wire leads		

- ASTM D971 Standard Test Method for Interfacial Tension of Oil Against Water by the Ring Method ASTM D974 Standard Test Method for Acid and Base Number by Color-Indicator Titration
- ASTM D1533 Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration
- ASTM D1816 Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using VDE Electrodes

Compatibility Testing Results

Table 12 lists the materials tested and approved for use in FR3 fluid. As the quality of a material can present large variations among different suppliers, varying results can be found when repeating the test in other regions and countries. However, it is important to notice that usually a compatibility problem of an already approved product is, usually, due to a quality issue.

For example, transformer manufacturer typically experiences frequent problems with nitrile rubber. Several batches of material from one supplier can be classified as compatible, while batches of other similar materials from another supplier are not compatible. The chemical compatibility test is very sensitive to the components used to formulate the material and to the production process. Therefore, confirming compatibility of specific materials to be used in FR3 fluid is recommended.

REPAIRING A FR3 FLUID FILLED TRANSFORMER

Similar to mineral oil impregnated materials, FR3 fluid impregnated materials should not have prolonged exposure to air. Unlike assemblies impregnated with mineral oil, drying processes using hot air circulation ovens are unacceptable for parts and assemblies impregnated with FR3 fluid.

This guide recommends repair and drying methods that take advantage of the hygroscopic characteristics of FR3 fluid and minimize thin film polymerization. The main precautions to be taken when repairing a transformer filled with FR3 fluid are:

- For nonporous surfaces, limit the exposure to atmospheric air and UV light to a maximum period of seven (7) calendar days;
- For porous surfaces, limit the exposure to atmospheric air and UV light to a maximum period of 20 calendar days;
- Do not use hot air circulation ovens for drying components impregnated with FR3 fluid.

Refer to Cargill Bulletin R2080 Thin Film Oxidation for additional details.

The use of hot air circulation oven for insulation materials impregnated with FR3 fluid results in polymerization of the fluid at the surface of the insulating material. This can make the surface impermeable, affecting its further impregnation and drying. This should be analyzed by the manufacturer, case by case, when no other option is available. Cargill recommends drying under vacuum or in an oxygen-free atmosphere.

Distribution Transformers

Regardless of their voltage and power class, refers to transformers which:

- Are transported assembled and filled with dielectric fluid;
- Allow its core-coil, assembled or disassembled, to be preserved (immersed) in tanks with dielectric fluid.

Power Transformers

Refers to equipment that will be disassembled and FR3 fluid will be partially or completely drained.

GUIDE A – STEPS FOR REPAIRING DISTRIBUTION TRANSFORMERS WITH FR3 FLUID

Step	Important Topics	Remarks
1. Define and follow all service recommendations, safety precautions, codes and regulations required.	Define and follow each transformer manufacturer's service recommendations; additionally, define and follow all safety precautions, codes and regulations.	
2. Transportation of the equipment	All equipment in this category is considered to be transported with its main body fully assembled and totally immersed in FR3 fluid.	If the equipment will have its fluid partially or completely drained, exposing core-coil to the atmosphere (atmospheric air), use Guide B for power transformers.
3. Transportation of disassembled accessories	Accessories transported separately from the main body and having some residual FR3 fluid should be transported sealed under nitrogen gas, or washed with a compatible solvent (e.g. kerosene or mineral oil heated to 60-80°C) to remove eventual thin films of FR3 fluid.	Thin films of FR3 fluid on metal surfaces can easily polymerize. The removal of fully polymerized layers can be difficult, since they have a finished look like a varnish layer, having insulating properties.
4. Main body opening and disassembling	After removing the cover and draining the FR3 fluid, it is recommended to rinse with a compatible solvent (e.g. kerosene or mineral oil heated to 60-80°C) to remove films of FR3 fluid from metal surfaces and on the surface of insulating materials.	The rinsing of compatible solvents contributes for removing thin films of FR3 fluid that may be deposited on the surfaces of materials. This process prolongs the period in which the materials can be exposed to the atmosphere.
5. Preservation of metal components to be reused	Once free of FR3 fluid thin films, use rigorously the same procedures applied for mineral oil immersed components - protect from weather, dust and contaminants.	If deposits and films of FR3 fluid are still identified, perform cleaning using compatible solvents.

6.	Preservation of insulating materials, windings and cellulose insulated wiring to be reused	The materials that will not be replaced during the repair of the equipment should be preserved through immersion in a tank containing FR3 fluid or even mineral oil. Oil quality should be maintained, especially for periods longer than 60 days. The maximum time components can be exposed, when sheltered from UV and protected from ventilation flow, is 20 days, but this period should be minimized. The reused components should be cleaned and verified according the procedures of each manufacturer. If there is no possibility to have the materials in a tank, follow recommendations of Guide B for power transformers.	A tank with FR3 fluid is preferred, since materials impregnation will not be affected and the tank will not add fire risk to the installation. If possible, keep the tank closed and headspace filled with nitrogen. Exposure to the atmosphere of materials impregnated with FR3 fluid may increase transformer's power factor. Before using the FR3 fluid from the preservation tank, verify its properties and, if required, filter / regenerate it. Pay attention to the fluid viscosity, neutralization index and dissipation factor.
7.	New components manufacturing	The manufacturing of new components should follow the procedures of each manufacturer. Windings drying and stabilization procedures should be fully applied according each manufacturer technology.	Proper drying and stabilization of the components before assembling is important for quick and effective drying. Excessive moisture can lead to excessively long drying time.
8.	Drying of the active part "vapor phase" oven	Drying can be performed following the same procedures applied to mineral oil transformers.	Drying in oxygen-free environment should not cause polymerization of FR3 fluid, even though higher temperatures are reached. Hot air circulation ovens should not be used in components impregnated with FR3 fluid. Each manufacturer may choose this option when, according to its calculation and experience, the possible lack of impregnation will not affect transformer performance.
9.	Drying of the active part in tank (tanks withstanding full vacuum or using a vacuum chamber for the complete tank)	Core-coil should be placed in the tank without drying in hot air circulation oven, but following vacuum filling procedures. For heating up the oil, apply the same procedure of a "heat run test". This would require a short-circuit in the high voltage terminals and application of a reduced current to the low voltage terminals (or vice-versa). Minimize heat dissipation by closing the radiators or keeping the oil level below radiator upper connection, to prevent oil circulation through radiators. In this case, the headspace should be filled with nitrogen gas. Generated losses should heat the fluid, until reaching a top oil temperature between 105°C and 110°C. Remove loading when temperature is reached. Drain the fluid while still hot and apply vacuum in the tank as quick as possible, without any contact with atmospheric air. It may require nitrogen injection to remove oil before vacuum. For vacuum pumps with condensate output, monitor water flow. If not, monitor dew point inside the tank. Repeat the filling procedure and check moisture content in the FR3 fluid.	Repeat procedure as needed to obtain the required insulation dryness. When the application of full vacuum in the tank is not possible, follow Guide B for power transformers. For applying vacuum to the tank, a vacuum chamber can be used.
10.	Field assembly and commissioning	If shipped with major components assembled and fully immersed in FR3 fluid, follow same procedures of mineral oil filled transformers. Time without oil, after removal of nitrogen gas, must not exceed the limit of 7 calendar days, or the equivalent in hours of exposition, when tank is under vacuum during work interruptions period (e.g.: weekends or nights).	Observe FR3 fluid recommended specification limits at commissioning according to Cargill's R2000 FR3 Fluid: Product Information, S10 Storage and Handling Guide, R2030 Test Summary, G2070 Dissolved Gas Guide and national standards.

GUIDE B- STEPS FOR REPAIRING POWER TRANSFORMERS USING FR3 FLUID

Step	Important Topics	Remarks
1. Define and follow all service recommendations, safety precautions, codes and regulations required.	Define and follow each transformer manufacturer's service recommendations; additionally, define and follow all safety precautions, codes and regulations.	
2. Transportation of disassembled accessories	Accessories transported separately from the main body and having some residual FR3 fluid should be transported sealed under nitrogen gas or washed with a compatible solvent (e.g. kerosene or mineral oil heated to 60~80°C) to remove eventual thin films of FR3 fluid. For radiators and heat exchangers, it is recommended to close with blind flanges, pressurizing the interior with gauge pressure of 0.03 MPa (0,3kgf/cm^2).	Thin films of FR3 fluid on metal surfaces can easily polymerize. The removal of fully polymerized layers can be difficult, since they have a finished look like a varnish layer, having insulating properties.
3. Main tank transportation, after FR3 Fluid draining	After FR3 fluid draining, the main tank should be sealed with blind flanges and have a pressure control system using nitrogen gas, the same used in the transportation of new equipment. Monitor the consumption of nitrogen gas bottle and replace if necessary.	Exposure to the atmosphere of materials impregnated with FR3 fluid may increase transformer's power factor and, in case of full polymerization of FR3 fluid, formation of an impermeable layer on the surface of insulating materials.
4. Opening and disassembling of the main body	After removing the cover and draining of FR3 fluid, it is recommended to rinse with a compatible solvent (e.g. kerosene or mineral oil heated to 60-80°C) to remove films of FR3 fluid from metal surfaces and on the surface of insulating materials.	The rinsing of compatible solvents contributes for removing thin films of FR3 fluid that may be deposited on the surfaces of materials. This process prolongs the period in which the materials can be exposed to the atmosphere.
5. Preservation of metal components to be reused	Once free of FR3 fluid thin films, use rigorously the same procedures used for components immersed in mineral oil: protect from weather, dust and contaminants	If deposits and films of FR3 fluid are still identified, remove using compatible solvents.
6. Preservation of insulating materials, windings and cellulose insulated wiring to be reused	The materials that will not be replaced during the repair of the equipment must be preserved through immersion in a tank containing FR3 fluid or even mineral oil. Oil quality should be maintained, especially for periods longer than 60 days. For materials or components of large dimensions, or no availability of a tank with the required size, plastic bags not permeable to oxygen can be used, or as last option, wrapped with stretch film (PVC film for packaging), with more than 50% overlap between layers. The Maximum time components can be exposed, when sheltered from UV and protected from ventilation flow, is 20 days, but this period should be minimized. The reused components should be cleaned and verified according the procedures of each manufacturer.	Exposure to the atmosphere of material impregnated with FR3 fluid may increase transformer's power factor. Before using the FR3 fluid from the preservation tank, verify its properties and, if required, filter / regenerate it. Pay attention to the fluid viscosity, neutralization index and dissipation factor.
7. New components manufacturing	The manufacture of new components should follow the procedures of each manufacturer. Windings drying and stabilization procedures should be fully applied according each manufacturer technology.	Proper drying and stabilization of the components before assembling the set is important for quick and effective drying. Excessive moisture can lead to excessively long drying time.
8. Drying of the active part "vapor phase" oven	Drying can be performed following the same procedures applied to core-coil of mineral oil transformers.	Drying in oxygen-free environment does not lead to polymerization of FR3 fluid, even though higher temperatures are reached. Hot air circulation ovens should not be used in components impregnated with FR3 fluid. Each manufacturer may choose this option when, according its calculation and experience, the possible lack of impregnation will not affect transformer performance.

9.	Drying of the active part in tank	Core-coil must be placed in the tank without drying in hot air circulation oven, but following vacuum filling procedures. For heating up the oil, apply the same procedure of a "heat run test". This would require a short-circuit in the high voltage terminals and application of a reduced current to the low voltage terminals (or vice-versa). Minimize heat dissipation by closing the radiators or keeping the oil level below radiator upper connection, to prevent oil circulation through radiators. In this case, the headspace must be filled with nitrogen gas. Generated losses should heat the fluid, until reaching a top oil temperature between 105°C and 110°C. Connect an oil treatment system type "thermo vacuum" to remove moisture from FR3 fluid, while maintaining oil temperature. Repeat fluid treatment as needed to obtain the required moisture content level.	FR3 fluid has a water saturation point about 16 times greater than mineral insulating oil, so it removes much more moisture from insulating paper. The thermo vacuum fluid treatment system allows transport of moisture from insulating material out of the transformer. The thermo vacuum device capacity can be determinant to keep fluid properties unchanged. Verify fluid moisture content, neutralization number and viscosity after processing.
10.	Transportation, field assembly and commissioning	Follow steps 2 and 3 of this Guide B for disassembling and transportation. Accessories impregnated with FR3 fluid should be sealed under nitrogen gas or washed using compatible solvent. Main tank should be pressurized under nitrogen gas and have a pressure control system. During field assembly, minimize the ingress of atmospheric air into the tank. Time without oil, after removal of nitrogen gas, must not exceed the limit of 7 calendar days or the equivalent in hours of exposition, when tank is under vacuum during work interruption period (e.g.: weekends or nights). After assembling is concluded, commissioning procedure shall follow same procedures applied for mineral oil filled transformers.	Observe FR3 fluid recommended specification limits at commissioning according to Cargill's R2000 FR3 Fluid: Product Information, S10 Storage and Handling Guide, R2030 Test Summary, G2070 Dissolved Gas Guide and national standards

LEAKAGES

Verifying possible leaks in transformers should be a routine activity. Despite of FR3 fluid causes much less impact to the environment, every leak point is an entrance for moisture, via osmosis, and other contaminants to the transformer. The fluid physical chemical analysis of is a very good way to identify sealing problems.

As previously explained, fluid oxidation should not be an issue during short term exposition of the fluid to the ambient. Oxidation will be minimized by fluid inhibitor additive, providing good planning to schedule transformer repair activities. Expected consequence of short term exposure will be some moisture ingress, which can result in fluid hydrolysis and some increasing of the fluid acidity. In addition, the acids formed by hydrolysis are not critical since they are a long-chain, mild, and non-corrosive fatty acids.

Units with pressure gauges presenting constantly periodic readings of zero gauge pressure are a strong indication of headspace leak or some other problem that should be investigated. Areas to check and repair include valves, bushings, gauges, tap changers, welds, sample ports, manhole covers, pipe fittings, and pressure relief valves. If the leak does not involve a replaceable seal, welding or epoxy sealing kits may be used to seal it.

Proper care should be taken to protect the integrity of the equipment insulation if leak repair requires lowering the liquid level. Clean and dry temporary fluid storage containers should be used. FR3 fluid testing is recommended before returning it to the equipment. Recommendations for transformer sampling, testing and filling presented in this guide should be followed.

Minor Spills

Minor spills such as those occurring during transformer manufacturing or repairing, or during fluid sampling or testing, can be cleaned using absorbent rags. Use of suitable cleaners facilitates the cleanup. Usual solvents suitable to clean up petroleum fluids may not be effective with natural esters. General household detergents are recommended for FR3 fluid. If thin films of FR3 fluid have partially or completely polymerized, household detergents will not be effective. The surface area should be saturated with a suitable cleaner (water-based, biodegradable, non-flammable, non-conductive cleaner/degreaser) and then steam or hot water spray can be applied. Refer to Cleaning Procedures section.

Contact your local Cargill Dielectric Fluids group for further suggested cleaning agents or email us at fr3fluid@cargill.com.

Spills on Soil

State environmental agencies typically have jurisdiction for spills onto soils. Many states currently do not list natural esters or FR3 fluid as soil spill-regulated material. However, state and local regulations should be consulted to enable compliance with all applicable regulations. Soil acts as an absorbent and typically offers excellent conditions for natural biodegradation (bio-remediation). FR3 fluid can be cleaned using absorbent rags.

Spills on Water

Because FR3 fluid and other natural ester fluids float on water, a spill can be contained by floating booms or dikes. If containment equipment is unavailable or impractical, FR3 fluid can be treated by applying surface-active dispersant chemicals, also known as detergents, designed to remove the oil from the water surface and into the water column.

Only chemical dispersants listed on the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) [80] should be used to treat oil spills.

For spills into water surfaces, check with the local authorities having jurisdiction for reporting and remediation requirements.

Once FR3 fluid has been concentrated, it can be removed from water surface by systems usually applied for vegetable oil spills. These systems include pumps, skimmers, and physical absorbents.

Refer to the section Fluid Disposal Methods for disposal procedures.

Cleaning Procedures

A thin film of FR3 fluid will polymerize over time making it increasingly more difficult to clean. The extent of polymerization depends on air exposure time, temperature and UV or sunlight. For example, the extent of polymerization of a thin film of FR3 fluid after 1 day at 39°C in air is minimal, while after 7 days it would be partially polymerized and tacky to the touch. Exposure of a thin film of FR3 fluid to 93°C in air for 5 days would result in polymerization to a dry state.

Cleanup of FR3 fluid on surfaces is most effective when the FR3 fluid spills and drips are fresh. S-34™ aqueous cleaner and the Amerisolve 123™ were found to be effective. Apply cleaner with a pump spray or cloth, followed by hand wiping with a clean cloth and/or spray washing. Refer to the S-34 [81] cleaner and Amerisolve 123 [82] Material Safety Data Sheet.

For partially polymerized (sticky) FR3 fluid, apply S-34 cleaner with a pump spray and allow a 15-minute soak time at 22°C, followed by hand wiping with a clean cloth using moderate rubbing. Multiple applications may be necessary depending upon the extent of polymerization of the FR3 fluid. Use shorter soak time at higher temperatures and longer soak time at lower temperatures.

For larger spills on impervious surfaces, wet down the area, apply powder based #15 Economy Floor Cleaner™. Let sit for 15 minutes, wash down using hot water.

For FR3 fluid polymerized to semi-hard or hard consistency, scraping, light sanding or paint touch-up may be required in addition to vigorous scrubbing. Users should consult with their company's policy regarding the use of personal protective equipment.

FLUID DISPOSAL METHODS

Cargill sample analysis of FR3 fluid aged along several years in transformers indicated no issues for fluid disposal. US EPA has defined exhausted FR3 fluid as 'used oil' (not hazardous or waste, due to its known recyclability). Potential methods for FR3 fluid disposal include:

Recycling

Used FR3 fluid is acceptable for use as biofuel feedstock. There are plentiful companies focused upon the production of biofuels from used biobased oils, including soybean oil and FR3 fluid. [References: Solvent Systems International, New Generations Biofuels, Nova Biosource Fuels, Google search for 'bio+fuel+feed+stock', etc.]

Used FR3 fluid is of interest to the rendering industry (e.g. companies that pick up used cooking oil and grease) as it may be suitable for recycling into oils, lubricants, and soaps. [References: Google search for 'renderers', Render Magazine 'www.rendermagazine.com', etc.]

Burning

Although burning process produces a more harmful impact to the environment, used FR3 fluid can be burned (for heat recovery), similarly to the dominant disposal method for used mineral oil. If burning disposal is chosen, Cargill recommends a burning process in an industrial boiler of a mix with 90% mineral oil plus 10% FR3 fluid.

Landfills

If disposed in landfills, used FR3 fluid will fully biodegrade over time due to its ready biodegradability.

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