SUSTAINABLE SAFETY USING ENVIROTEMP™ FR3™ FLUID
Dielectric Aspects and Reliability

Envirotemp™ FR3™ fluid is a valid long term insulation liquid for transformer designs through 550kV when standard quality requirements are applied. Invented nearly 25 years ago, FR3 fluid performance has been verified by substantial testing, in laboratories and in the field. Supported by more than one half million transformers in service on six continents for almost 20 years, new exciting projects applying FR3 fluid in voltages above 420kV are currently in process.

25 Years of Validation

Envirotemp FR3 fluid is an electrical insulating liquid based on renewable vegetable oil; it is readily biodegradable, non-toxic, sustainable, recyclable and possesses a high fire point (K class). It is suitable for electrical equipment where its improved fire safety, environmental properties, and superior thermal behavior are valuable attributes.

In addition to these significant advantages, FR3 fluid has been proven (in both laboratory testing and in the field) to maintain strong dielectric performance in transformers. Over the past 20 years, no dielectric fluid has been tested as extensively as FR3 fluid, and most of that testing has been performed in a true side-by-side comparative setting with mineral oil. Every test our technology team participated in was deeply studied and designed to reflect the real and valid aspects of transformers; where test procedures could influence or bias the results, care was taken to execute the tests in a scientific way, such that results would be easily replicated around the world. The diligence used, along with the results obtained have been leveraged, and today FR3 fluid has successfully been applied in new transformers rated up to voltage class of 420 kV, and is being considered in several applications above this level.

Studies of the dielectric phenomena, initiated for mineral oil at least forty years ago and still under discussion, have indicated some possible differences in comparison to mineral oil when FR3 fluid is overstressed. The testing, while interesting in academia, does not reflect industry acceptable dielectric design constructions or manufacturing practices for transformers.

The use of very concentrated fields, such as needle to plane or needle to sphere, are alternatives to simulate high voltage stress conditions without applying very high voltages and theoretical research, impacting the design of power transformer just in very specific points. A discussion of the relevancy of these tests is included below.

To be clear: FR3 fluid can be applied at any voltage through 550kV and in transformers of any capacity. This statement is based on the extensive list of performed tests (all supported with data):

1. All basic dielectric tests, as per ASTM D877, ASTM D1816 and IEC 60156, worldwide accepted tests, showed dielectric capability equal to or higher than mineral oil. Tests were performed at Thomas A. Edson Technical Center, Doble Engineering, Waukesha Electric Systems (SPX Transformer Solutions), Universities of Manchester, Stuttgart, Hannover, Graz and Monash, and EHV Weidmann Industries.

2. Eaton - Cooper Power Systems, Waukesha Electric Systems and Weidmann Electrical Technology
The developer of the most used reference curve for transformer design, the “Weidmann Curve”, was our choice for designing further tests. The set of electrodes represent quasi-uniform and semi non-uniform conditions present in transformers, both with FR3 fluid and mineral oil.

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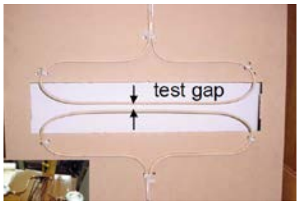
<td>
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<tr><td>Oil Gaps up to 50mm</td><td>Stress between discs up to 12mm, with radial spacers.</td><td>Turn to turn oil gaps in transformer coils, from 3mm to 12mm</td><td>Tap Changer Contacts</td></tr>
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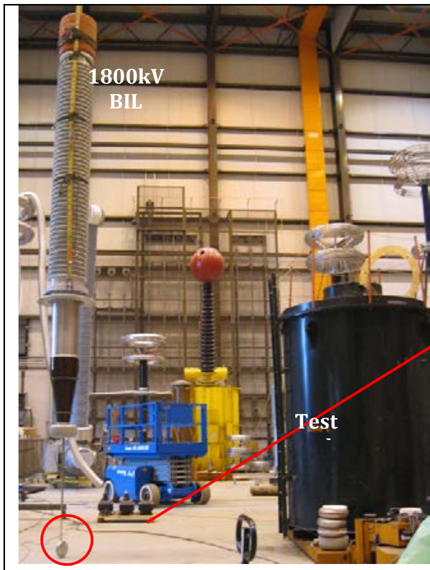
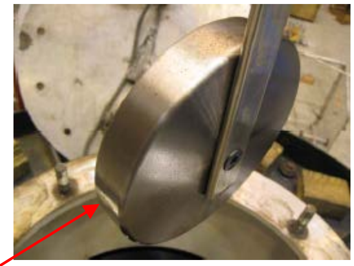
The results of all tests, for AC 50/60Hz, Impulse wave, Chopped Wave, Switching Wave, at positive and negative polarities can be reviewed in papers [1], [3] and [4], showing equivalent performance and a good safety margin to Weidmann design curves.

3. Electrical Creep Interface tests
One more time Weidmann was the partner for designing and testing the dielectric withstand capability under creep conditions. The behavior of the fluids under AC 60Hz and Impulse Wave with positive and negative polarity has been compared and, again, the result showed the equivalency of FR3 fluid and mineral oil for all gap distances, maintaining the safety factor to the Weidmann design curve. Detailed results can be found in [1] and [3].

4. Low temperature Performance
Breakdown voltage (BDV) of FR3 fluid has been tested to a temperature of -50°C using ASTM D1816 electrodes and dielectric tests have been applied in a transformer stabilized at -35°C. As FR3 fluid maintains a high water saturation point and does not form cracks or voids, the BDV at low temperatures is not reduced.

5. “Harold R. Moore testing Matrix”
Focused upon the extra high voltages, one of the most recognized power transformer specialists, Harold R. Moore, designed a matrix of dielectric tests, as described in [2], using oil gaps up to 150mm and practical non-uniform field conditions. Tests explored the high voltages and power available at both Powertech Lab and the SPX Transformer R&D laboratory along with the University of Stuttgart. The electrode configurations were designed to create non-uniform field distribution representative of the real structures inside a power transformer.





Detail showing the 216 mm diameter × 38 mm thick with a edge radius of 4.3 mm installed below a 550kV (BIL 1800kV) bushing

The breakdown voltage tests have been performed using mineral oil and FR3 fluid at the gaps of 50mm, 100mm, 125mm and 150mm, whose results can be reviewed in [4] and [5].

Despite slightly lower for FR3 fluid at the 50mm gap, the value at the larger gaps presented superior dielectric withstand capability for FR3 fluid, reaching the bushing limit for the larger gaps.

6. Tap Changer contacts tested at SPX Transformer Solutions and University of Stuttgart
The testing of the OLTC tap selector rod and contacts has been repeated, using the most critical configuration indicated by the manufacturer who supplied the parts. Breakdown voltage between contacts with FR3 fluid was equal to or surpassed the value of mineral oil. For the tests from the contacts properly spaced to the tank, the limitation of the laboratory voltage capacity was reached, with results equivalent for both fluids. Detailed results can be found in [4] and [5].

7. Partial Discharge Inception Voltage (PDIV)
Several universities tested the PDIV of FR3 fluid in comparison to mineral oil. The published papers from Hannover Institute (IEH), New South Wales University and University of Manchester presented, in all cases, an Inception Voltage of Partial Discharges in FR3 fluid equal or superior to mineral oil at same relative moisture content. See papers [6], [7] and [8].

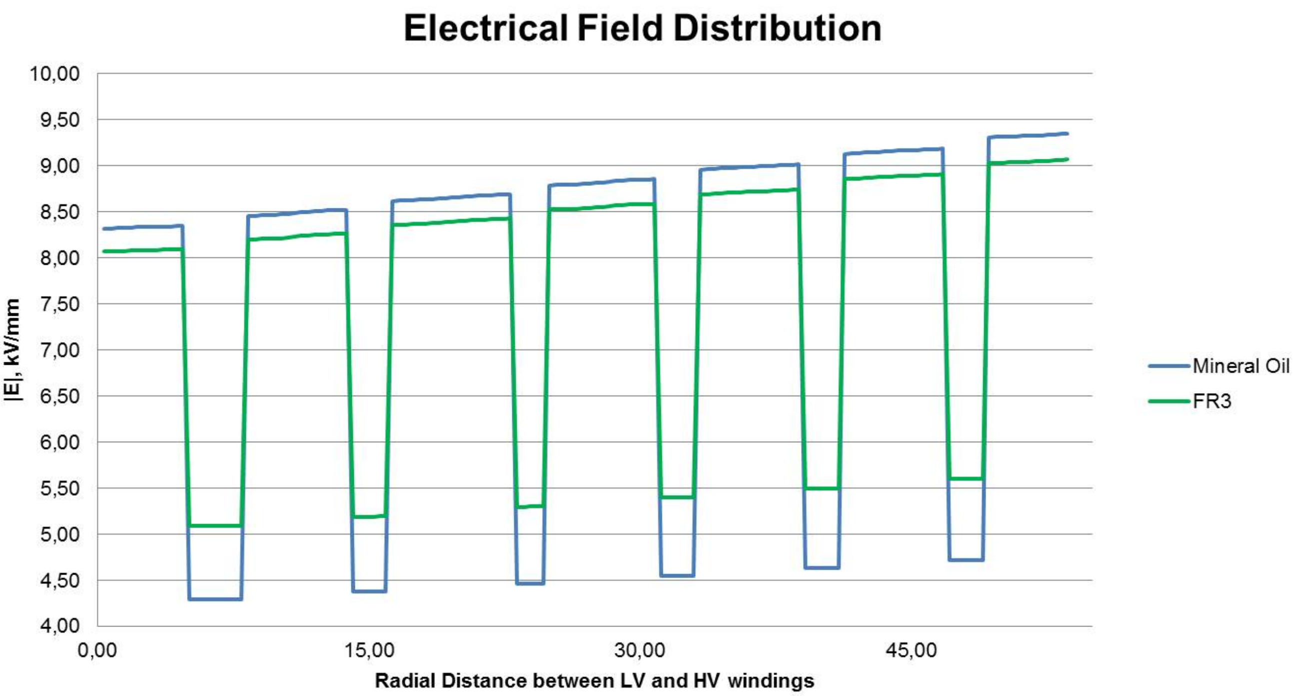
Dielectric Design overview

The most relevant aspect to be taken into account for the dielectric design of a power transformer is the dielectric constant or the permittivity. The 40% higher permittivity of FR3 fluid shifts the dielectric stress from the liquid to the solid insulation, requiring adjustments in the dielectric design when the voltage increases.

There are essentially two effects:

- Increase the safety factor for the solid-liquid insulation system between windings, since the limiting factor is the liquid and the stress on it is reduced;
- Changed field distribution, increasing the voltage stress in the solid insulation, potentially requiring extra paper at the leads fixing points and supports. Adjustments on winding assembly may also be required.

The impact of the permittivity can be clearly seen in the next picture, where the graphical results of the solved analytical equations for the field distribution in both mineral oil and FR3 fluid are shown. They show the electrical field modulus in the region between the low voltage and high voltage winding for a hypothetical 230kV transformer (BIL 1050kV). The blue lines show the electrical field modulus with mineral oil, while the green lines show the distribution when changing the fluid to FR3. The effect of the permittivity is very clear: reducing the kV/mm in the oil gap and increasing in the solid insulation. This modification allows increasing the level of average field value, which can enable the reduction of the total clearance between windings and, maybe, even allowing the removal of some oil barriers.



One of the aspects of the recent studies of dielectric phenomena on ester fluids is a reduction of the ratio between the Inception Voltage and the Breakdown Voltage. However, in addition to be the obvious that a transformer should keep a safety margin to the Inception Voltage, most technical specifications and standards around the world already adopt very low tolerance levels for partial discharges. Power transformer manufacturers around the globe apply the design concept known as “Partial Discharge Free” and, for the higher voltages, even the concept of preventing charging accumulation, having design limits much lower than partial discharge inception level.

Achieving a partial discharge free design does not necessarily mean the usage of more material. It is about adjusting the geometry and reducing allowed electrical field modulus. Factory tolerances, quality, impregnation, no contaminations and no sharp edges are essential aspects, in addition to having a good design. Since the partial discharge inception level of FR3 fluid is recognized as being higher than mineral oil, a “partial discharge free” design for mineral oil will achieve a higher safety factor when using FR3 fluid.

A classification according to the voltage level can help the understanding:

• Voltage class equal or lower than 69kV:
Proper dielectric design for mineral oil should be sufficient for FR3 fluid. A number of successful retrofills with up to 10 years of field application are currently operational on several continents.

• Voltage class around 138kV:
The dielectric design for mineral oil has been proven to be sufficient for FR3 fluid. Some verification can be required at leads and winding assembly, due to the modification of field distribution, not due to different dielectric strength. A good number of retrofills have been successfully completed, as well as new transformers have been designed, and there is not a single failure attributable to the fluid in more than 10 years of operation.

• Voltage class around 230kV:
More detailed verification of the design is recommended, including the winding assembly, leads and tank clearances, usually with some increase in safety margin for the long gaps. Some cases of retrofills, with the participation of the manufacturer, have been completed without any modification of the dielectric design, and are operational for more than

five years. Also there have been no issues with the new transformers designed in this class.

• **Voltages above 230kV:**
Despite having transformers in service for some years above this voltage, we still consider these as R&D applications, suggesting a detailed review of the design. Use of finite element analysis for evaluating the field distribution and some increment on the long gap safety margin have been identified. For most cases the windings arrangement and distances are the same.

Streamers and their relevance

For many years, papers have been published on the subject of streamers. The use of the needle-to-plate or needle-to-sphere arrangement started as a way to test higher voltage gradients without applying very high voltage levels. On this aspect they are a kind of "scaled test", whose "applicability" must be verified case by case, since they are extremely high concentrated field conditions, as stated by Top et al in the paper Streamer Propagation in Mineral Oil in Semi-Uniform Geometry [9]. The presence of unshielded needle like structures inside a transformer, using any dielectric fluid, is completely unacceptable. They would result in high levels of partial discharges or even discharges during factory tests.

However two main aspects of testing are relevant:
• **Concentrated field stress voltage, such as winding edges and winding exits:**
The limits applied for a "partial discharge free" design are much more restrictive, for both mineral oil and FR3 fluid. Permittivity influence can be relevant above 138kV.

• **Long gaps (above 150mm):**
As the testing of very long gaps would require too high voltages and unsafe conditions, the field concentration is used to extrapolate the behavior for long gaps. The results from the extrapolation should match with the actual breakdown voltage for tested gaps.
Comparing test results from different universities, coupled with the results from [5], the deviations reveal these studies using severe asymmetric fields are still on qualitative stage as research. The most meaningful conclusion, up to now, which is the smaller ratio between Inception and the Breakdown Voltage, reinforces the relevancy of a Discharge Free design, which is already the applied concept.

The success and credibility of more than half a million transformers in service for almost 20 years is ample evidence that FR3 fluid is an adequate long term insulation fluid when transformer designs incorporate standard quality requirements. New projects applying FR3 fluid at voltages above 420kV are now under consideration, clearly showing the excellent potential of the technology.

[1] T.A. Prevost, "Dielectric Properties of Natural Esters and their Influence on Transformer Insulation System Design and Performance", 2006 IEEE Transmission & Distribution Conference, May 21-26, 2006, Dallas USA

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[3] A. Prevost, M. Franchek, K. Rapp, "Investigation of the Dielectric Design Criteria for Pressboard/Natural Ester Interfacial Stress", 75th Int. Conf. Doble Clients, April 6-11, 2008, Paper IM-3, Boston USA

[4] K. J. Rapp, J. Corkran, C.P. McShane, T. A. Prevost, "Lightning Impulse Testing of Natural Ester Fluid Gaps and Insulation Interfaces, IEEE Trans. Dielectrics and Electrical Insulation, Vol. 16, No. 6, Dec. 2009, pp. 1595-1603.

[5] Rapp, K., McShane, C.P., Vandermaar, J., Vukovic, D., Tenbohlen, S., "Long Gap Breakdown of Natural Ester Fluid", 2010 International Conference on High Voltage Engineering and Application, Oct. 11-14, 2010, New Orleans USA

[6] T. C. Wei, "A report of the partial discharge test conducted on Envirotemp FR3 fluid for Cooper Power Industries", Thesis, June 2004, School of Electrical Engineering and Telecommunications, The University of New South Wales, Australia

[7] H. Borsi, E. Gockenbach, B. Dolata, "Ester fluids as alternative for mineral based transformer oil", IEEE Intl. Conf. Dielectric Liquids (ICDL), June 30 - July 3, 2008, Futuroscope-Chasseneuil, France.

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[9] Top, T. V., Masala, G., Lesaint, O., *Streamer Propagation in Mineral Oil in Semi-Uniform Geometry,* IEEE - 2002

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