

Natural ester liquids have been used as an insulator in power transformers for nearly three decades. They are the third generation of fire-resistant fluids – or “k-class” liquids – used in transformers, but their fire resistance was not their only benefit. In fact, it is outshined by the fluid performance. Prior to the introduction of natural ester liquids, mineral oil was the go-to transformer insulator, despite its known limitations, and the fact that it is highly flammable. The synthetic ester liquids were introduced more than 10 years before natural, but the seasonal availability of carboxylic acids (derived from petroleum), and its inherently higher cost limited its use to niche applications. To have an effective superior alternative for its transformers, Copper Power Systems (CPS at that time, now Eaton) began exploring alternatives. In 1991, Eaton's research found that vegetable oil was also an ester, but they needed a formulation that would assure long-term transformer performance. And so began a four-year research and development journey involving the evaluation of over 40 different vegetable oils and blends. From these, Eaton narrowed the list down to seven possible formulation candidates, taking into consideration many prototype pole and pad-mounted distribution transformers, ultimately resulting in what is now known as FR3 fluid.

The immense amount of data and information now available on natural ester liquids has demonstrated their functionality. Add to that the other undeniable advantages flash and fire point and environmental characteristics, and it's clear that natural ester liquids may be the future go-to insulation liquid.

Tried & Tested: How FR3 Fluid Performance Testing Has Demonstrated It Offers More Than Fire Safety and Sustainability

by **Alan Sbravati**
and **Kevin Rapp**

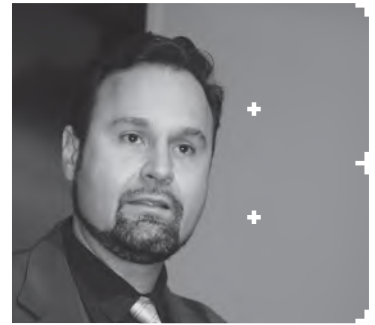
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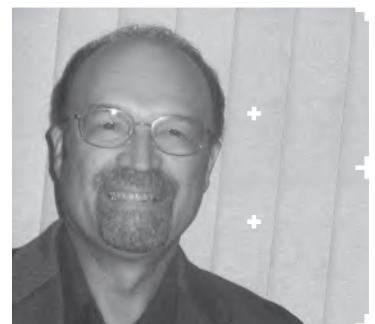
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Alan Sbravati started his career working for a transformer manufacturer, mainly developing calculation and design tools for power transformers. After almost 9.5 years in the same company, he was the R&D&E manager for power transformers in Brazil and responsible for two global R&D projects directly related to transformer design and thermal calculation. After three years in a commercial role, he moved back to a more technical position at Cargill. Over the last six years he has been working with the development and application of alternative insulating liquids, especially natural ester fluid (Envirotemp™ FR3™), holding the position of Global Technical Manager since 2018. Alan chaired the Brazilian Standards Committee from 2012 to 2016, prior to moving to USA. He participates in IEC TC 14 and Cigre working groups. Currently he is a member of IEEE Transformers Committee, and he is active in many subcommittees and task forces.



Kevin J. Rapp is the Principal Chemist for Global Dielectric Fluids of Cargill Bioindustrial. With over 40 years in the electrical industry, including 27 years in R&D where he invented Envirotemp™ FR3™ fluid and found that ester liquids enhance the life of cellulose insulation in transformers. Kevin is involved in standards as Technical Advisor/Chairman of USNC of ANSI/IEC TC10, ASTM D27.15 and D27.91 Subcommittees. Kevin was awarded IEC 1906 Award in 2011, US-EPA Presidential Green Chemistry Award in 2013, ASTM Service Award in 2015 and installed as ASTM Fellow with Distinguished Merit Award in May 2018. He holds many patents and has published numerous papers as a member of ACS, AOCS, ASTM, CIGRE, IEC and IEEE.

But First, Due Diligence Testing

Before it could be commercialized, the natural ester liquid underwent a series of required "due diligence" testing, including the electrical industry's Lockie Test (IEEE C57.100). This three-year functional test consisted of three groups of transformers:

- Each group of transformers had different thermal cycles of high peak temperature accelerated aging periods.
- The aging periods were evenly divided into 10 test periods with mechanical and dielectric testing performed at the end of each period, composed by four thermal cycles (from ambient temperature to the defined hotspot temperature, accumulating only the hours at peak temperature).
- The dielectric tests include a short-circuit test for generating mechanical stress to the insulating

structure, followed by lightning impulse, applied voltage and induced voltage tests.

- The transformer containing the insulation system under test had to survive the entire test duration representing *five times* the IEEE nominal life expectancy period to be approved.

All mineral oil and the natural ester filled units completed five units of life successfully, in all three hotspot temperatures. Since the test duration was shorter for the group aged at the highest temperature, CPS decided to extend the test beyond the required time. While the mineral oil unit failed in the subsequent period, the last failure of the four natural ester units happened only after 19.5 times the unit of life, almost four times longer than the five units of life that were required.

While the test was still running, the first transformers filled with FR3

fluid were commissioned, including two units that provided power to the Eaton plant core annealing ovens, and another installed in a large amusement park in Florida. In the years to follow, also motivated by the outstanding results of the Lockie Test, production of 36 kV voltage class transformers was accelerated by Eaton.

Expanding Manufacturers, Expanded Testing

In order to expand the technology to other manufacturers, Eaton had to verify the standard dielectric design curves for the insulation system design. Transformer experts (including the one of the reference transformer designers, Harold Moore, who was the engineering manager in Westinghouse when the design curves were originally developed) helped to develop a testing matrix in the early 2000s.

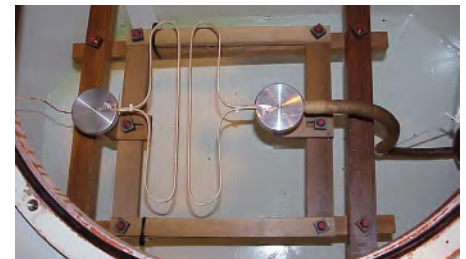
Figure 1. Three "generations" of electrodes designed for testing the breakdown voltage of the insulating liquid gaps for the transformer windings.



Turn to turn oil gaps, from 3 mm to 12 mm

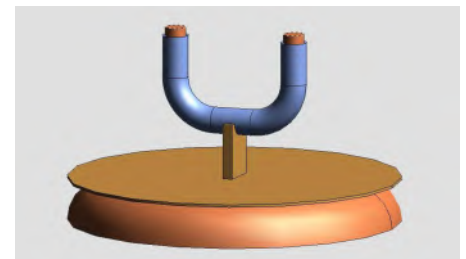
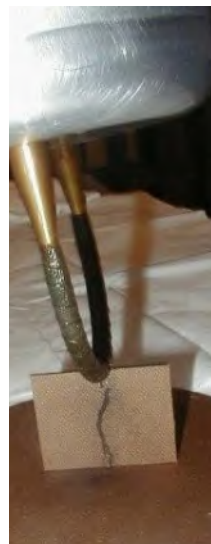


Stress between discs up to 12 mm, with radial spacers



Oil gaps up to 50 mm

Figure 2. Test setup and electrodes for testing the interfacial creep breakdowns.



Insulation design experts identified what they would classify “essential validation points” to allow the use of mineral oil design curves for the natural ester filled transformers.

The matrix included dielectric tests for validating the dielectric capacity in comparison to mineral oil, as well as detailed measurement of its properties, such as: permittivity (dielectric constant), differences

of power factor for insulation models, and even the volumes of gas formation under severe arcing conditions (flashovers).

These tests often had to be repeated and modified to ensure the accuracy of the results. As a transformer manufacturer, Eaton’s highest priority was the high-quality standards of

their transformers. Thus, the transformer designers were a very demanding first internal customer for the application of the fluid, requiring a thoughtful validation of the fluid performance for new transformers and on long term perspective. When their new fluid started to be offered to other transformer manufacturers, the road was already very well paved.

Figure 3. Tap changer selector rods and contacts used for comparative tests of FR3 fluid and mineral oil.

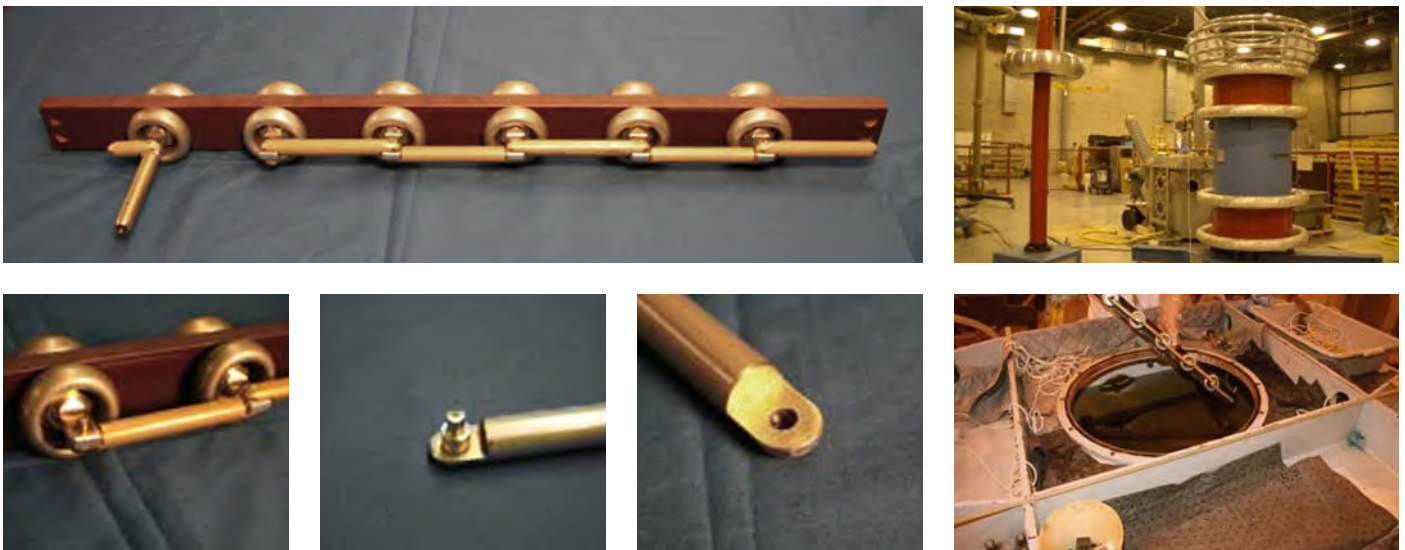
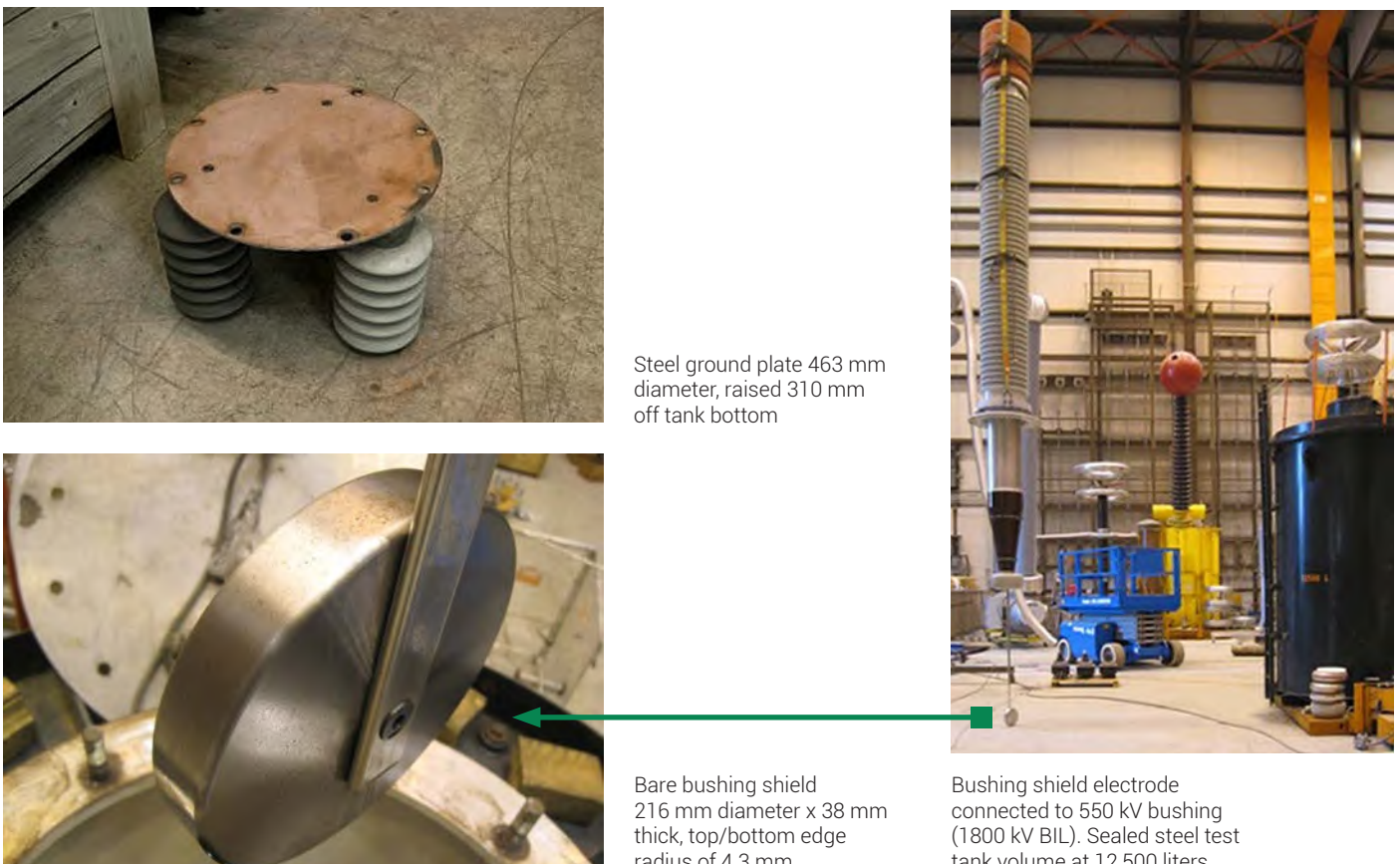


Figure 4. Electrode and test setup used for testing gaps up to 150 mm.



Steel ground plate 463 mm diameter, raised 310 mm off tank bottom

Bare bushing shield 216 mm diameter x 38 mm thick, top/bottom edge radius of 4.3 mm

Bushing shield electrode connected to 550 kV bushing (1800 kV BIL). Sealed steel test tank volume at 12,500 liters

The full test matrix was completed in 2010, totaling over seven years and millions of dollars across several research institutes and experts. The detailed results and insights from the test allowed for the optimization of a natural ester transformer design, alleviating the use and expense of additional safety margins. Most of the test details and results were published and are available in IEEE Xplore library, but the overall test conclusions were:

- The dielectric capacity of FR3 fluid, for all construction elements of a properly designed transformer, is equivalent to mineral oil. No additional safety margins are required.
- The different dielectric constant or permittivity of a natural ester liquid affects the distribution of the electrical field in a transformer. While the impact may be small for lower voltage classes, it is essential

to be taken into consideration for higher voltage levels.

- Special attention is required for designing and performing the tests, avoiding the presence of sharp edges, oil wedges, gas bubbles and increasing the time for purging the gases formed after each flashover.

More Data, More Testing

The comprehensive testing program offered the required confidence level for the application of the natural ester liquids in higher voltage classes, achieving the first 420 kV transformer in 2013, before any other alternative liquid. This also drove the application of natural ester in instrument transformers used to monitor the voltage of the transmission line, and the development of a standard "lead exit" for transformers of such voltage class, used to connect the high voltage winding exit to the bushing.

Cargill supported and joined the testing phase of the lead exit with EHV Weidmann, wherein the final configuration had the same diameter of the solution used for mineral oil, validating the equivalency of the dielectric capacity of the two insulating liquids. Moreover, the successfully performed tests exceeded IEC test protocols, including basic impulse levels applied for 765 kV transformers, and the achieved level of partial discharge was extremely low, outperforming what was obtained when testing the lead exit with mineral oil.

To understand the differences for highly divergent field configurations, a two-year investigation was initiated, exploring a sequence of sharp electrodes, ranging from sphere-to-sphere configuration to needle-to-sphere configuration. The tests were performed with different variables (i.e. gaps, electrodes, moisture contents

Figure 5. Images showing the position of the "lead exit" in a power transformer and a full representation of the final structure developed to be used with FR3 natural ester liquid.

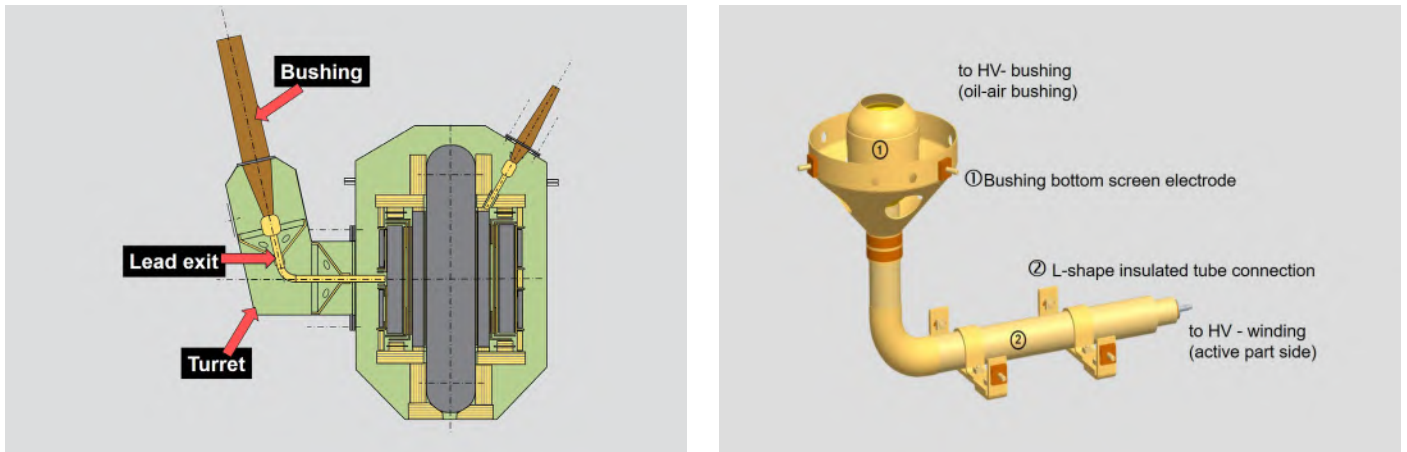
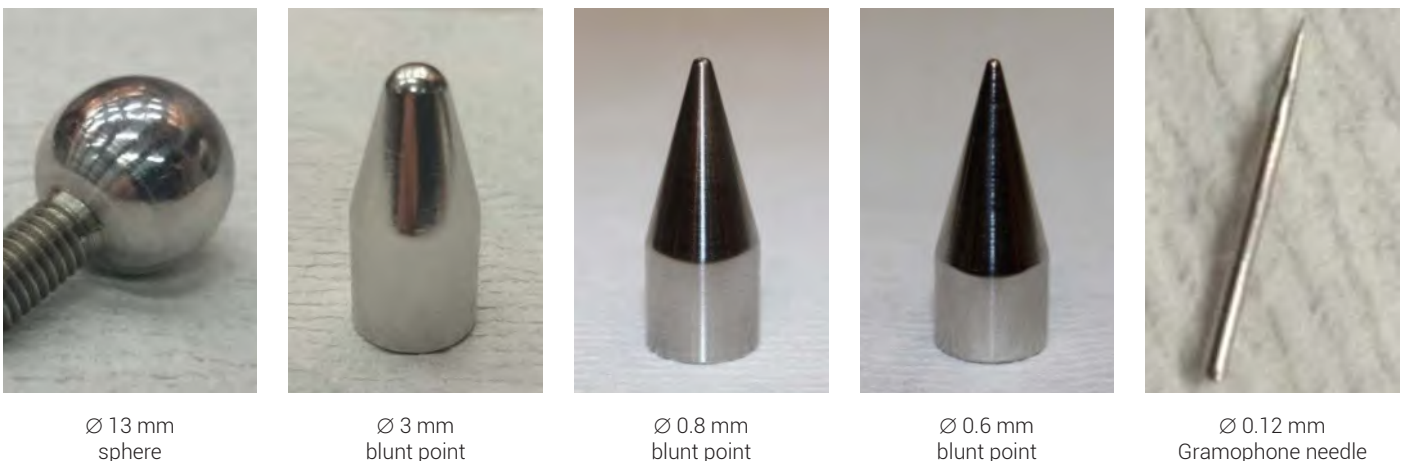


Figure 6. Electrodes designed for the investigation of the highly divergent fields behavior.

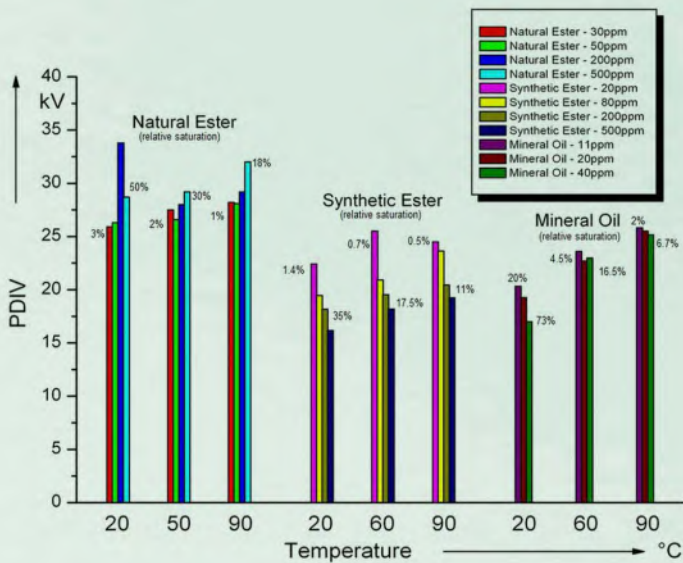


and particle contents), testing the natural ester side-by-side with mineral oil. The obtained breakdown voltage for the different electrodes when tested in natural ester and in mineral oil were equivalent down to the 0.4 mm radius for a 25 mm gap. Since this is sharper than what would be acceptable for any medium and high voltage transformer, it does not imply larger gaps nor increased design clearances.

The most recent investigation projects are around the "pre-discharge" process, namely the inception and effects of partial discharges. Identified as a failure mode since a while, the generation of x-wax, a wax-

like substance identified in failed transformers, especially lately in wind generators, is directly related to the presence of partial discharges, as reported by the published papers from Schering-Institute (Leibniz University of Hannover). Relevant advantages were identified when natural ester behavior was investigated, triggered exactly by the difficulties in reaching a stable level of partial discharges activities. While the tests with mineral oil and synthetic ester allowed for keeping the discharges along several days, with natural ester liquids the partial discharges were self-extinguished in a few hours, regardless of increasing the voltage almost to the breakdown level.

Figure 7. Results of Partial Discharge Inception Voltage (PDIV). Lower values indicate higher susceptibility to high voltage.



To date, the investment to test and validate the performance of natural ester liquids exceeds all other alternative liquids by far, totaling over 25 years of research. The potential of natural ester liquids to transition from an “alternative liquid” to a mainstream material – as the market share in some regions already indicates – is the driver for maintaining investments in research and development.

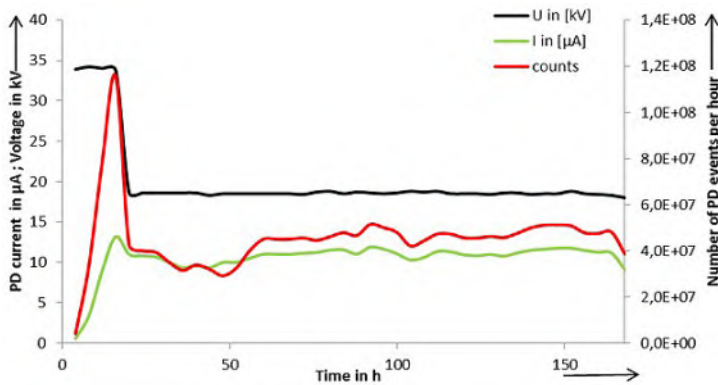
A deeper understanding of the inception and extinguishing process is expected as an outcome of the currently active project with Rome University. The differences of the molecular structure of esters may be key parameters for understanding the “quenching” behavior, as a side effect of the presence of double bonds.

The knowledge acquired from research and development activities continues to drive new tests and investigations. To date, the investment to test and validate the performance of natural ester liquids exceeds all other alternative liquids by far, totaling over 25 years of research. The potential of natural ester liquids to transition from an “alternative liquid” to a mainstream material – as the market share in some regions already indicates – is the

driver for maintaining investments in research and development.

There is inherently a high level of responsibility with the design of power transformers, either due to the expense and complexity, or the decades-long life expectancy. But over time, transformer designers have increased their confidence level in applying transformer design limits with natural ester liquids, similar to those used with traditional mineral oil filled transformers. The immense amount of data and information now available on natural ester liquids has demonstrated their functionality. Add to that the other undeniable advantages flash and fire point and environmental characteristics, and it's clear that natural ester liquids may be the future go-to insulation liquid.

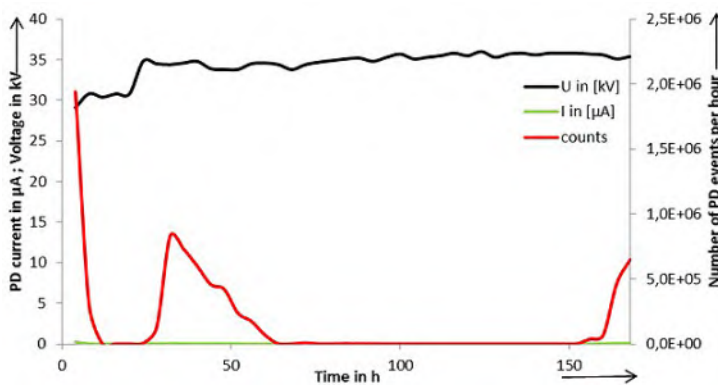
Figure 8. The charts (left) present the different profile for the partial discharges. The photos (right) show the solidified materials formed after the 200 h of ageing under PDs.



Voltage and PD activity during a typical test with synthetic ester



X-Wax formed from synthetic ester



Voltage and PD activity during a typical test with natural ester



Traces of solidified product from natural ester

