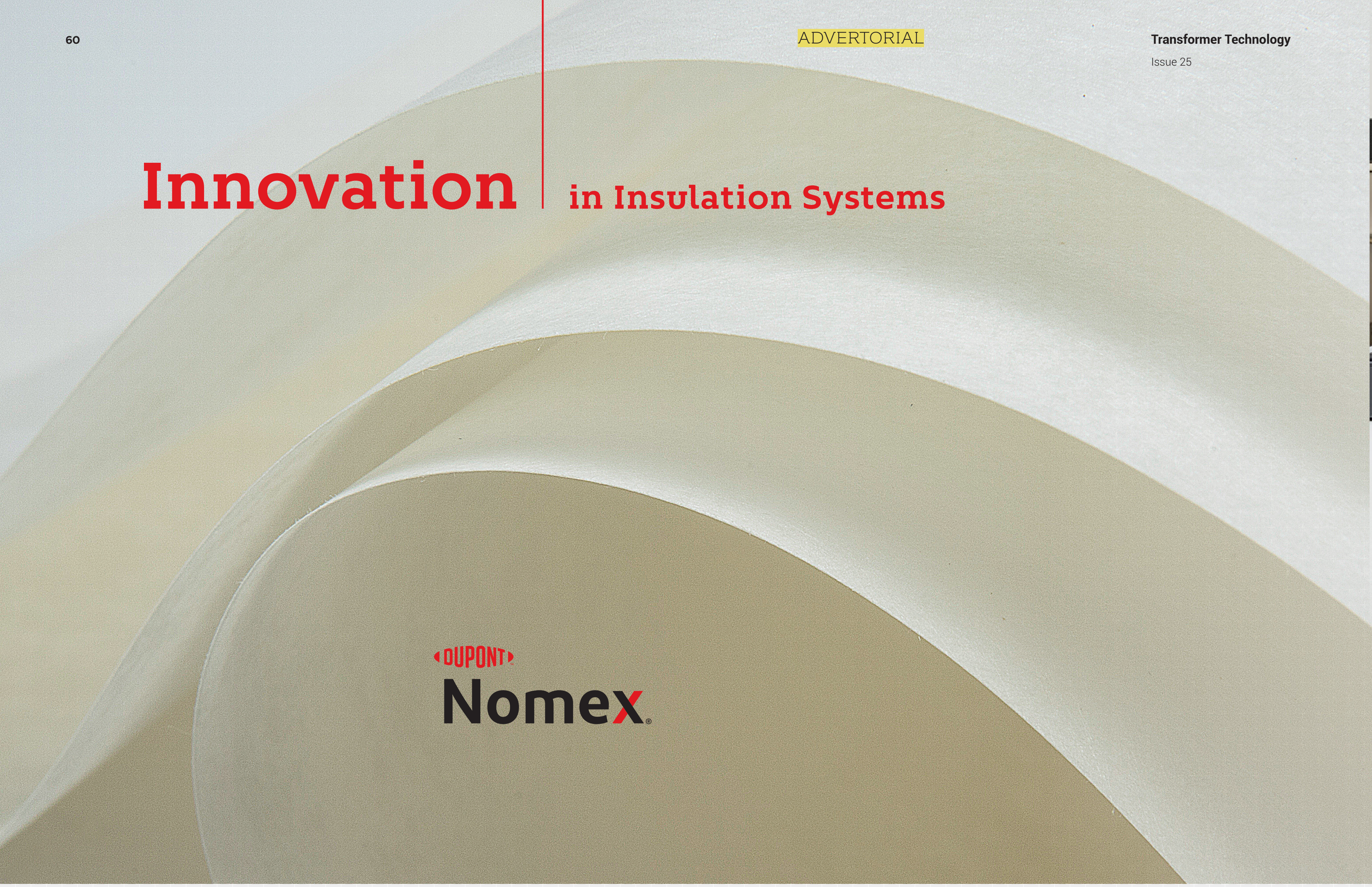
Innovation in Insulation Systems



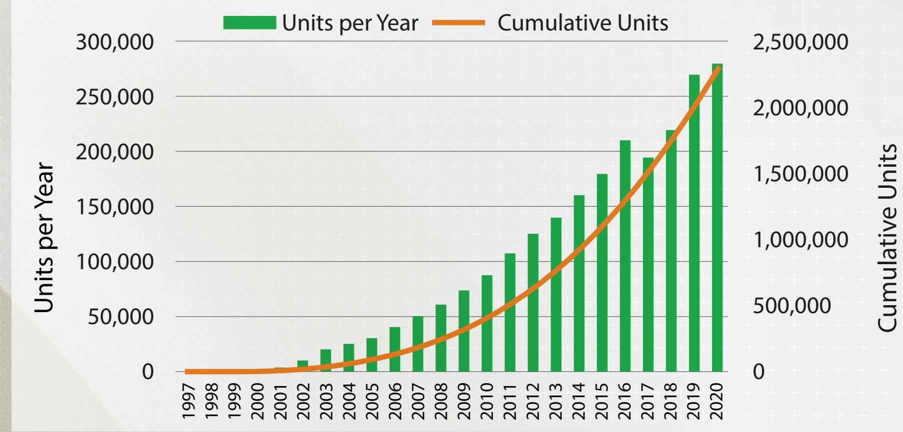


Figure 1: Estimated number of transformers filled with natural ester globally

In the last three decades, there have been important evolutions in the use of advanced insulation systems for liquid-filled transformers. Before that, more than 60 years ago, some new synthetic fibers were discovered, leading to the development of meta-aramid papers. With the commercialization of silicon fluids, it impacted the development of electrical insulation systems for liquid-filled transformers in the late 70's and early 80's.

However, in recent years the use of natural esters coupled with solid insulating materials of higher performance (like aramid Nomex® insulation) has been emerging as another insulation system for more flexible and resilient transformers [1]. The development of ester fluids, synthetic or natural, has answered the need to have transformers that would use biodegradable and sustainable liquids. Spreading initially in traction transformers and small distribution transformers, these fluids have also emerged in applications like solar and wind turbine transformers, and more recently larger power transformers for transmission and distribution networks, as well as industrial uses.

They are also becoming a more and more popular solution in urban substations due to the safety of these liquids in case of fire, as compared to traditional mineral oils.

An important aspect of the use of combined solid and liquid materials is to have a good understanding of the properties of their combination. In that sense, the characterization through the analysis of insulation system thermal performance is critical. This is needed to support the development of adequate design rules for transformers using that specific combination of materials. The IEC 60076-14 and the IEEE Std. C57.154™ are probably the most descriptive standards that exist today in the world providing detailed information on the use of combinations of those materials. However, to serve this, as indicated earlier, a characterization of the thermal behavior is critical, and the IEEE Std. C57.100™ provides details of procedures for the thorough evaluation of insulation system thermal properties.

While those standards have been developed in the last two decades, the innovative approach taken recently has led to the certification of an insulation system for liquid-filled transformers by a third-party entity, for the first time ever. This is aimed to ensure the highest quality of the generated test data, as well as an indicator that will be used by transformer manufacturers or transformers users.

The system certified can then be compared and benchmarked to existing insulation systems like cellulose and mineral oil that are being used for decades.

Photo: DuPont

1. The interest in natural esters fluids

Mineral oil has been considered the most preferred liquid insulation over the past 140 years for power transformers. With its strong credentials as an efficient dielectric and cooling medium coupled with low cost, it sounded unlikely that any alternative liquid could significantly replace the mineral oil, at least in a short time. As the environmental impact and, more recently, sustainability has been a growing concern, including for electrical equipment, the need to look for alternatives to materials that could impact the environment during a spillage or even worse during a failure that could result in fire, has led to the consideration of materials that would improve the safety as well as the sustainability.

That scenario has favored the acceptance of fire-safe, eco-friendly, and sustainable materials like vegetable esters. The use of natural esters coupled with solid insulating materials of higher performance provides a solution for overcoming such complex requirements that transformers must meet.

We can see that the use of natural esters has grown exponentially (see Figure 1), even if initially it was limited to small distribution and industrial transformers only. While most ester applications were combined with conventional cellulose papers and pressboards, the association with thermally upgraded cellulosic papers has also been considered. It was then a natural step to look at enhanced cellulose papers with aramid ingredients, a new generation of thermally stable papers invented and commercialized less than a decade ago [2]. The transformers would benefit not only from improved fire safety performance and reduced environmental footprint. Additionally, it would have improved overloadability and better resistance to high ambient temperature which becomes more significant for insulation systems, particularly in the case of more frequent heat waves that appear now during each summer. It would be however foolish to consider that winter is better for transformers and their insulating materials as ambient temperature may help to cool the transformer and limit the aging of the insulating materials. Cold waves also lead to increased consumption of energy and the important dependency on heat generated from electricity. This has led to dramatic situations of blackouts during the winter season, as well.

As overheating can happen in transformer windings resulting from higher power demand due to several conditions, looking at the lifetime of the insulation system is important in order to anticipate the lifetime of the transformer.

2. Test method for thermal evaluation of insulation system

The test method is described in the IEEE Std. C57.100™-2011 [3], the "IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Liquid Immersed Power and Distribution Transformers". These procedures help evaluate the thermal capability of an insulation system by carrying out relative thermal aging where a candidate insulation system is aged and compared to an industry-proven system (IPS) to determine the relative performance of the two systems. While lengthy and complex, this evaluation allows for the development of a life expectancy curve for the candidate system.

The two materials considered for a thermal evaluation described below were the thermally upgraded cellulose paper enhanced with aramid DuPont™ Nomex® 910 immersed in the high-oleic sunflower natural ester A&A Parodi Paryol Electra 7426. For this testing, the sealed tube test methodology was selected from Annex B of the standard: "Materials testing – standard test procedure for sealed tube aging of liquid-immersed transformer insulation".

As test is carried out, critical parameters like material ratio, presence of water must be carefully monitored as they will have an impact on the end-of-life of the insulation system. The method to prepare the insulation materials through impregnation process before placing in sealed tubes is also a critical element of the preparation of this test. Also, the combination with other materials used in transformers like copper, magnetic steel, pressboard, paper and insulating fluid (see Figure 2). The tubes are then sealed with a nitrogen blanket and equipped with a pressure relief valve.

3. Evaluation of insulation system

The first step in the test procedure is to age the industry proven system at three specific temperatures to determine the end-of-life criteria as a target for the aging test of the new candidate material. The industry proven system is a combination of Thermally Upgraded Kraft (TUK) paper with mineral oil. A minimum of three cells must be tested at the three specified temperatures for a time determined by the life equation for TUK paper, as defined in IEEE Std. C57.12.00™. This reference life curve is based on the expected life of 180 000 hours (20.5 years), when the TUK paper is continuously exposed to the temperature of 110°C (the temperature index of the reference insulation system).

For evaluation of a candidate insulation system, the list of materials loaded to the aging cells is the same as in the reference system, except the new fluid and the new insulating paper: in our case the fluid tested is the natural ester Paryol Electra 7426 while the paper is the Nomex® 910.

thermally upgraded cellulose + Nomex® aramid
thermally upgraded cellulose
thermally upgraded cellulose + Nomex® aramid

Figure 3. Simplified structure (cross-section) of aramid enhanced thermally upgraded cellulose paper Nomex® 910

As indicated previously, the choice of a natural ester for this study is important as the trend for new insulation system with environmentally friendly fluids is clear nowadays. Similarly, the need of an innovative solid insulating materials led to the choice of the Nomex® 910 paper, a paper designed for liquid immersed transformers. This paper is made of thermally upgraded cellulose combined with aramid ingredients (Figure 3). This engineered paper can be used to allow for higher operating temperature of transformer windings. When used at conventional operating temperatures, the solution can provide extended insulation and transformer life.

Figure 2: Materials loaded into the aging cell – example

Photo: DuPont

For the best quality of test results, this evaluation of the insulation system required long preparation and proper selection of additional aging temperatures that helped improving the curve fit of the Arrhenius' equation.

The program ended up with more than forty (40) sealed tubes being aged in laboratory ovens. Insulation system was aged for five to seven different durations at each aging temperature, while a regular test would only require three durations. Upon completion of testing and generation of data on the achieved end-of-life of the system, the test information was validated by an independent third-party body, the Underwriters Laboratories, Inc.

4. Temperature index achievement

At pre-selected temperatures, the individual aging cells were aged to reach the paper end-of-life point. This end-of-life point, typically set at 50% of the remaining tensile strength in the past, was set to 29.6% to match the value reached for the industry proven system. Once this condition was obtained at each pre-selected temperature, the life curve (Arrhenius' curve) was plotted with end-of-life time vs. temperature. This curve was then projected to 180 000 hours to arrive at the relative temperature index of the evaluated candidate insulation system (Figure 4).

The Arrhenius curve for the tested insulation system has been model by the following equation:

$$LIFE = e^{\left[\frac{17087}{T+273} - 30.778\right]}$$

where:
LIFE is the life in hours and T is the aging temperature in °C.

As a result of the assessment verified by the third-party laboratory, the temperature index of the system has been defined as 125.5°C at 180 000 h.

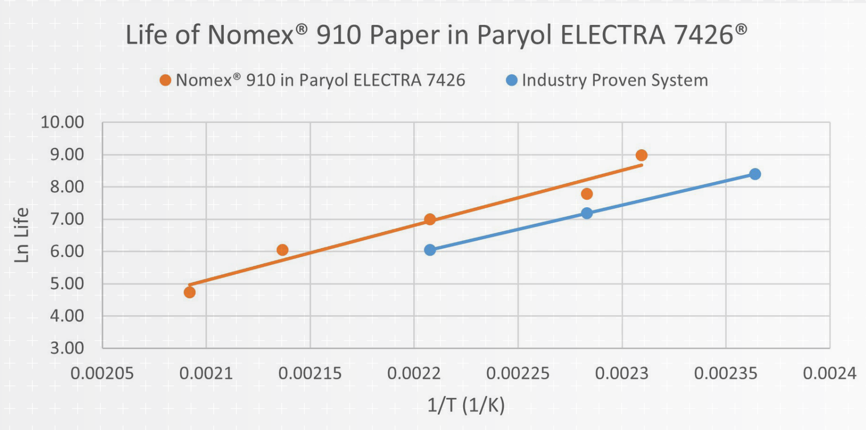


Figure 4: Thermal performance life curve of Nomex® 910 paper in Paryol Electra 7426 compared with industry proven reference system

The resulting thermal class is then 130. Today this system is the only and first ever insulation system for liquid filled transformers that has been certified. While this UL certification concept did emerge in the 1960's and 1970's for insulation systems for dry type equipment like motors, generators or dry type transformers, it is only now that it is extended to fluid filled transformers (Figure 5).

5. Continued aging test program

As this is a first step, we know that for better understanding of performance of various insulation systems it will be critical to conduct further studies. The number of advanced insulation materials that exist today will also open for more combinations that will need to be evaluated thanks to this presented methodology. We hope that this new step leading to the certification of insulation systems will allow a better understanding of the materials and their combinations. This should also lead to a better adjustment of the future design of transformers as they integrate these advanced insulation systems, providing more flexibility to users and transformer manufacturers to meet more and more critical operating requirements.

Electrical Insulation System Components E57692

DuPont Specialty Products USA, LLC
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System Component	System Designation	System Class
Nomex® 910	Nomex® + Ester 130	130(B)

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An Authorization Letter is Required for Adoption of this System

Construction Details (Table I)

The use of this insulation system is limited to the combination of materials specified below. Where more than one item is designated under insulation function, they may be used together, unless otherwise indicated, or they may be used as alternates to one another. Functions designated "optional" are not necessarily required for every design. Insulation thicknesses and/or layers below indicated are minimum.
Description: Liquid Immersed distribution transformer EIS
Note: Intended for use in liquid immersed distribution transformers evaluated to IEEE Std C57.154

Bare Conductor - copper wrapped or interleaved with Nomex 910

Ground and Interwinding Insulations

Designation	mils(mm)	comments
A&A. Fratelli Parodi S.p.A		
Paryol Electra 7426®		Dielectric Fluid - Natural Ester
DuPont Specialty Products USA, LLC		
Nomex® 910	5 (0.13)	Cellulosic/aramid paper

any sheet insulation or tape described in this table with no minimum thickness requirement may be used as a minor sheet material

Spacer and Wedges

Designation	comments
Various Manufacturers	
Pressboard	pre-compressed or calendered cellulosic material
Weidmann Electrical Technology AG	
HiVal	Cellulosic Pressboard
T4	Cellulosic Pressboard

any material described in this table with no thickness requirement may be used as a spacer or a wedge

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Figure 5: Description of insulation system "Nomex® + Ester 130" in UL IQ database

Bibliography

[1] F. Scatiggio, G. Campi, E. Wang, R. Szewczyk "Supporting development of transformers with natural esters by comprehensive evaluation of insulation systems" Proceedings of Cigre Session 2022, Paris, paper A2 #10772

[2] B. S. Kang, M. R. Levit, R. P. Marek, R. C. Wicks, R. L. Provost "Development of a New Solid Insulation for Liquid-Immersed Transformers" – Proceedings of IEEE Electrical Insulation Conference (EIC), 2014. Pp. 344-347

[3] IEEE Std. C57.100™ "IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Liquid Immersed Power and Distribution Transformers", 2011