WEBINAR

Accelerated Aging Test – A Determination of Transformerboard Thermal Class

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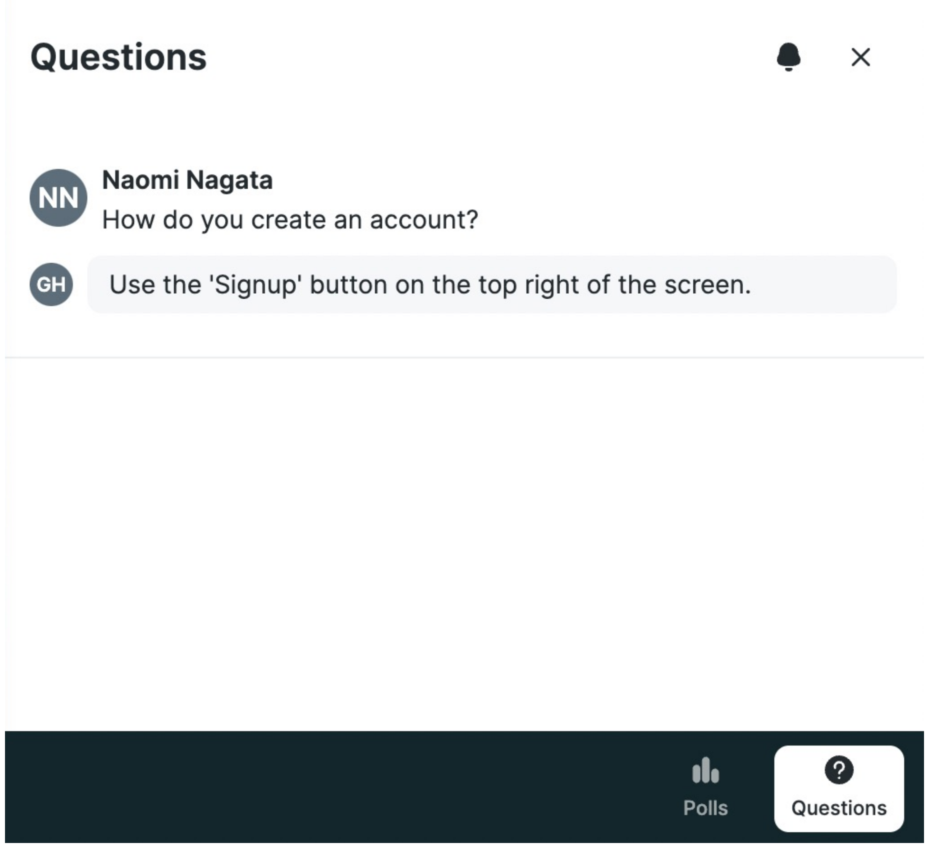

ACCELERATED AGING TEST – A DETERMINATION OF TRANSFORMERBOARD THERMAL CLASS

THOMAS PREVOST & BRAD GREAVES

ACCELERATED AGING TEST – A DETERMINATION OF TRANSFORMERBOARD THERMAL CLASS

01 **Evolution of Insulation Thermal Class in Liquid Immersed Transformers**

02 Sealed Tube Accelerated Aging

03 Observations

04 Results & Conclusions

EVOLUTION OF INSULATION THERMAL CLASS

THERMAL UPGRADING OF INSULATION

In the late 1950’s transformer manufacturers developed Thermally Upgraded Kraft Papers (TUK).

In 1962 NEMA (USA) officially recognized TUK in standard TR-1-1962 by establishing another temperature rise limit of 65 °C for oil-immersed transformers using TUK.

Today 65 °C rise transformers are the norm in North America.

Thermal upgrading is achieved by the addition of chemicals to protect the cellulose from oxidation: this is primarily achieved with nitrous compounds such as dicyandiamide.

While thermally upgraded papers have been available since 1962, thermally upgraded pressboard has not.

EVOLUTION OF INSULATION THERMAL CLASS

INTRODUCTION OF THERMALLY UPGRADED PAPER - IEEE

Insulation Life

The thermal limit of transformer windings is the insulation on the conductor at the winding hot spot. The average winding rise is calculated as follows:

	55 °C Rise	65 °C Rise
Average Ambient	30 °C	30 °C
Average Winding Rise	55 °C	65 °C
Hot Spot Differential	10 °C	15 °C
Hot Spot Temperature	95 °C	110 °C*

* Only attained with thermally upgraded paper

EVOLUTION OF INSULATION THERMAL CLASS

THERMAL INDEX VERSUS THERMAL CLASS

- IEEE C57.100-2022, "IEEE Standard Test Procedure for Thermal Evaluation Of Insulation Systems for Liquid-immersed Distribution and Power Transformers"
- The thermal index is the maximum hottest spot temperature for which the insulation system is expected to provide normal life.
- The maximum hottest spot temperature is determined by using a standard aging test, IEEE C57.100, and then rounded down to the nearest value given in Table 2.
- The thermal class is then 10 °C higher than the thermal index. The thermal class is 10 °C higher than the thermal index because it is based on a 40 °C maximum ambient, versus a 30 °C average ambient.

Table 2—Potential insulation system thermal classes

Thermal class	Thermal index/hottest spot temperature °C
105	95
120	110
130	120
140	130
150	140
155	145
160	150
170	160
180	170
190	180
200	190

EVOLUTION OF INSULATION THERMAL CLASS

IEEE BASIS FOR TEMPERATURE LIMITS

IEEE Standard C57.12.00 – 2021 "General Requirements for Liquid-Immersed Transformers"

5.11.3 Basis for temperature limits

Transformers that meet the temperature and loading conditions in this standard shall be manufactured using thermally upgraded paper or an alternative insulation system that has been proven to possess minimum aging characteristics that either match or exceed those of thermally upgraded paper. Cellulose paper that has not been chemically modified to improve its thermal characteristic does not qualify as thermally upgraded insulation. **This requirement applies to the insulation components that determine the minimum life expectancy, such as winding insulation, layer-to-layer insulation, lead insulation and other components.**

EVOLUTION OF INSULATION THERMAL CLASS

IEC 60076-2 2011 POWER TRANSFORMERS – PART 2: TEMPERATURE RISE FOR LIQUID IMMERSED TRANSFORMERS

The temperature rise limits given in Table 1 are valid for transformers with solid insulation designated as class 105 °C according to IEC 60085, and immersed in mineral oil or synthetic liquid with fire point not above 300 °C (first code letter: O).

The limits refer to steady state conditions under continuous rated power, and 20 °C average yearly temperature of the external cooling medium.

If not otherwise agreed between manufacturer and purchaser, the temperature rise limits given in Table 1 are valid for both Kraft and upgraded paper (see also IEC 60076-7).

Table 1 – Temperature rise limits

Requirements for	Temperature rise limits K
Top insulating liquid	60
Average winding (by winding resistance variation):	
– ON.. and OF.. cooling systems	65
– OD.. cooling system	70
Hot-spot winding	78

EVOLUTION OF INSULATION THERMAL CLASS

IEC 60076-1 CD POWER TRANSFORMERS – PART 1: GENERAL

Table 2 – Maximum permissible temperatures of transformer windings for continuous service at rated load at rated temperature of external cooling medium

Insulation system thermal class	**105**	**120**
Average winding temperature in °C Natural or forced oil flow	85	95
Average winding temperature in °C Directed oil flow	90	100
Winding Hot-spot temperature in °C	98	110

NOTE 3 Sufficient experience is available for transformers designed, tested and operated according the IEEE standard series with thermal class 120 using thermally kraft upgraded paper to introduce this thermal class here.

ACCELERATED AGING TEST & TRANSFORMERBOARD THERMAL CLASS

HISTORY

- Evolution of 120 °C class insulation systems
  - Non-TU to TU
  - To 65 °C rise system
  - Current IEEE standard, 65 °C rise system (TU paper & non-TU board)
  - Current and Upcoming IEC 60076 Part 1 CD; introduction of 65 °C rise system
  - Problem statement
    - Industry practice and International Standards recognize the utilization of non thermally upgraded pressboard with thermally upgraded paper as a 120 °C class insulation system for mineral oil immersed transformers
    - **Can we determine the thermal class of Pressboard using an industry recognized test procedure?**

ACCELERATED AGING TEST – A DETERMINATION OF TRANSFORMERBOARD THERMAL CLASS

01 Evolution of Insulation Thermal Class in Liquid Immersed Transformers

02 Sealed Tube Accelerated Aging

03 Observations

04 Results & Conclusions

ACCELERATED AGING TEST & TRANSFORMERBOARD THERMAL CLASS

SEALED TUBE ACCELERATE AGING – INDUSTRY PROVEN SYSTEM

IEEE C57.100 provides guidance for such an evaluation with the Sealed Tube Accelerated Aging Test (STAAT)

Industry Proven System – Per Table B.1

- Power Transformer Materials Ratio (PTMR)
  - Weidmann TU kraft (TUK) paper; 0.08 mm [3 mil]
  - Weidmann cellulose HD Precompressed TB “T4”; 2 mm
    - Density ~1.20 g/cm³
- Distribution Transformer Materials Ratio (DTMR)
  - Weidmann TU kraft (TUK) paper; 0.13 mm [5 mil]
  - Weidmann cellulose LD TB “Hi-Val”; 1 mm
    - Density ~1.05 g/cm³
- Both systems
  - New de-gassed ASTM D3487 Type II inhibited transformer mineral oil (Univolt N-61B)
  - Copper
  - Core steel

Table B.1—Sealed tube materials ratios

	Transformer type	
Material	Power	Distribution
Insulating liquid	200 cm^3	200 cm^3
0.05 to 0.10 mm conductor insulation	6.4 cm^3	
0.13 to 0.38 mm layer insulation		11.2 cm^3
1.00 to 3.00 mm low-density pressboard		1.2 cm^3
2.00 to 8.00 mm high-density pressboard	16.4 cm^3	
Ratio—liquid to solid	8.8 to 1	16.3 to 1

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SEALED TUBE ACCELERATE AGING – INDUSTRY PROVEN SYSTEM

- Transformer Standards
  - Minimum life expectancy curve as defined by IEEE C57.12.00-2021
  - Minimum life expectancy of 20.5 years (180,000 hours)
  - 65 °C average winding rise
  - 80 °C hottest-spot rise
- Accelerated Aging
  - Maximum 40 °C extrapolation from the thermal index (110 °C) to the minimum aging temperature
  - Aging temperatures to be 15 °C apart
  - Using equation (1)
    - 150 °C for 4434 hours
    - 165 °C for 1316 hours
    - 180 °C for 424 hours

$$\text{LIFE} = e^{\left[\frac{15\,000}{T+273} - 27.064\right]} \quad (1)$$

where

LIFE is the life in hours
T is the hottest-spot temperature in °C
e is the base of natural logarithm

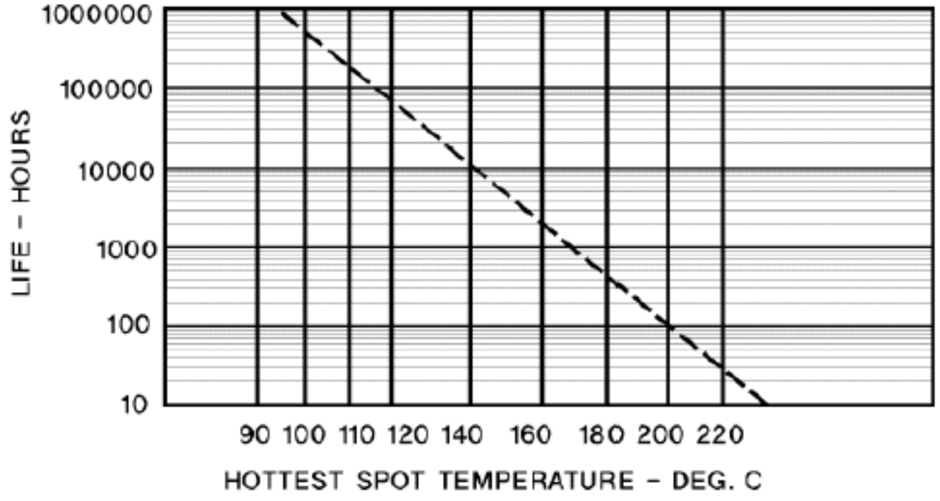

Figure 3—Minimum life expectancy curve for liquid-immersed distribution, power, and regulating transformers rated in accordance with Clause 5, at 65 °C average winding rise, 80 °C hottest-spot rise

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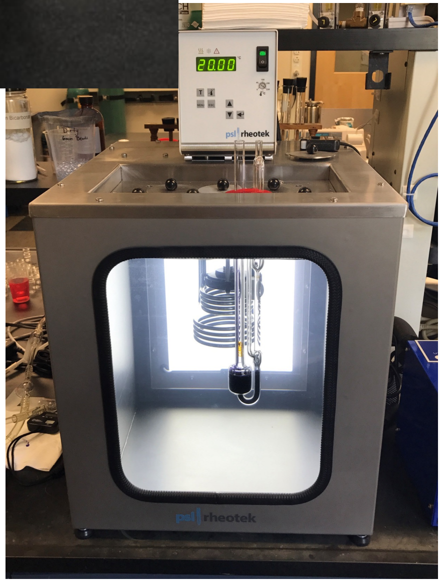
SEALED TUBE ACCELERATE AGING – TEST SET-UP AND PROCEDURE

- Vessel
  - Stainless steel tube; ~100 mm diameter and 210 mm tall
  - Approximately 2 liter volume
  - Viton® gasket with clamp on lid
  - 10 PSI [69 kPa] pressure relief device
- Material Preparation
  - Solid dried to <0.5% moisture content
  - Liquid dried to less then 4 ppm
  - Flushed with dry Nitrogen & sealed
- Tests completed on solid insulation:
  - Machine direction tensile strength per ISO 1924
  - Viscometric DP (DPv) per IEC 60450



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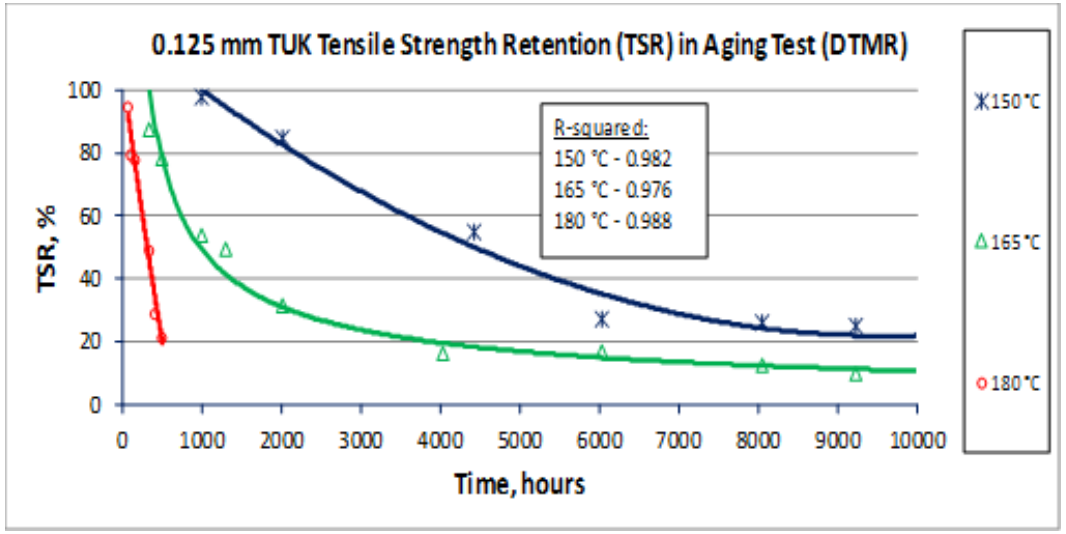
SEALED TUBE ACCELERATE AGING – TEST SET-UP AND PROCEDURE

- End-of-life criteria determined using the IPS and the 3 time/temperature combinations on previous slide
  - Typically tensile strength retention of the paper
  - May be other criteria; e.g. DP, tear strength, etc.
- Candidate system is aged in the same manner as the IPS until the end-of-life criteria is achieved
  - Three aging temperatures; 15 °C apart
  - Maximum of 40 °C from expected thermal index
  - Minimum of 3 aging times per temperature
- Time required to achieve end-of-life at each aging temperature is interpolated from the aging curves
- Time to achieve end-of-life is plotted as 1/T [in Kelvin] vs. LN(time) [in hours] to create the life equation
- Thermal index is extrapolated from the life equation as the temperature at which 180,000 hours is achieved



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SEALED TUBE ACCELERATE AGING – TEST SET-UP AND PROCEDURE

- Test Program:
  - Standard PTMR test with T4 and TUK
  - Standard DTMR test with Hi-Val and TUK
- Three Temperatures
  - 150, 165, & 180 °C
- Multiple aging periods per temperature
  - PTMR – 8
  - DTMR – 6
- Candidate system was the Transformerboard

PTMR									
Temperature, °C	Time, weeks								
150	0	3	8	12	26.3	36	48	55	62
165	0	2	3	6	7.8	12	24	36	48
180	0	1	2	2.5	3	7	15	-	-

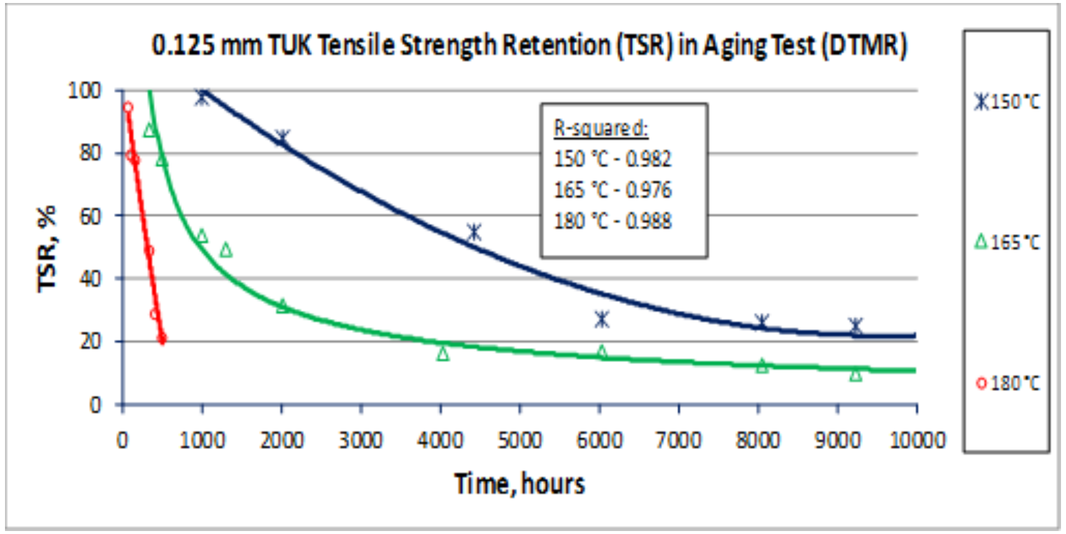
DTMR							
Temperature, °C	Time, weeks						
150	0	12	26.3	36	48	55	62
165	0	6	7.8	12	24	36	48
180	0	1	2	2.5	3	7	8

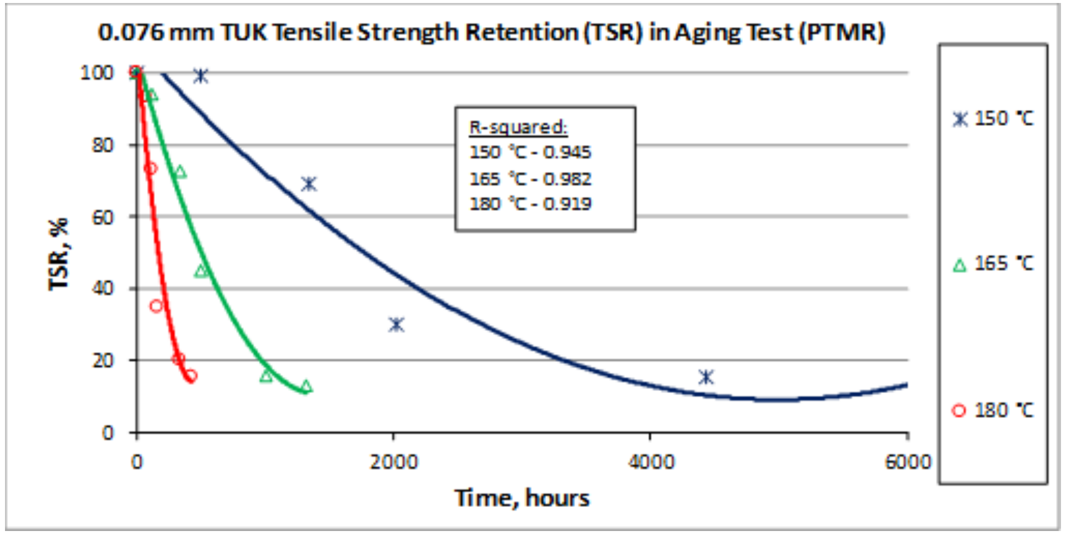
ACCELERATED AGING TEST – A DETERMINATION OF TRANSFORMERBOARD THERMAL CLASS

ACCELERATED AGING TEST & TRANSFORMERBOARD THERMAL CLASS

OBSERVATIONS – END-OF-LIFE

- Three time/temperature points are used to determine the end-of-life criteria:
  - PTMR
    - Tensile strength retention of paper = 14.6%
    - DPv of paper = 146
  - DTMR
    - Tensile strength retention of paper = 44.2%
    - DPv of paper = 256
- Relatively more TU paper in the DTMR system slowing the aging of all solid insulation materials (including TB)
- Relatively more solid insulation in the PTMR system resulting in more aging byproduct generation and further accelerating aging





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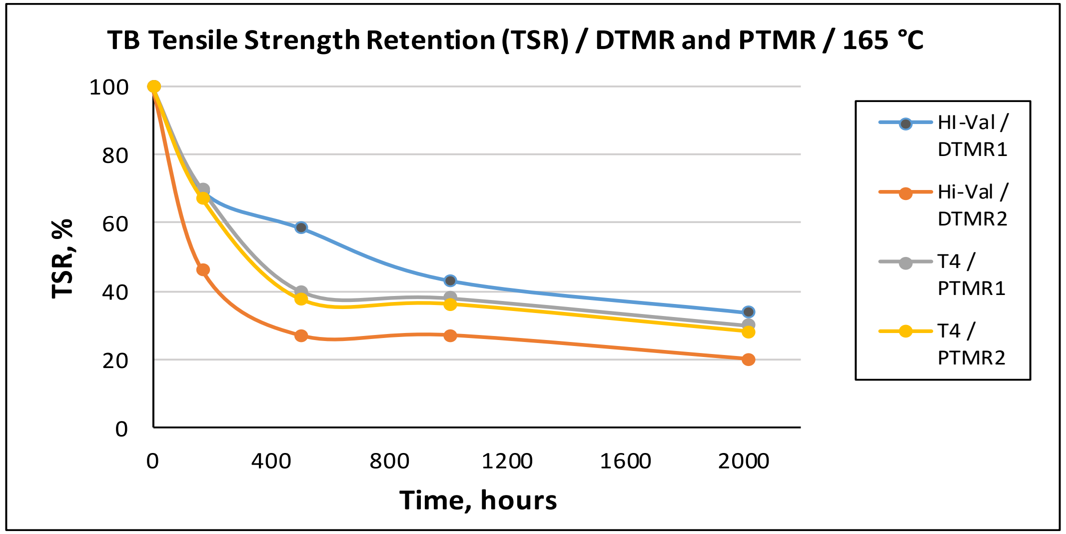
OBSERVATIONS – TB AGING IN SYSTEMS WITH TU AND NON-TU PAPER

- Testing completed with the standard material ratios but exchanging TU paper with non-TU paper
  - PTMR 1 = TU paper & T4
  - PTMR 2 = non-TU paper & T4
  - DTMR 1 = TU paper & Hi-Val
  - DTMR 2 = non-TU paper & Hi-Val
- Presence of TU paper in a relatively high proportion has a strong influence on TB aging.
- Indicating that the same type of material may have different aging rates depending on the system of materials in which it is tested
  - The same material may have different TIs when in different insulation systems.

Temperature, °C	Time, weeks				
165	0	1	3	6	12
180	0	0.57	2	3	6



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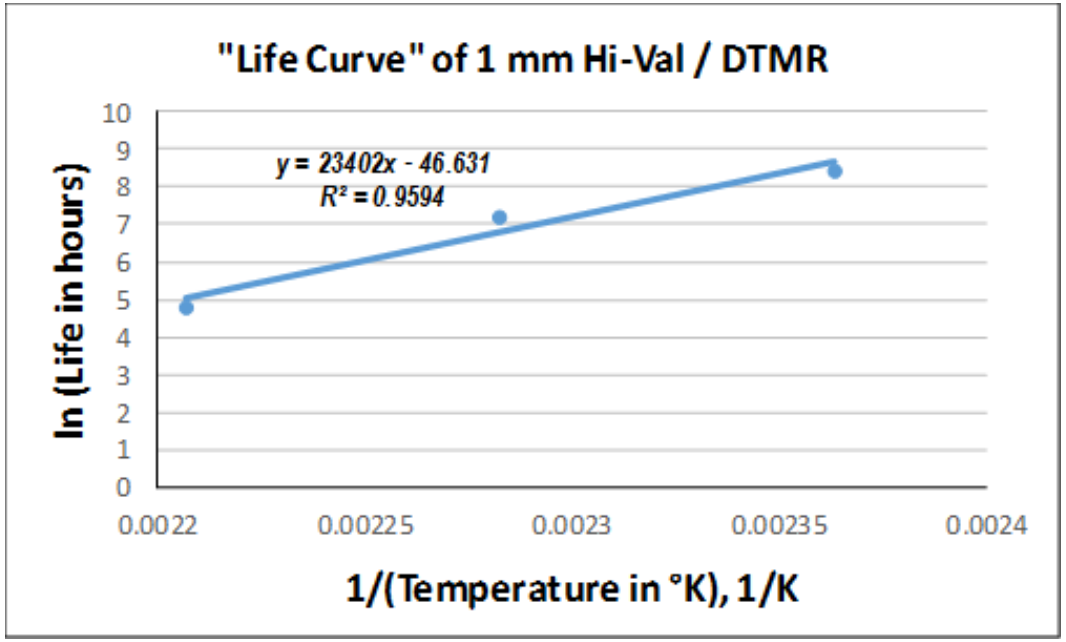
ACCELERATED AGING TEST & TRANSFORMERBOARD THERMAL CLASS

THERMAL CLASS OF TRANSFORMERBOARD – METHODS

- Method 1 – IEEE C57.100-2011
  - TUK is considered the IPS (TSR & DPv at end-of-life)
  - TB (LD & HD) is considered the candidate system
- Method 2 – IEEE C57.100-1999, TSR
  - All materials (TUK & TB) are evaluated with a criteria of 50% TSR at 65,000 hours
- Method 3 – IEEE C57.100-1999, DPv
  - All materials (TUK & TB) are evaluated with a criteria of 200 DPv at 150,000 hours



Thermal Index Results (°C)				
Test	Material	Method 1	Method 2	Method 3
DTMR	1 mm Hi-Val	125.3	127.3	115.4
DTMR	0.13 mm TUK	-	123.8	116.7
PTMR	2 mm T4	129.4	116.2	113.0
PTMR	0.08 mm TUK	-	110.8	105.0

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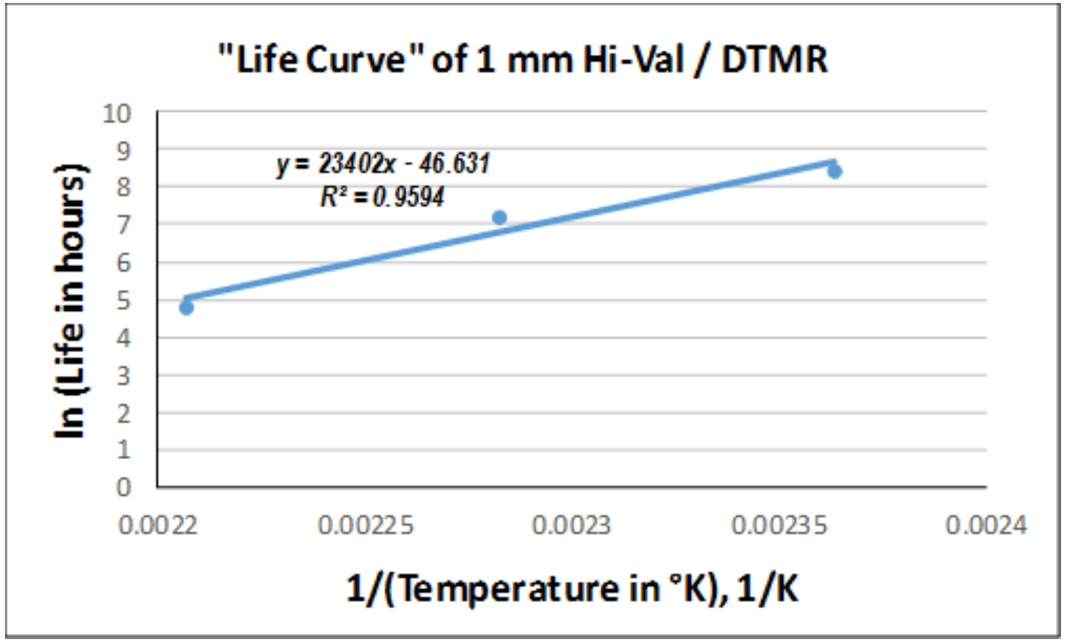
THERMAL CLASS OF TRANSFORMERBOARD – RESULTS

- Method 1 – IEEE C57.100-2011
  - TIs of TB (both LD and HD) were 120 °C
- Method 2 – IEEE C57.100-1999, TSR
  - TIs of TB were higher than the paper
  - Absolute TI of the DTMR was higher than the TI of the PTMR as expected considering the faster aging rate of both TB and paper
  - TI of DTMR is 120 °C & TI of PTMR is 110 °C
- Method 3 – IEEE C57.100-1999, DPv
  - TI of TB in DTMR was close to paper (1.3 °C lower)
  - TI of TB in PTMR was higher than paper
  - TI of both DTMR & PTMR is 110 °C



Thermal Index Results (°C)				
Test	Material	Method 1	Method 2	Method 3
DTMR	1 mm Hi-Val	125.3	127.3	115.4
	0.13 mm TUK	-	123.8	116.7
PTMR	2 mm T4	129.4	116.2	113.0
	0.08 mm TUK	-	110.8	105.0

ACCELERATED AGING TEST & TRANSFORMERBOARD THERMAL CLASS

CONCLUSIONS

- **Can we determine the thermal class of Transformerboard using an industry recognized test procedure? YES!**
- For the first time in the industry the thermal class of Transformerboard (both LD and HD) was confirmed to be 120 °C through sealed tube accelerated aging testing.
- Thermal class definitions cannot be determined on an individual material.
- The thermal class is on the entire insulation system
  - Thermally upgraded Kraft paper
  - Non-thermally upgraded Transformerboard
  - Mineral oil
- Additional Observations
  - Materials have a higher aging rate using the PTMR compared to the DTMR.
    - DTMR has less solid insulation, but more TU paper compared to the PTMR
  - The presence of TU paper in the system reduces the aging rate of all materials present, including transformerboard
    - As a result, these findings suggest that materials may have different TIs depending on the specific insulation system utilized (e.g. specific liquid or companion materials).

Q&A

ACCELERATED AGING TEST & TRANSFORMERBOARD THERMAL CLASS

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