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# ENGINEERING INSIGHTS INTO INSULATION AGING: TESTS, CHALLENGES, AND RESULTS

WEBINAR

# Engineering Insights into Insulation Aging: Tests, Challenges, and Results

September 30th | 16:00 CEST | 10:00 EST

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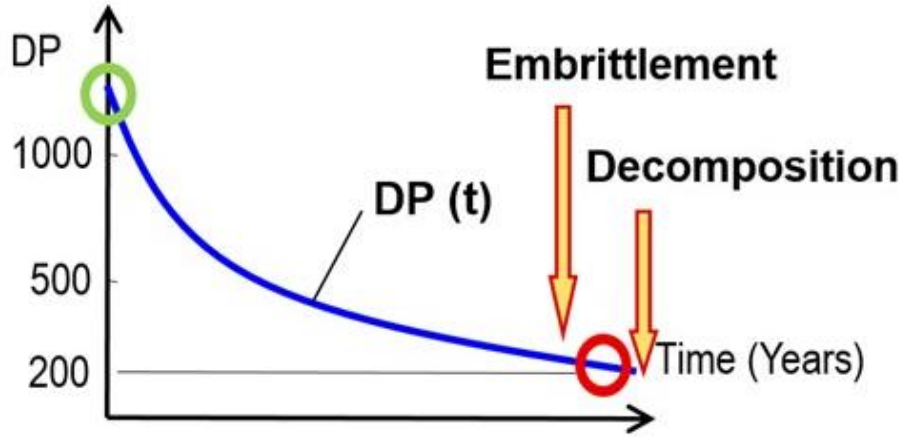
# ENGINEERING INSIGHTS INTO INSULATION AGING: TESTS, CHALLENGES, AND RESULTS

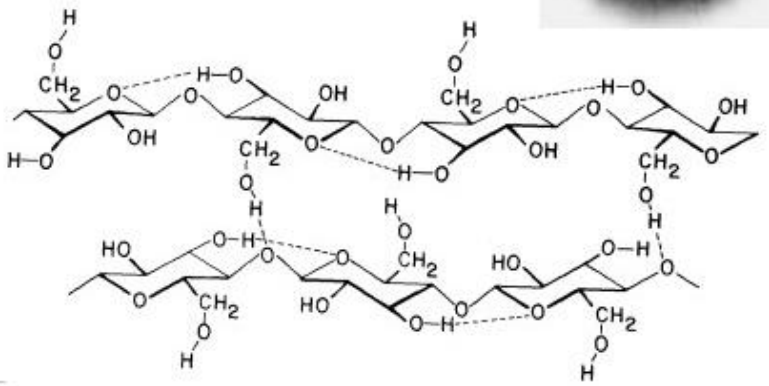
01 Theory, basics and challenges of aging experiments

02 Results of aging experiments





$$k = Ae^{-Ea/RT}$$



# 01

## THEORY AND BASICS OF AGING EXPERIMENTS

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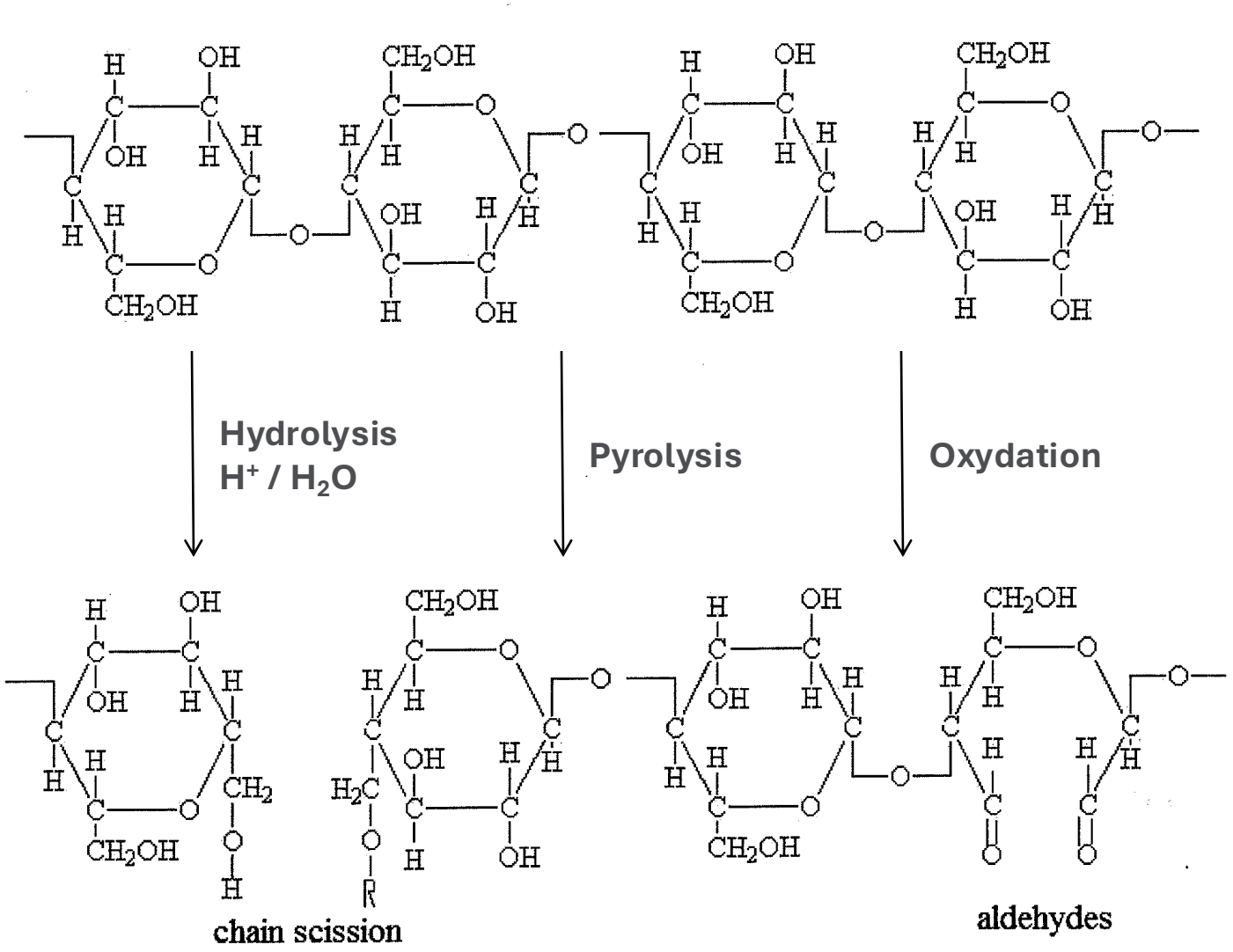
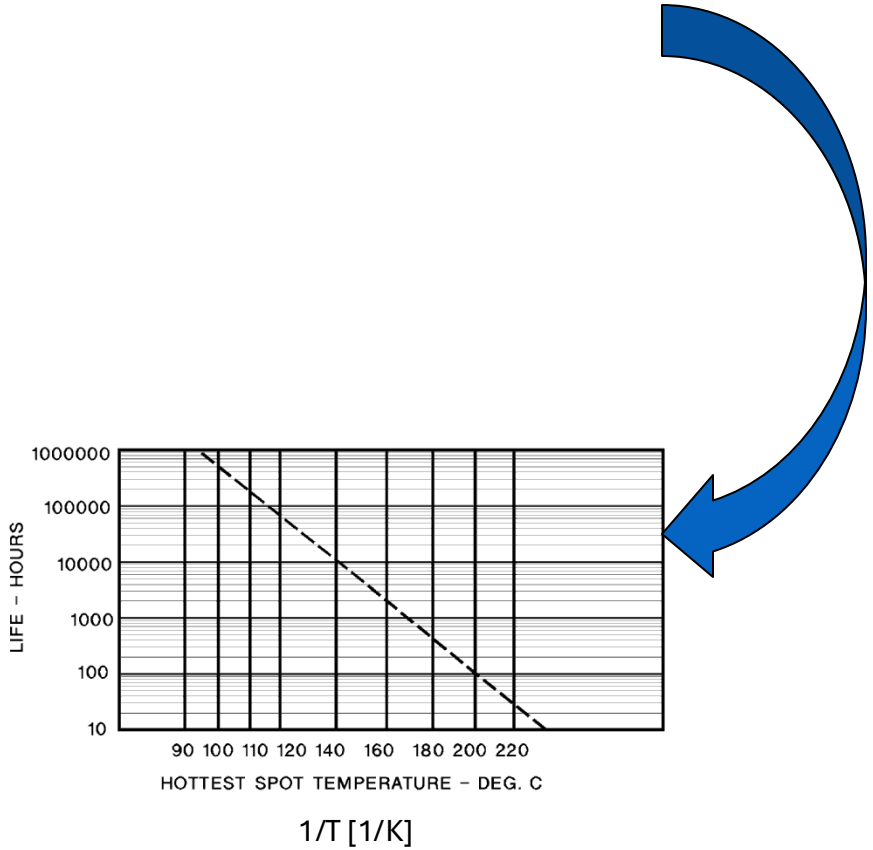
## AGING CHEMISTRY AND INFLUENCING FACTORS



# THEORY AND BASICS OF AGING EXPERIMENTS

## AGING CHEMISTRY AND INFLUENCING FACTORS





Svante Arrhenius 1859 – 1927
Swedish chemist
Nobel prize winner 1903
Kinetics, electrolytic dissociation, meteorology (greenhouse effect), physiology, cosmology

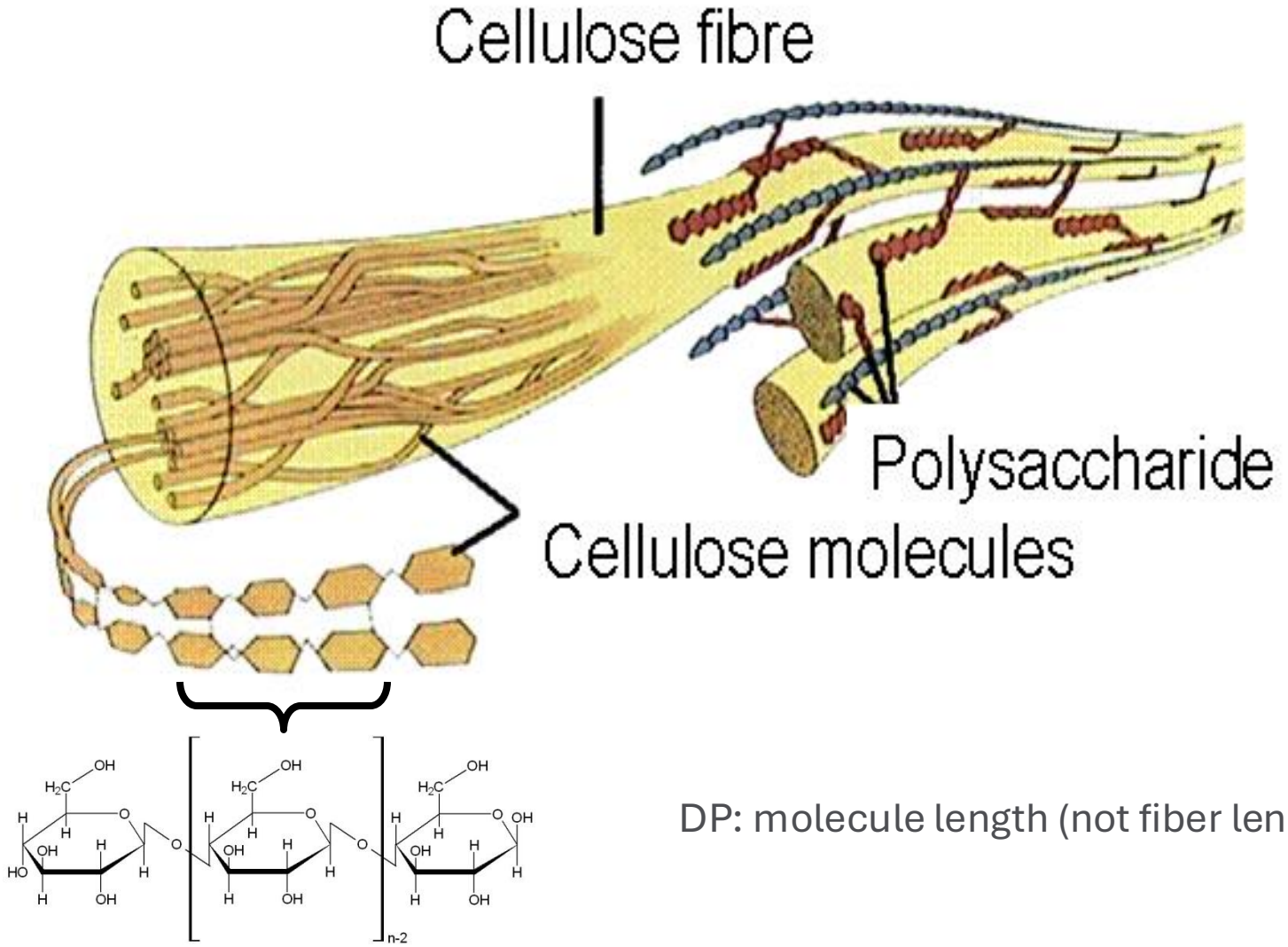
# THEORY AND BASICS OF AGING EXPERIMENTS

## DETERMINATION OF THE AGING CONDITION OF AN INSULATION MATERIAL

| Properties | Comments |
|---|---|
| Degree of polymerization (DP) | Small sample size needed, sample collection possible on transformers, |
| Tensile strength and elongation | Physical intact samples needed for meaningfull test results (warping, folding, cuts, ...), large samples needed, sample handling might impact the test results |
| Burst strength | |
| Tear strength | |

# THEORY AND BASICS OF AGING EXPERIMENTS

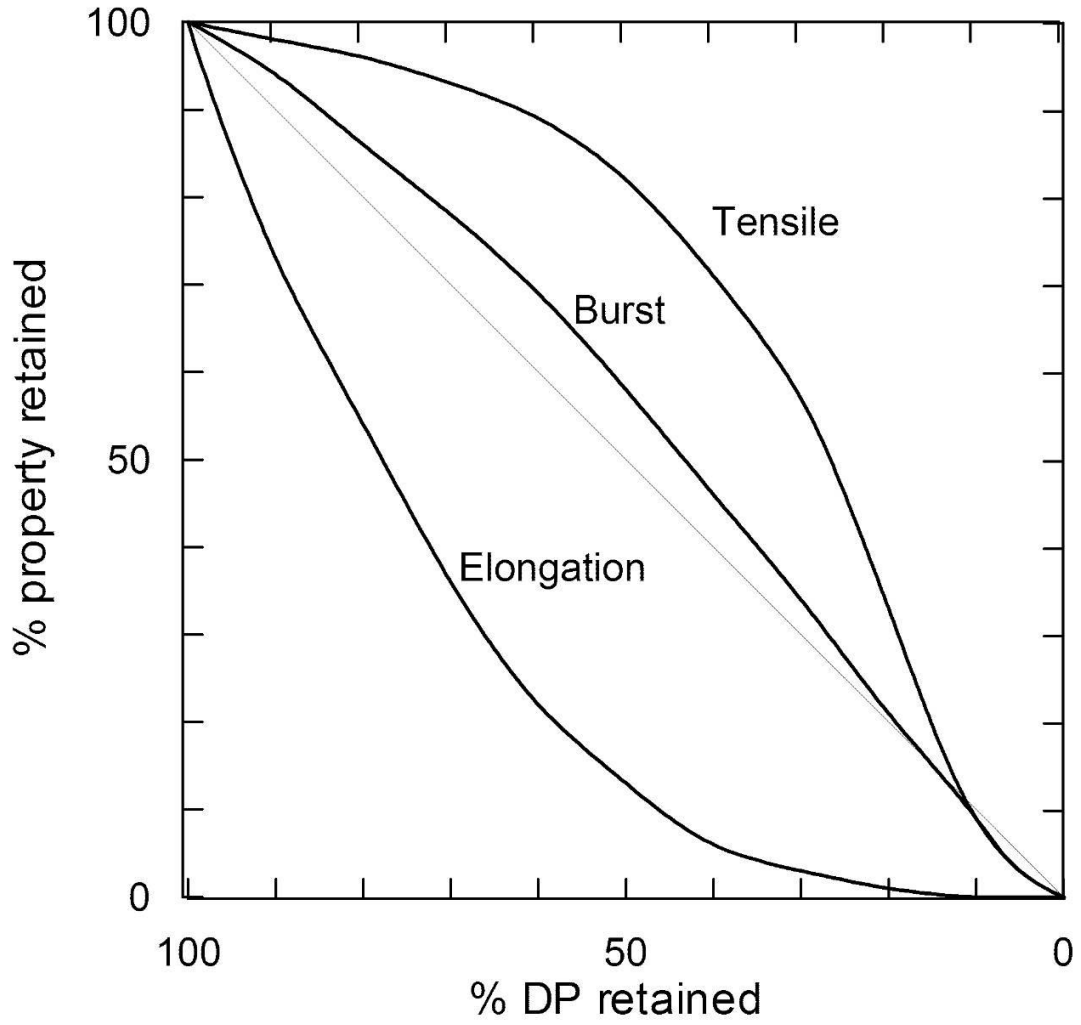
## DEGREE OF POLMERIZATION

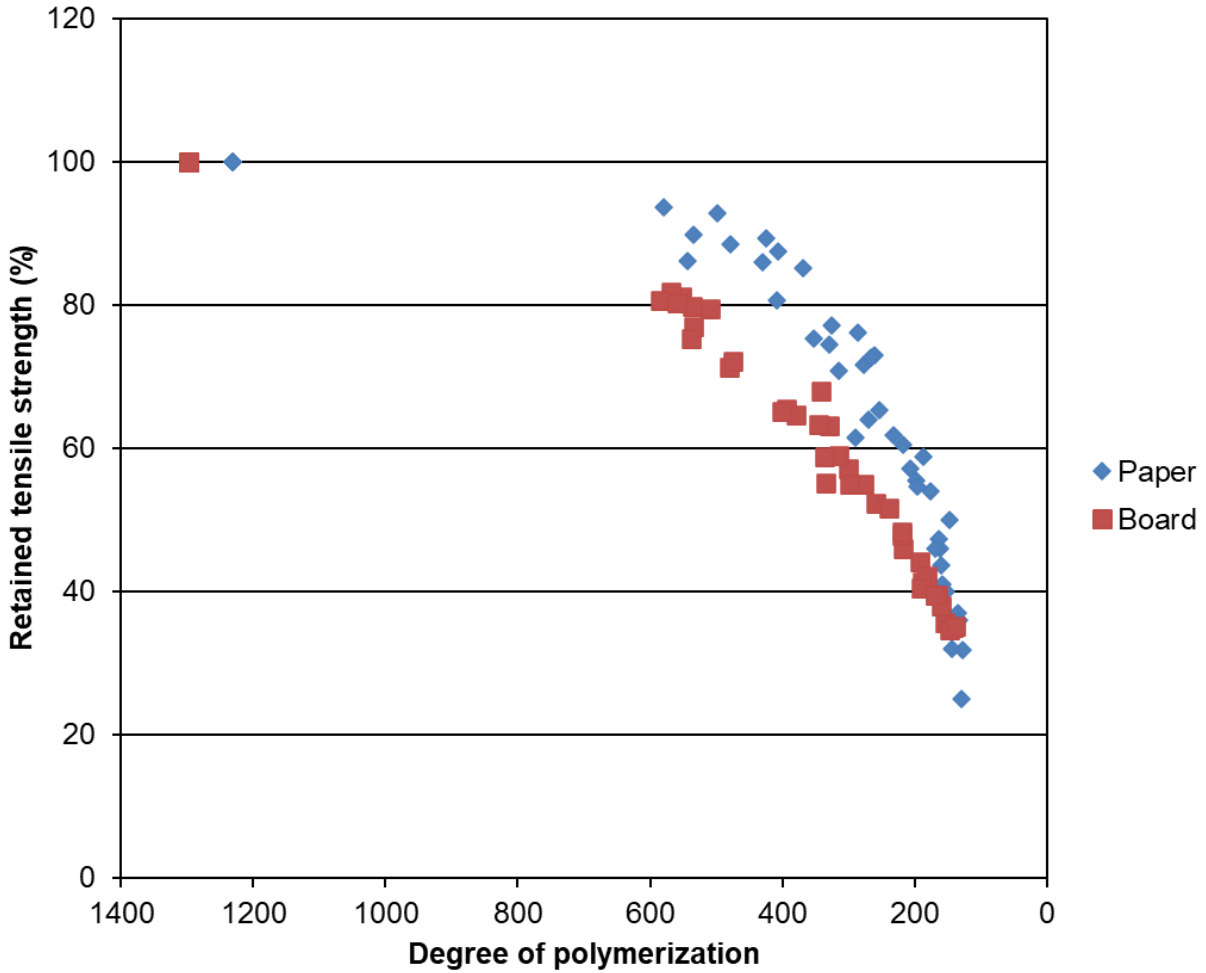



DP: molecule length (not fiber length!)

# THEORY AND BASICS OF AGING EXPERIMENTS

## CORRELATION BETWEEN DP AND TENSILE STRENGTH

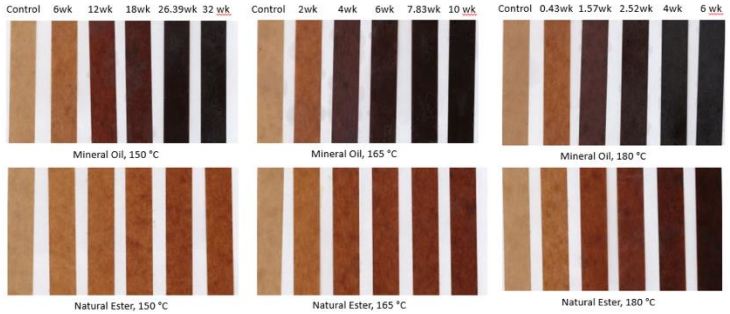


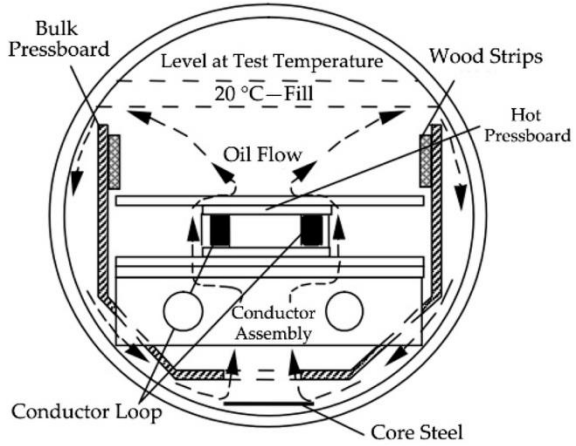
# THEORY AND BASICS OF AGING EXPERIMENTS

## STANDARDS

- IEEE C57.100 and IEC 62332
  - Main differences:
    - Industry proven system (TUK or Kraft paper)
    - Liquid to solid ratio
    - Aging temperatures
    - Aging times
    - End of life criterium








# EXECUTION OF AGING TESTS

# EXECUTION OF AGING TEST

## RESOURCES (TIME, MANPOWER, AND EQUIPMENT)

| Temperature | Measuring point (h) | | | | |
|---|---|---|---|---|---|
| 125°C | 0 | 2000 | 4000 | 6000 | 8000 |
| 140°C | 0 | 500 | 1000 | 1500 | 2000 |
| 155°C | 0 | 100 | 200 | 300 | 400 |

# EXECUTION OF AGING TEST

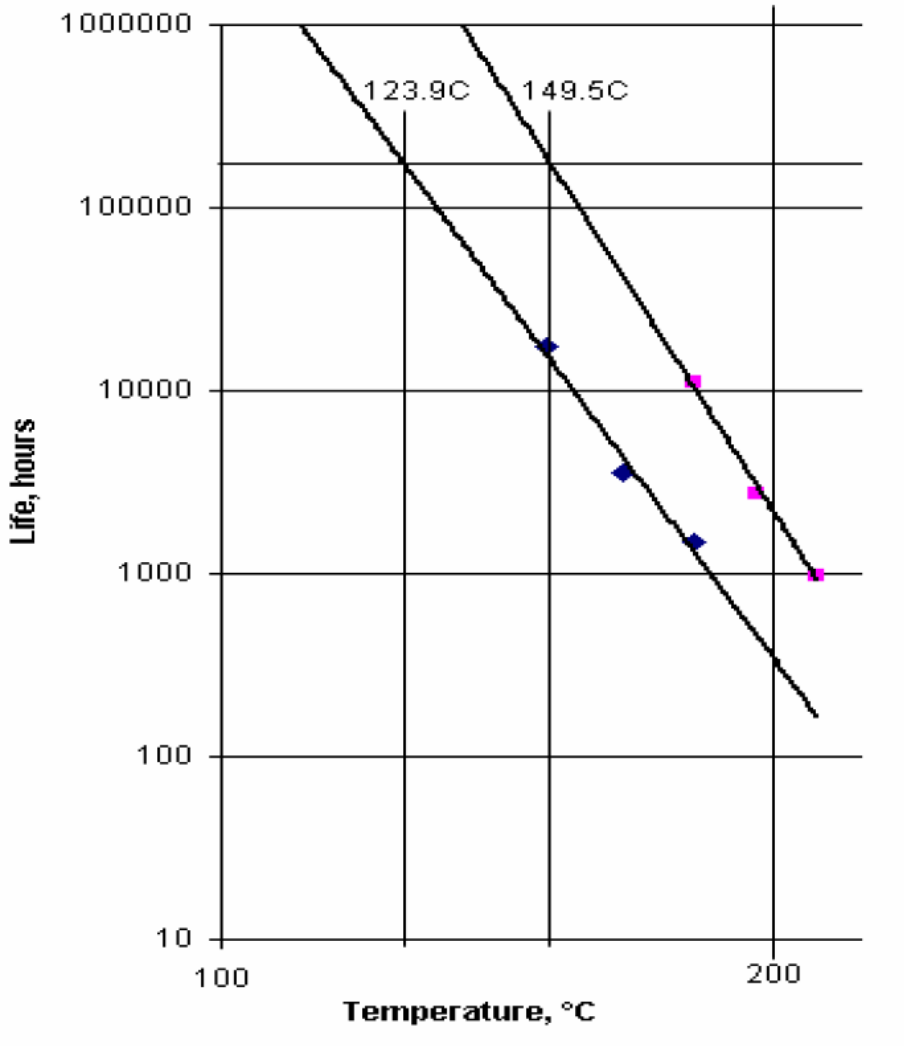
## IMPORTANT FACTORS THAT INFLUENCE THE RESULT

- Aging test vessels
- Temperature(s)
- Evaluated property (DP, tensile strength, elongation, …)

# EXECUTION OF AGING TEST

## RELATIVE TEMPERATURE INDEX

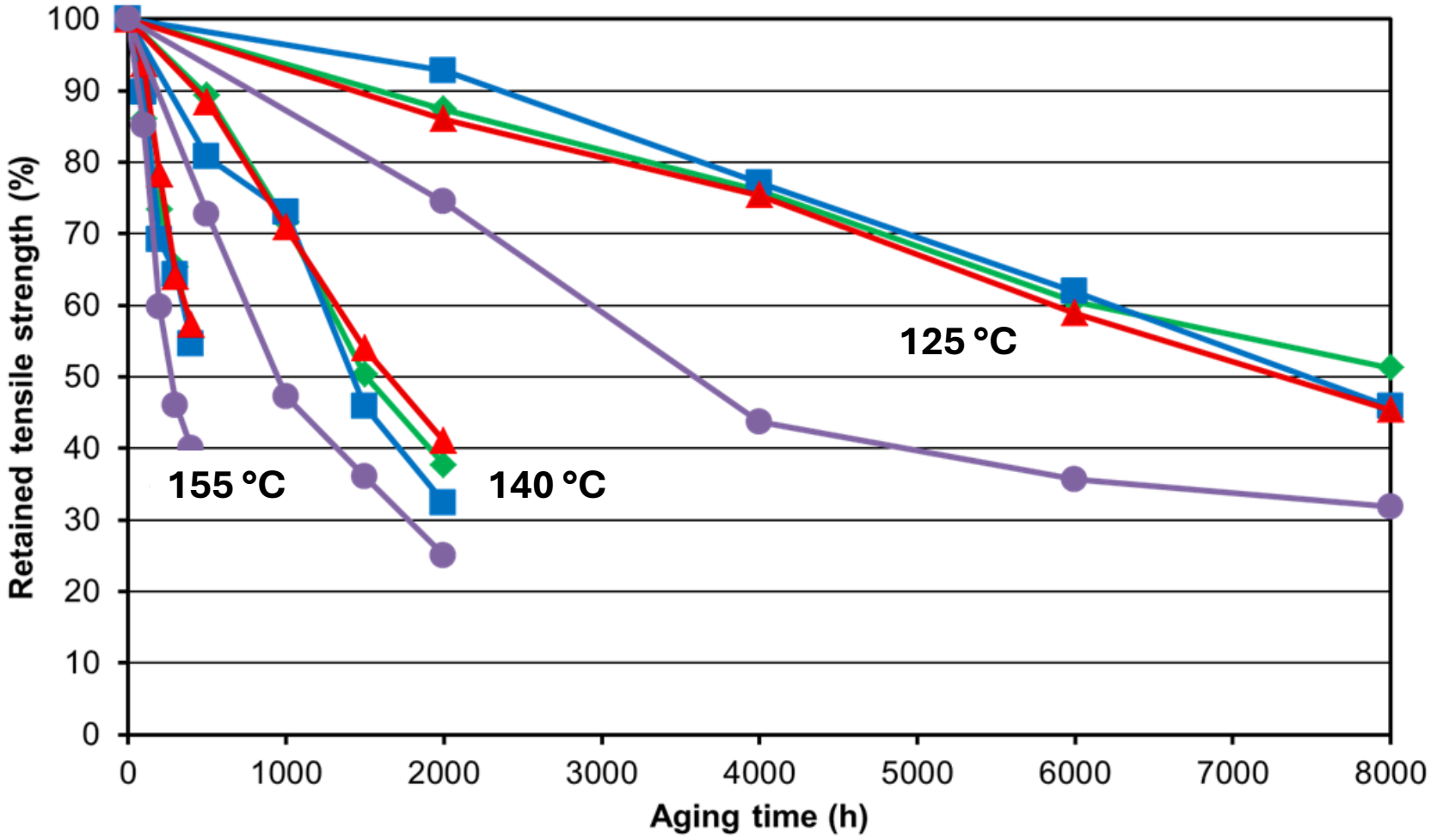
- Choice of the reference system (industry proven system)
- IEC: Standard Kraft paper
- IEEE: Thermally upgraded paper




## ANALYSIS AND CHALLENGES

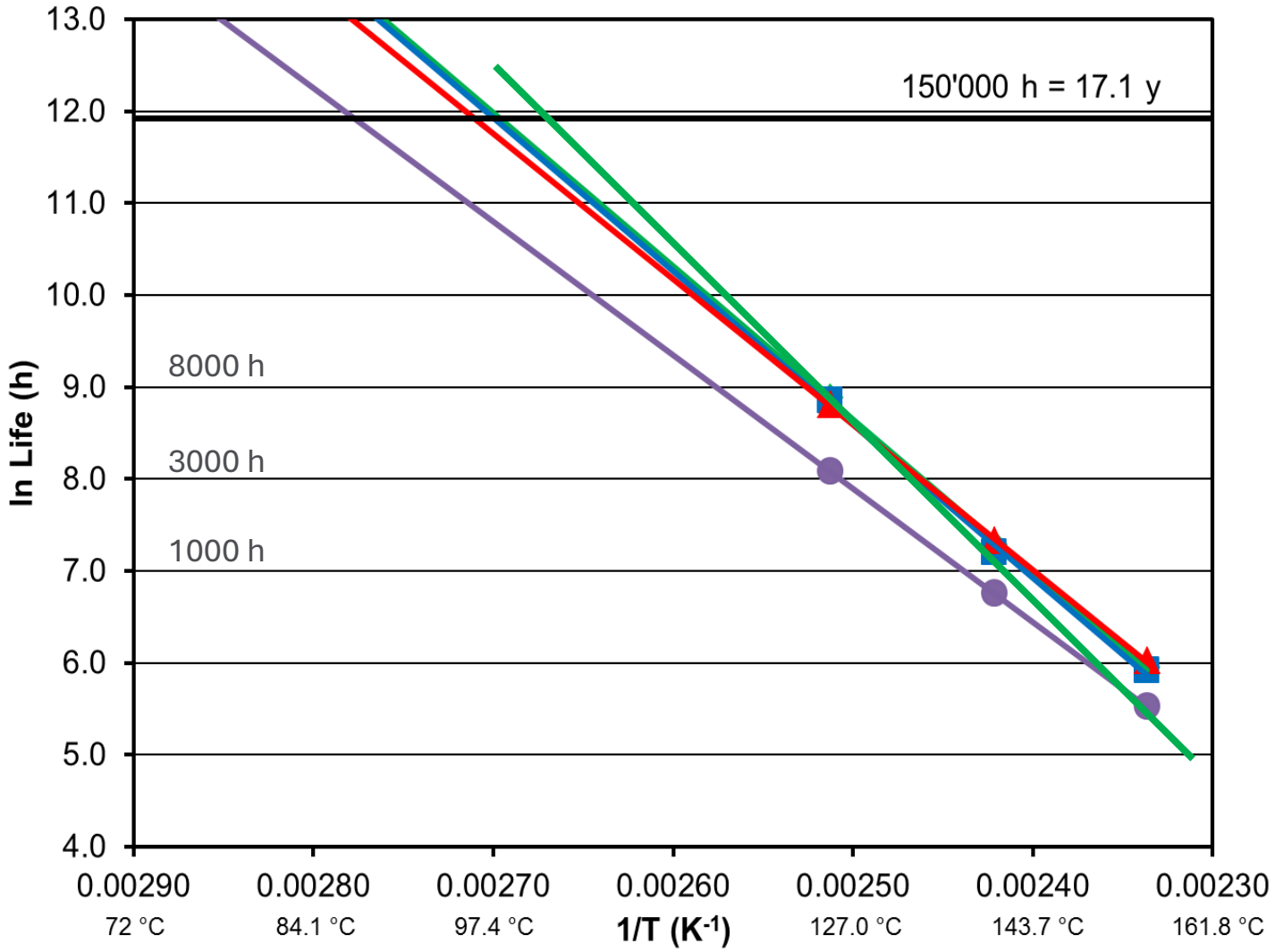
# THEORY AND BASICS OF AGING EXPERIMENTS

## ANALYSIS AND CHALLENGES



# THEORY AND BASICS OF AGING EXPERIMENTS

## ANALYSIS AND CHALLENGES



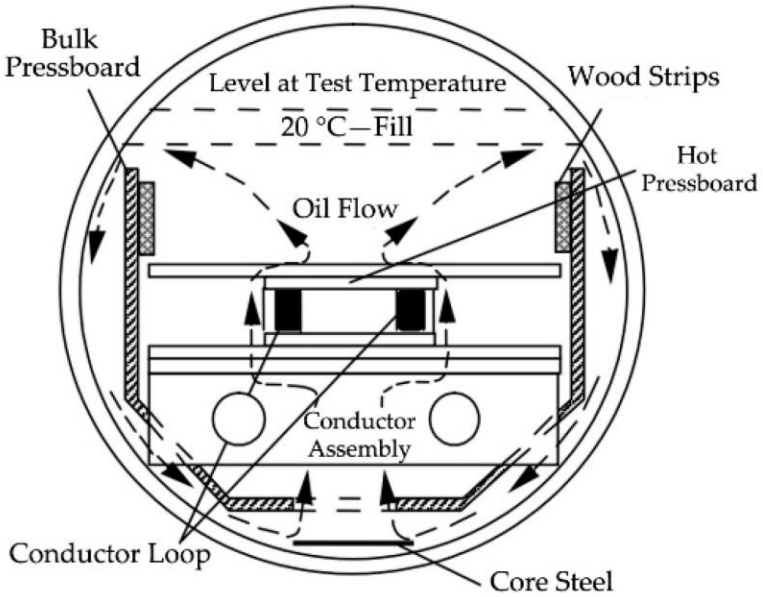
# THEORY AND BASICS OF AGING EXPERIMENTS

## ANALYSIS AND CHALLENGES

Sealed tube test

≠

Dual temperature test Transformer




Main differences:

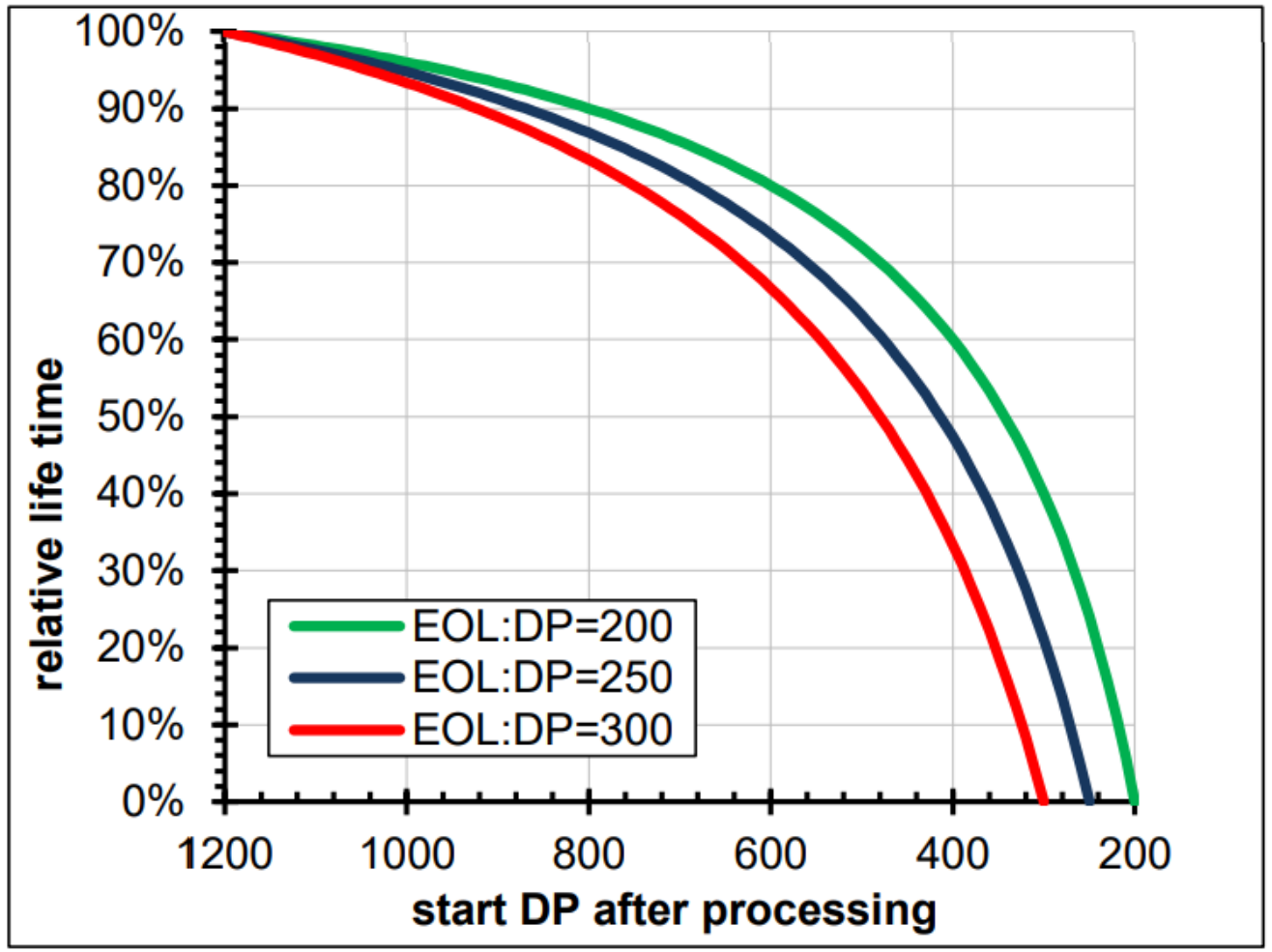
- Temperature distribution / gradients
- Water and acids distribution

→ Paper at the hot spot for dual temperature system is dry and contains low acids

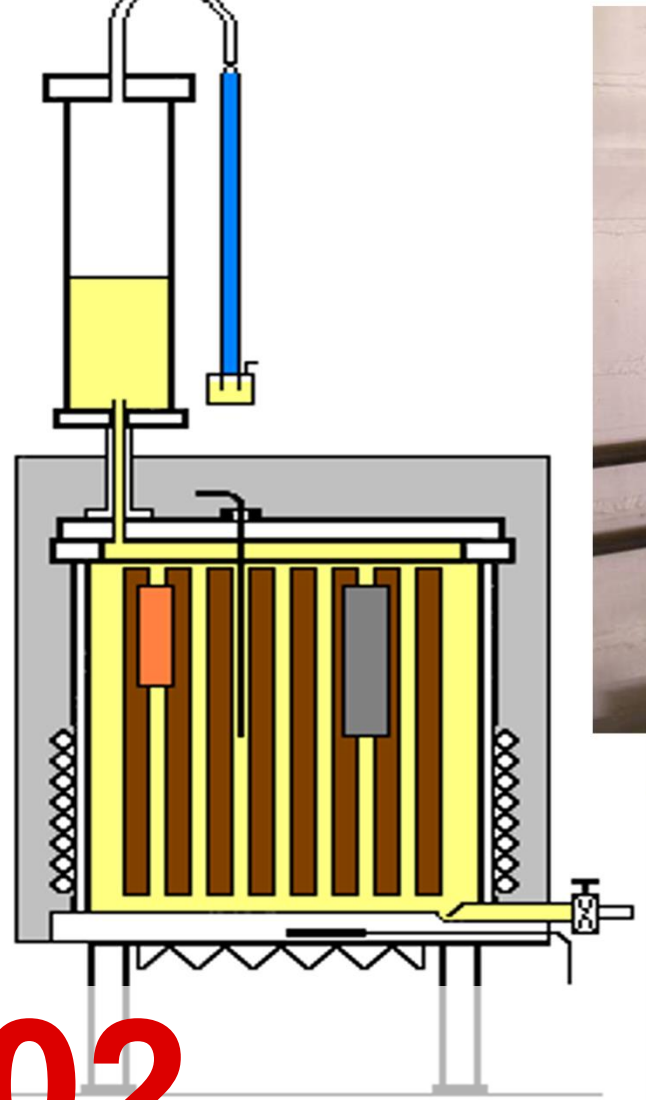
→ Water and acids migrate to cold parts and will be taken out of the system

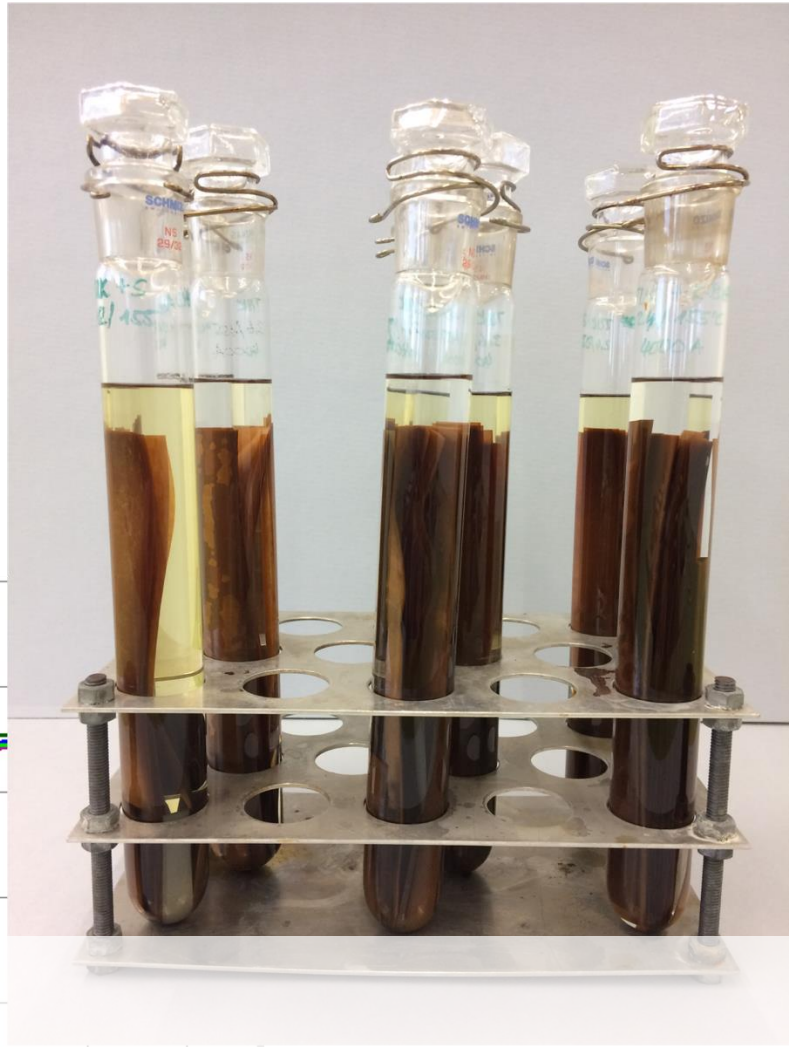
# THEORY AND BASICS OF AGING EXPERIMENTS

## POST-MORTEM ANALYSIS FOR FLEET ASSESSMENT




Basis: A. Ekenstam



# 02

## RESULTS OF AGING EXPERIMENTS

# AGING ALTERNATIVE LIQUIDS

## INTRODUCTION

**Four vegetable-based natural esters:**

- 2x Rapeseed oil
- Soybean oil
- Sunflower oil

**One synthetic ester:**

- Pentaerythritol ester

**Four mineral oils:**

- Isoparaffinic mineral oil
- Naphthenic mineral oils
  - top, standard, and medium grade

**The Experiment:**

- Examination the impact of thermal aging on pressboard and different insulating liquids.
- The aging is performed at different temperatures and in closed and open systems for comparison.
- Simulated load cycles were applied, with cooling and heating phases.

**Evaluating Insulating Liquids:**

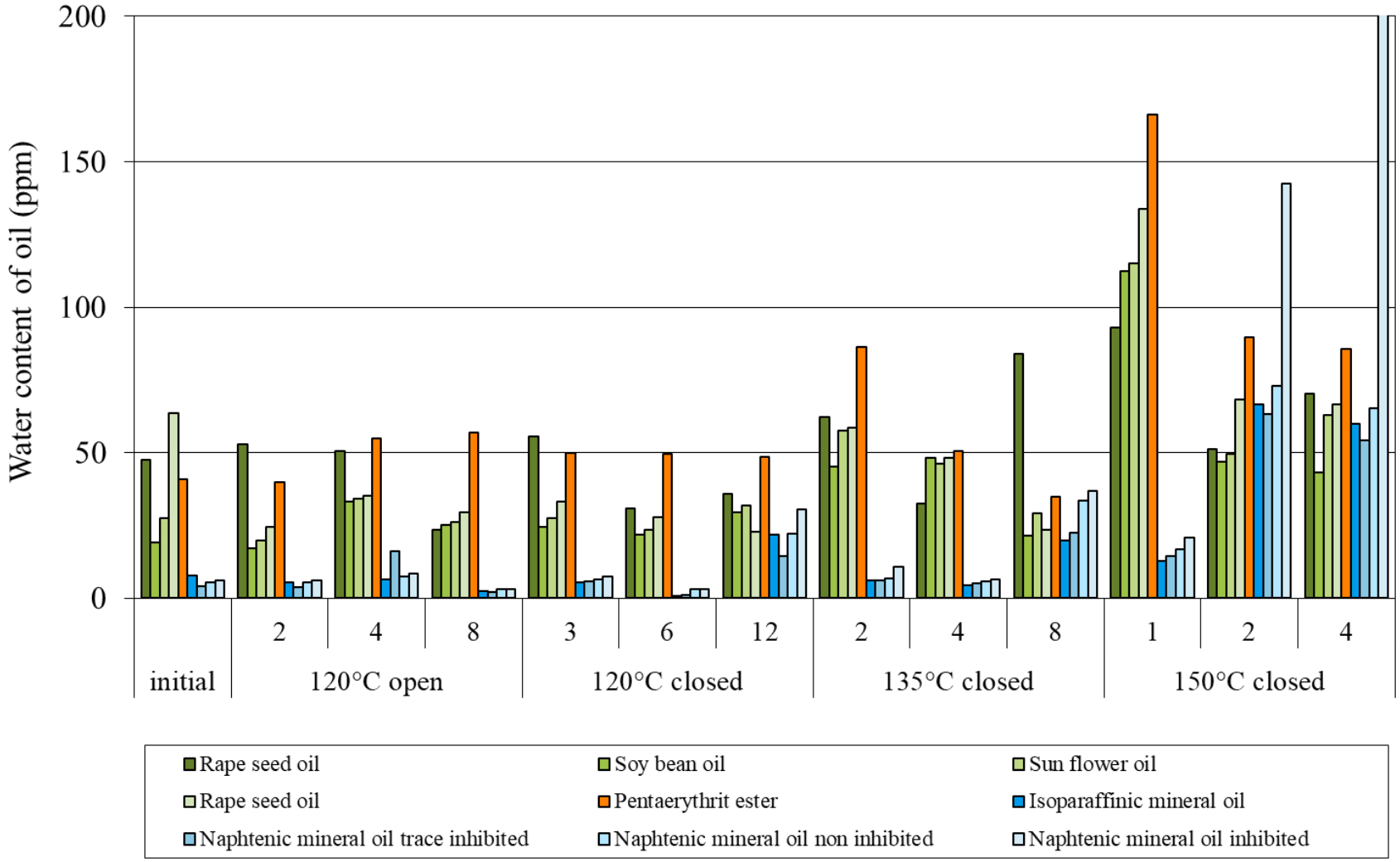
- Water content
- Dielectric strength (breakdown voltage)
- Acidity

**Evaluating Pressboard (Solid Insulation):**

- Water content
- Tensile strength
- Degree of polymerization (DP)

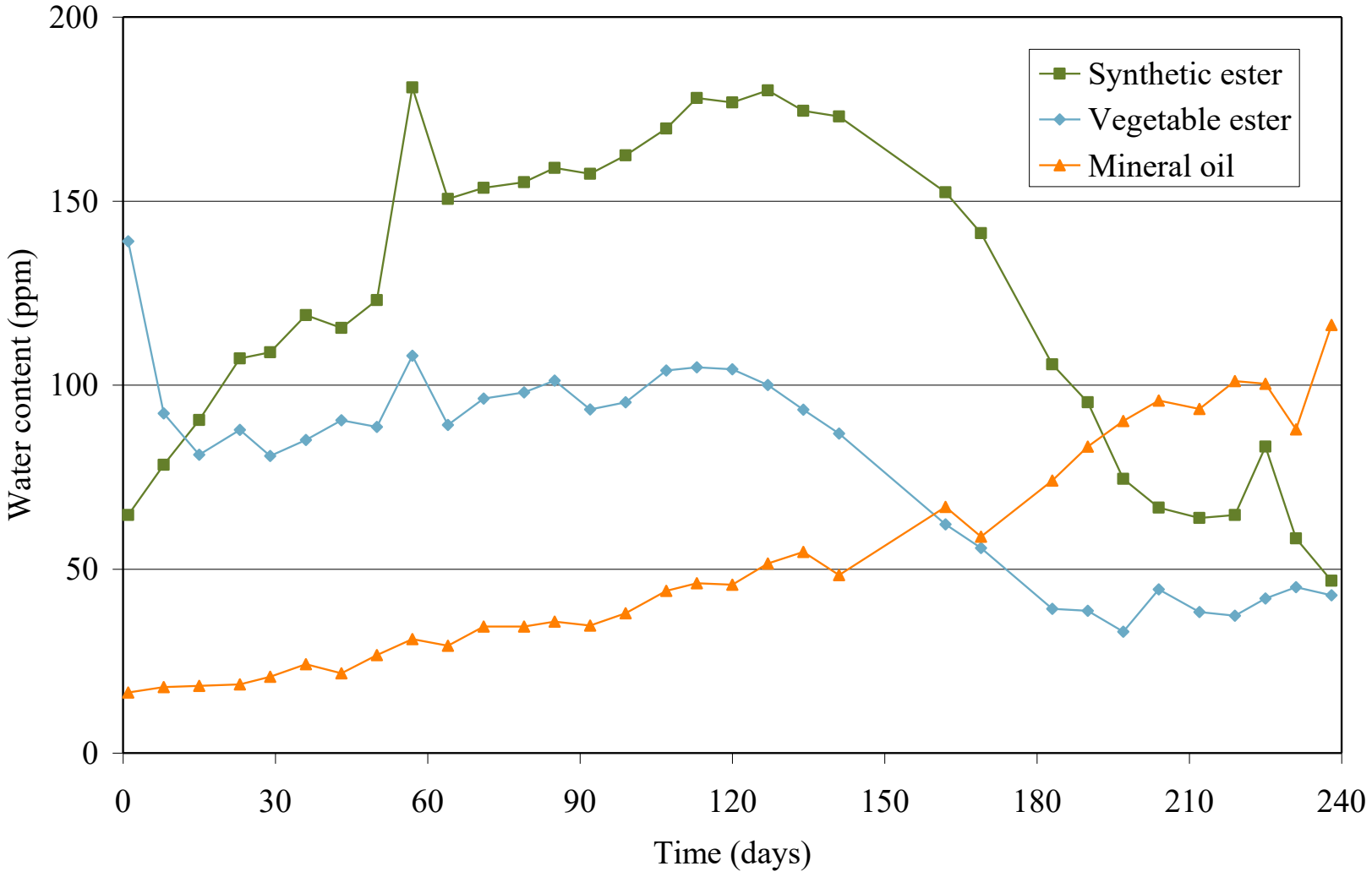
# AGING ALTERNATIVE LIQUIDS

## INSULATING LIQUIDS: WATER CONTENT IN OIL



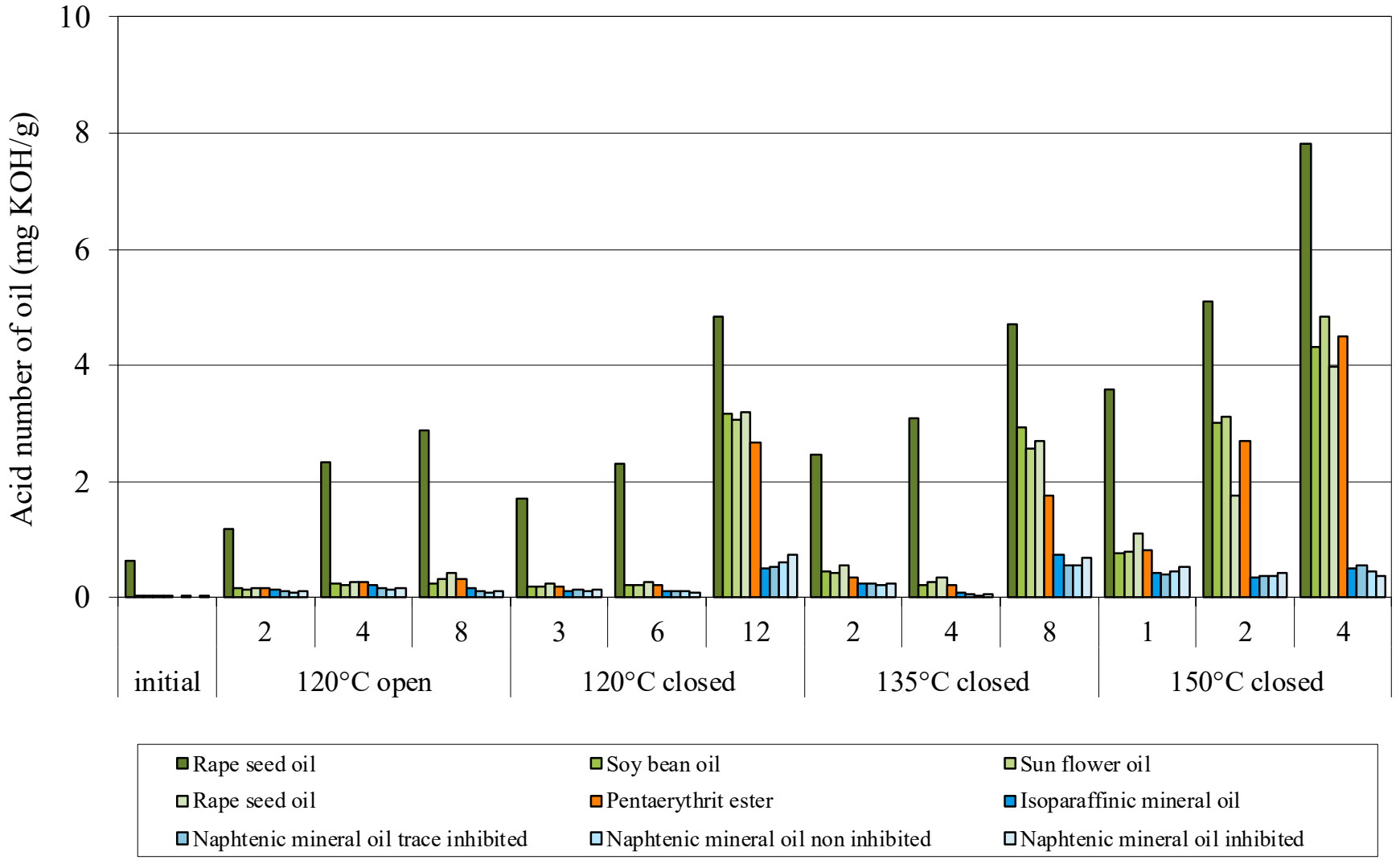
# AGING ALTERNATIVE LIQUIDS

## INSULATING LIQUIDS: WATER CONTENT, 8 MONTHS 135°C (CLOSED SYSTEM)



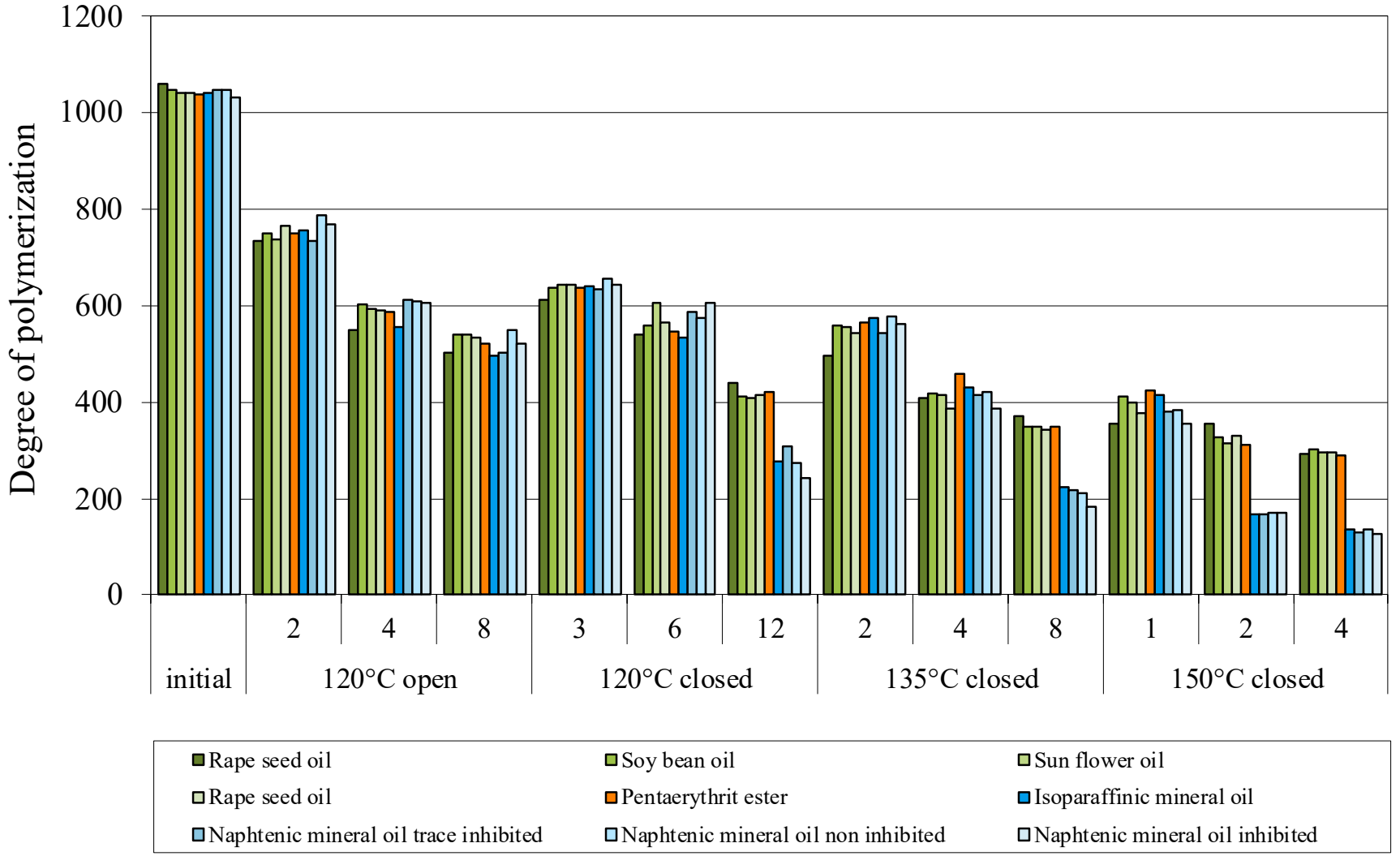
# AGING ALTERNATIVE LIQUIDS

## INSULATING LIQUIDS: ACID NUMBER IN THE OIL



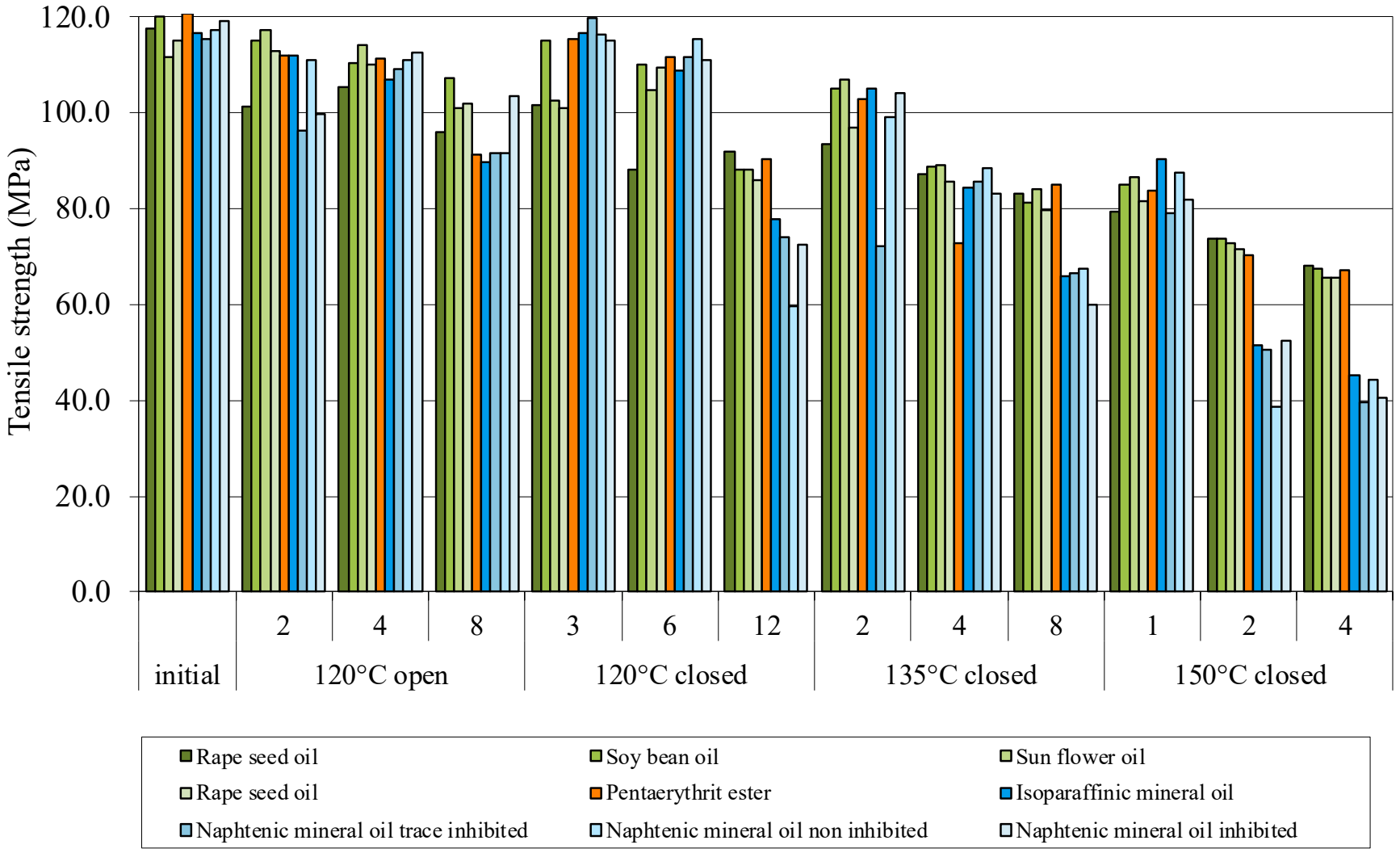
# AGING ALTERNATIVE LIQUIDS

## SOLID INSULATION: DEGREE OF POLYMERIZATION (DP)



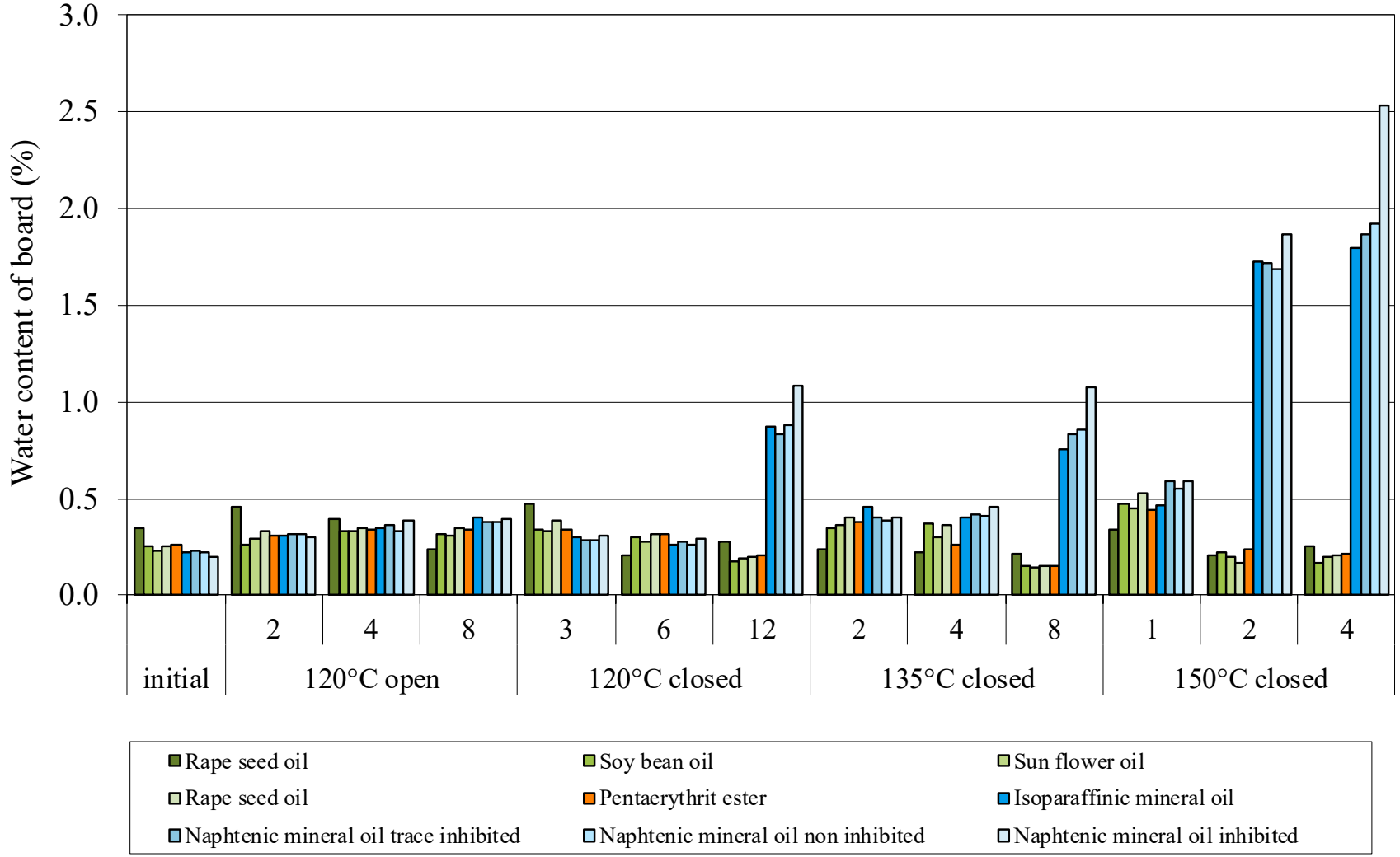
# AGING ALTERNATIVE LIQUIDS

## SOLID INSULATION: TENSILE STRENGTH



# AGING ALTERNATIVE LIQUIDS

## SOLID INSULATION: WATER CONTENT IN PRESSBOARD



# AGING ALTERNATIVE LIQUIDS

## CONCLUSION

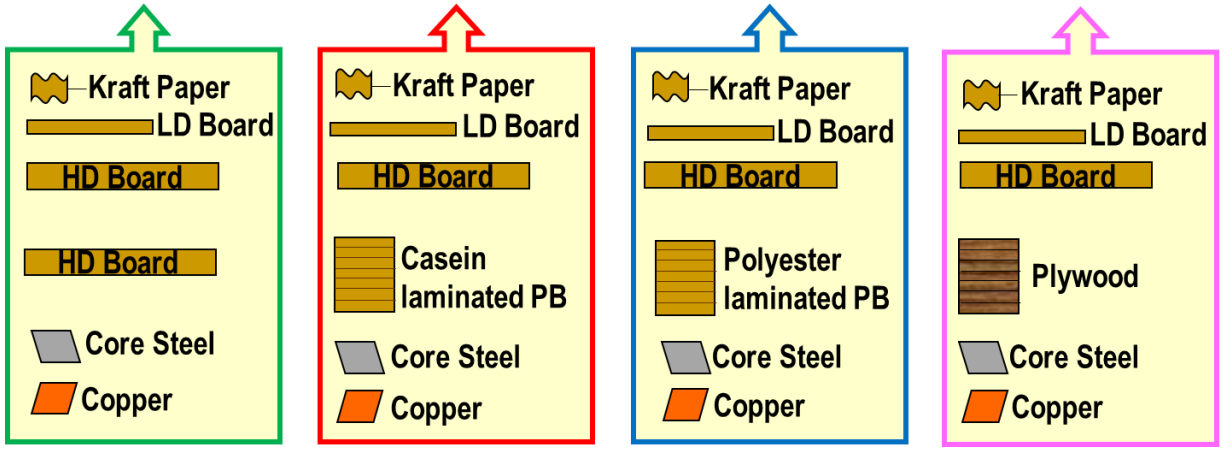
- In ester liquids, water reactions slowed aging over time, varying with temperature.
- In closed system ester liquids consumed water through hydrolysis at high temperatures, reducing cellulose deterioration.
- Ester hydrolysis produced long-chain fatty acids.
- High acidity did not accelerate pressboard aging and did not affect the dielectric strength of the oil.
- The dielectric strength of the insulating liquids are predominantly influenced by its water content.
- Mineral oil quality did not significantly affect cellulose aging rate.

- Pressboard aged at the same rate in both ester liquids and mineral oils initially.
- The water content within the pressboard can be correlated to the water content present in the insulating liquids.
- The dielectric properties of the pressboard are influenced by the formation of conductive ionic compounds, observable through conductivity measurements.

Weidmann paper reference: Aging of Pressboard in Different Insulating Liquids

# AGING INTERACTIONS: LAMINATED MATERIALS AND PAPER INSULATION

## INTRODUCTION




### The Experiment:

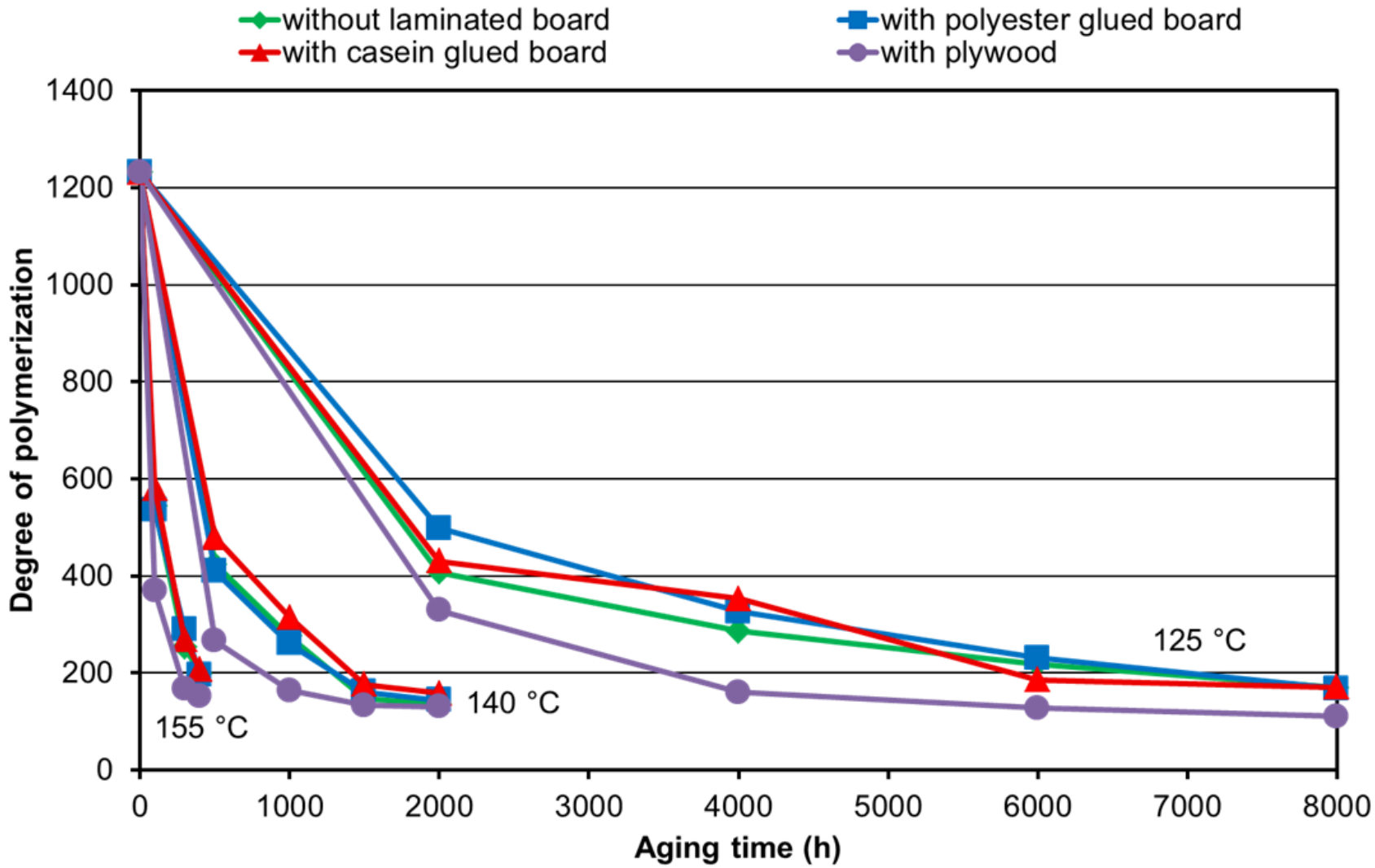
- A past study on the aging of laminated insulating materials in mineral oil identified significantly higher acid content and water absorption in laminated wood compared to pressboard.
- Additional experiment to compare the aging of laminated pressboard and laminated wood in transformers, focusing on their impact on kraft paper.
- Materials included kraft paper, thin/high-density pressboard, laminated pressboard, and wood, tested in sealed tubes.
- Aging was accelerated at 125°C, 140°C, and 155°C for up to 8000 hours (acc. to IEC 62332-2).

### Test Evaluation:

- Measurements focused on paper's tensile strength and degree of polymerization.

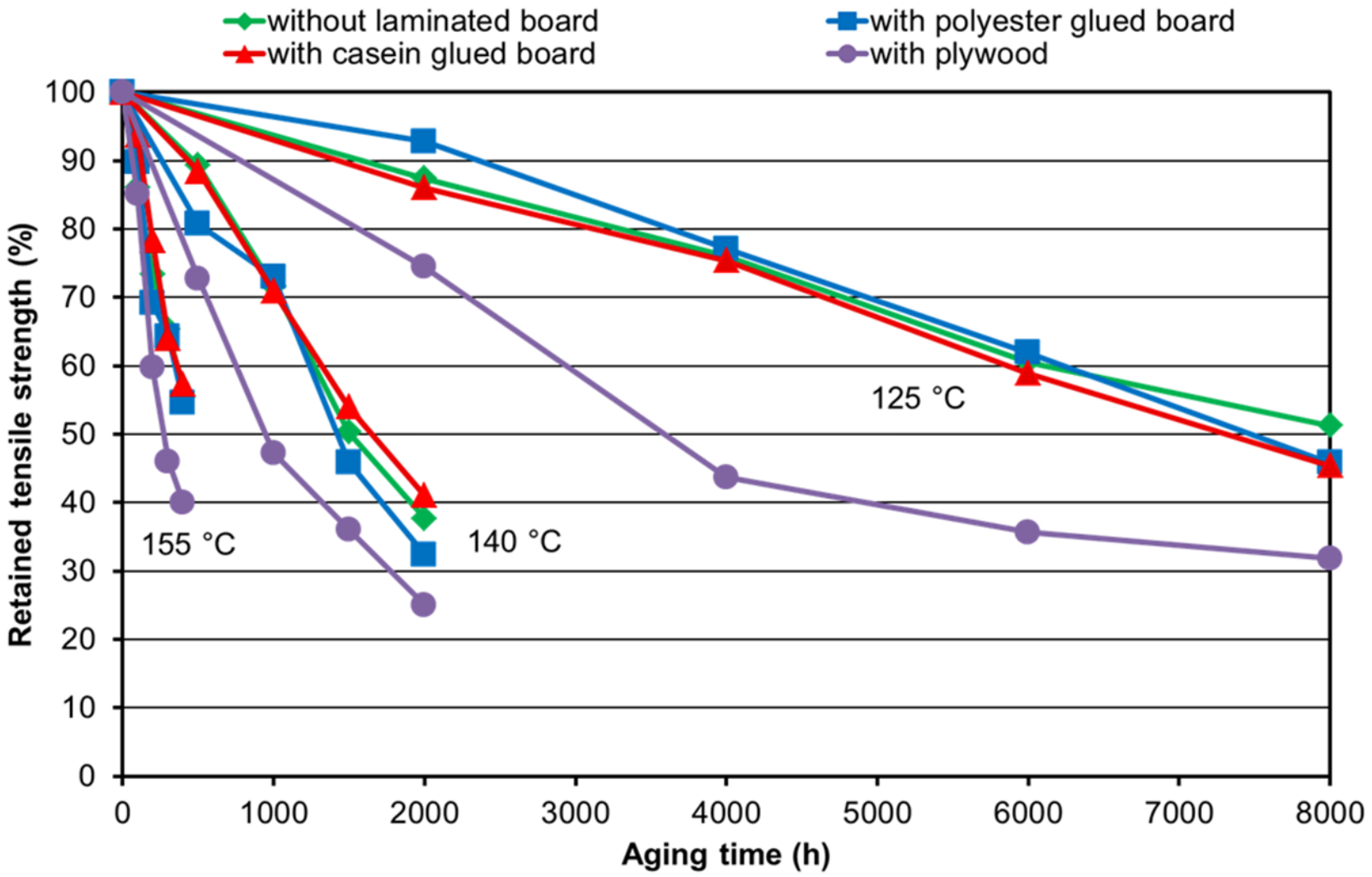
# AGING INTERACTIONS: LAMINATES AND PAPER INSULATION

## RESULTS: DP OF PAPER



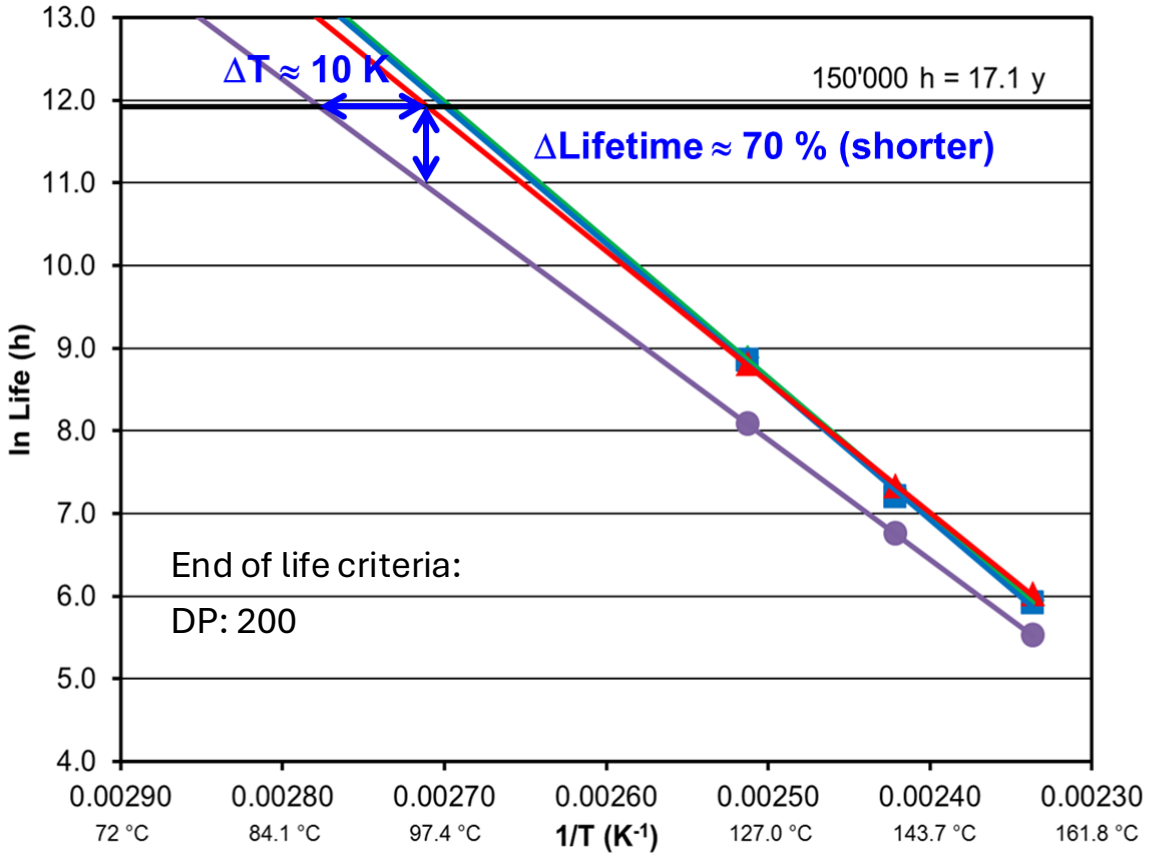
# AGING INTERACTIONS: LAMINATES AND PAPER INSULATION

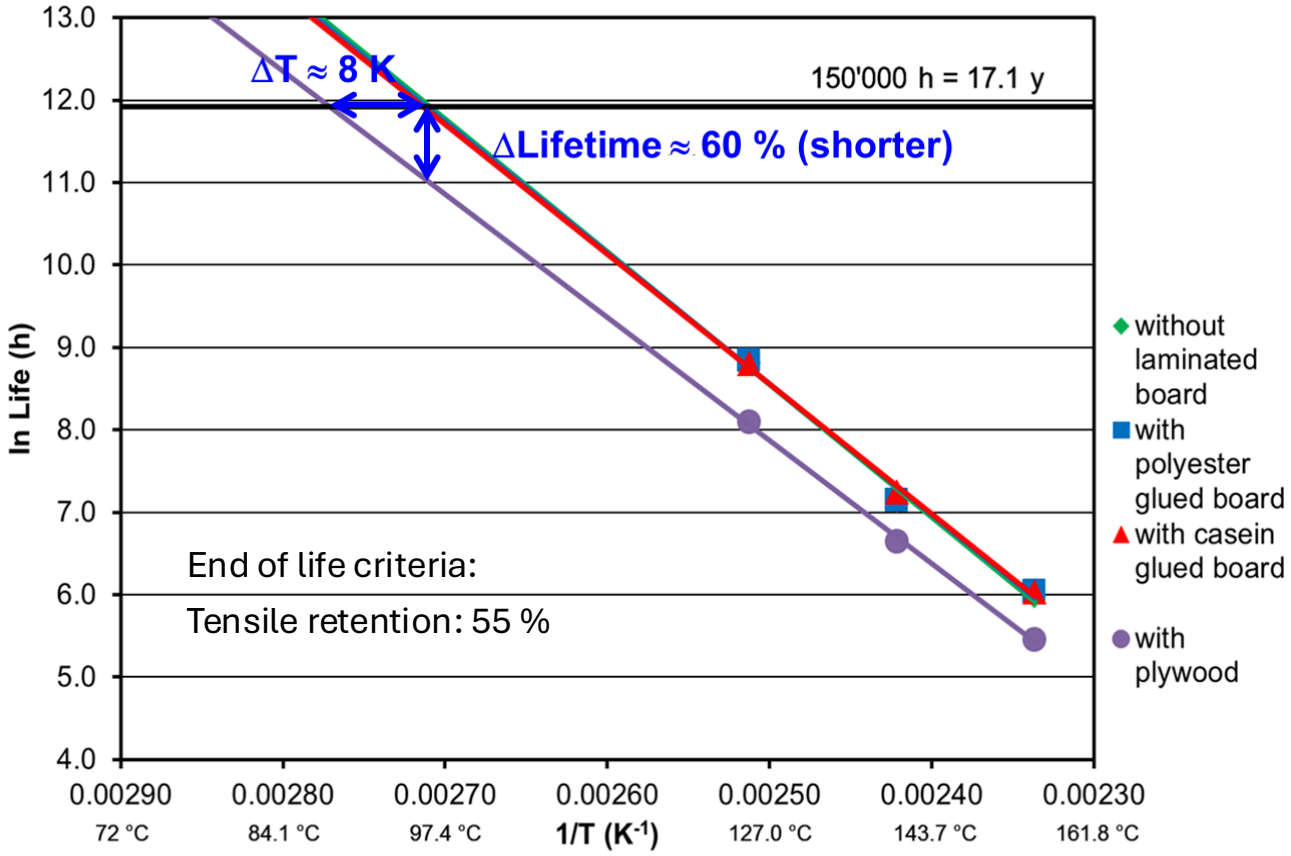
## RESULTS: TENSILE STRENGTH PAPER OF PAPER



# AGING INTERACTIONS: LAMINATES AND PAPER INSULATION

## RESULTS: PAPER END-OF-LIFE CONDITION



# AGING INTERACTIONS: LAMINATES AND PAPER INSULATION

## CONCLUSION

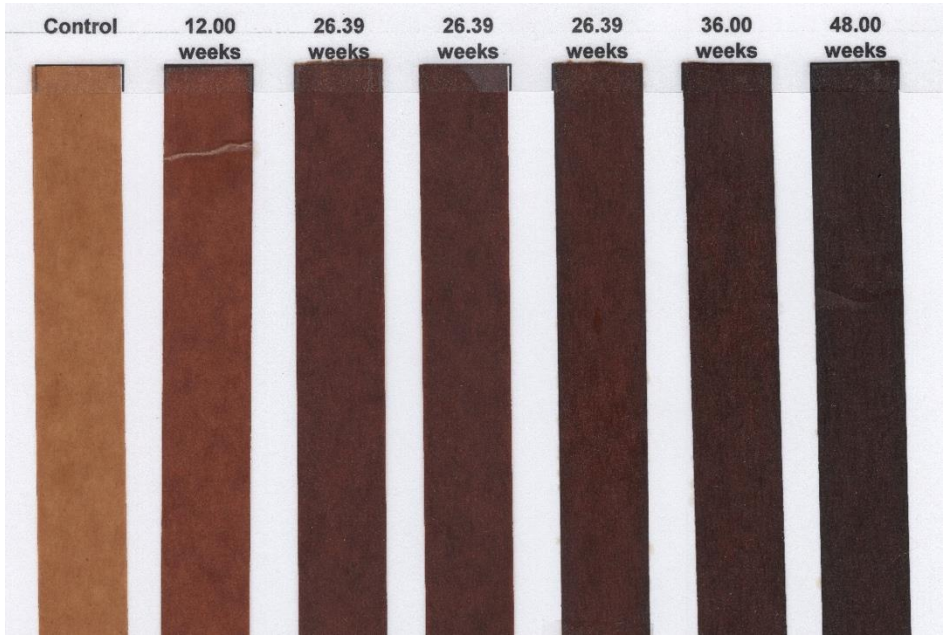
- **Material Choice:** Laminated pressboard better preserves transformer paper insulation compared to plywood.
- **Aging Effects:** Plywood accelerates kraft paper degradation, reducing polymerization and tensile strength.
- **Lifespan Impact:** Using plywood can significantly shorten transformer lifespan due to faster paper aging.
- **Recommendation:** Choose laminated pressboard to ensure longer transformer durability.

Weidmann paper reference:

- The Impact of Laminated Cellulosic Products on Transformer Lifetime
- The Aging Characteristics of Laminated Pressboard and Laminated Wood in Oil Cooled Power Transformers

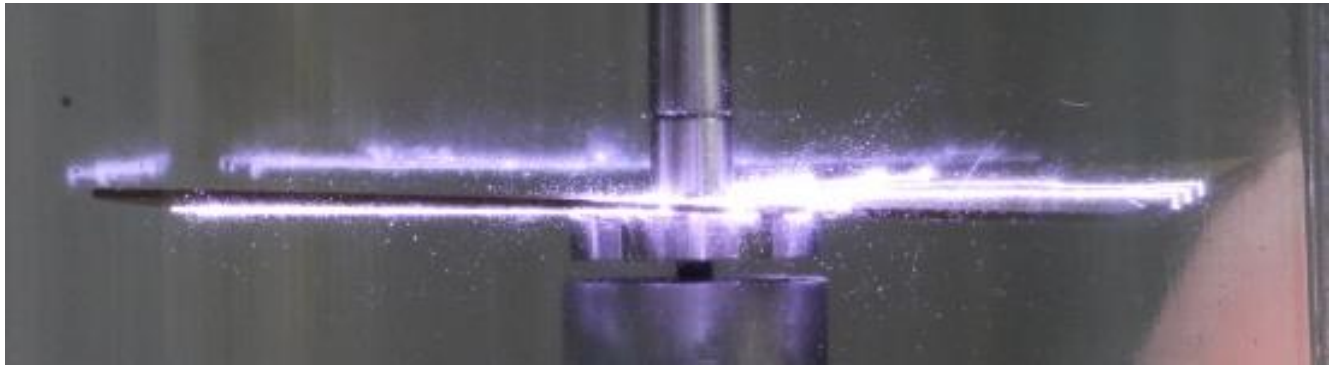
# IMPACT OF AGING ON DIELECTRIC PROPERTIES PRESSBOARD AND PAPER

## INTRODUCTION




**The Experiment:**

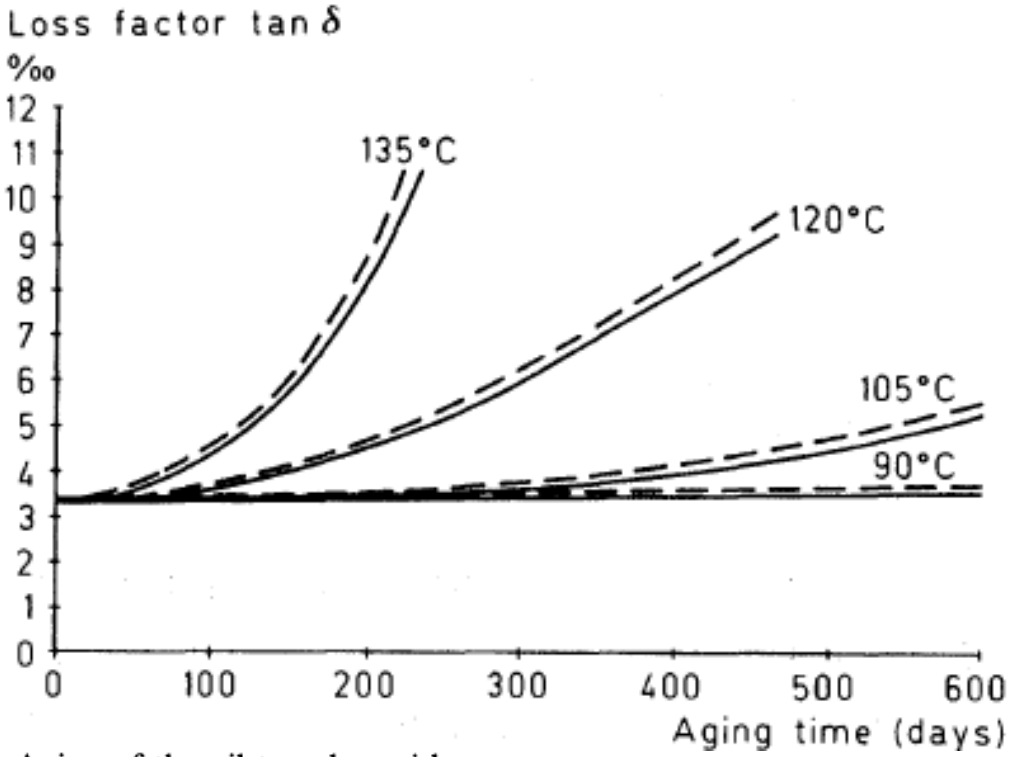
- Investigation about the dielectric properties of Transformerboard and paper, focusing on dielectric strength and loss factor.
- Evaluated how thermal aging affects these properties at temperatures from 90°C to 135°C.
- Examination of the influence of ionic decomposition products.



# IMPACT OF AGING ON DIELECTRIC PROPERTIES PRESSBOARD AND PAPER

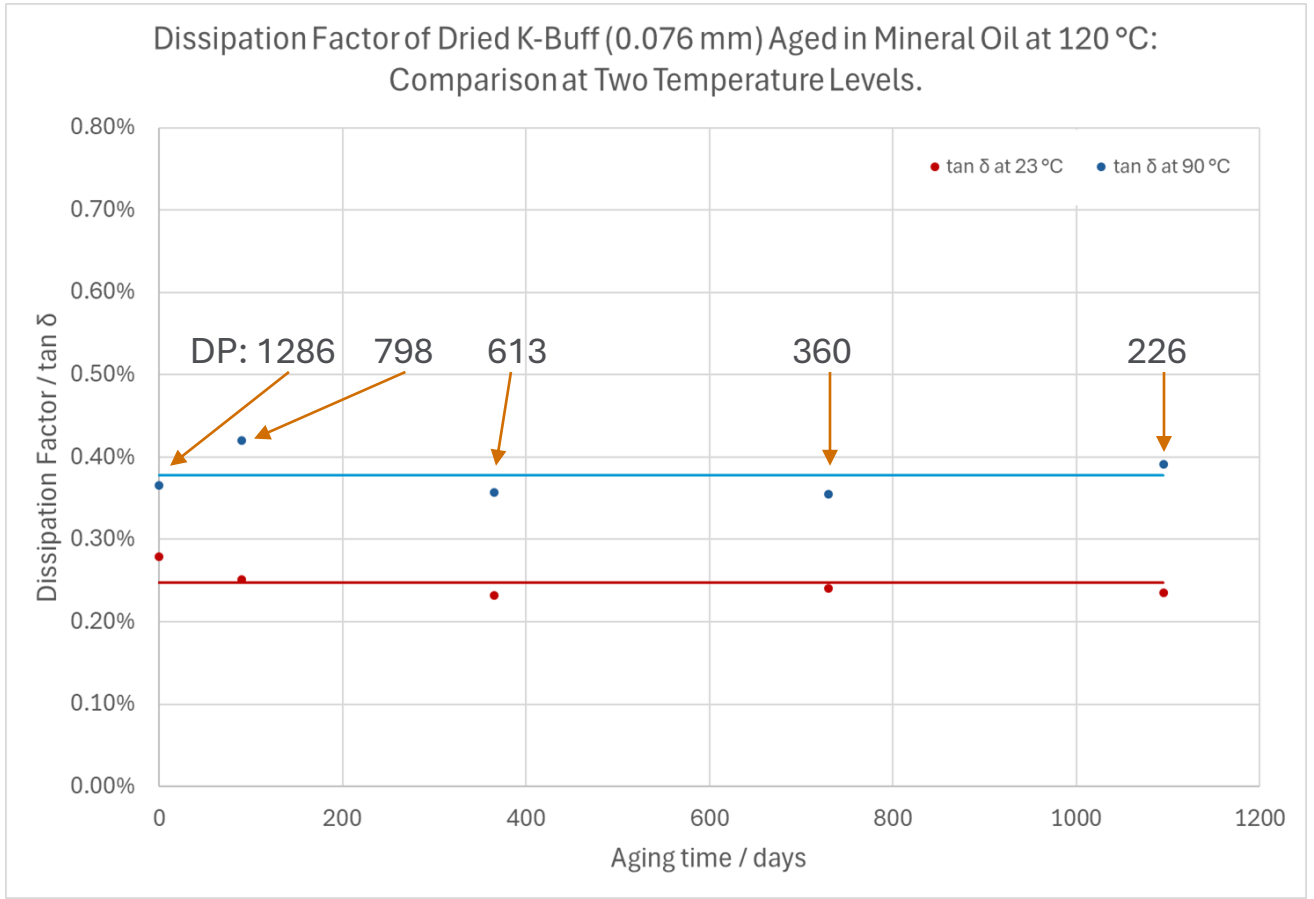
## LOSS FACTOR

- Water significantly impacts the loss factor




Aging of the oil together with:
——— TRANSFORMERBOARD T IV
– – – – – TRANSFORMERBOARD T III
Thermal stress: 90°C, 105°C, 120°C, 135°C, with thermal cycling

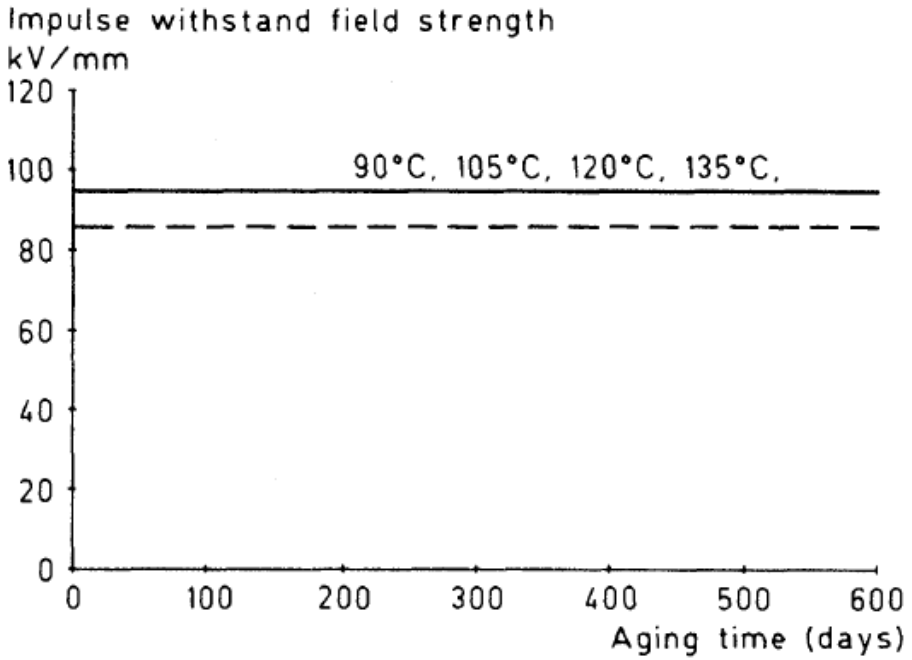
- Measurements of dried aged K-Buff verify this statement




Weidmann reference: Transformerboard 2 / Chapter S. Thermal and electrical aging measurements

# IMPACT OF AGING ON DIELECTRIC PROPERTIES PRESSBOARD AND PAPER

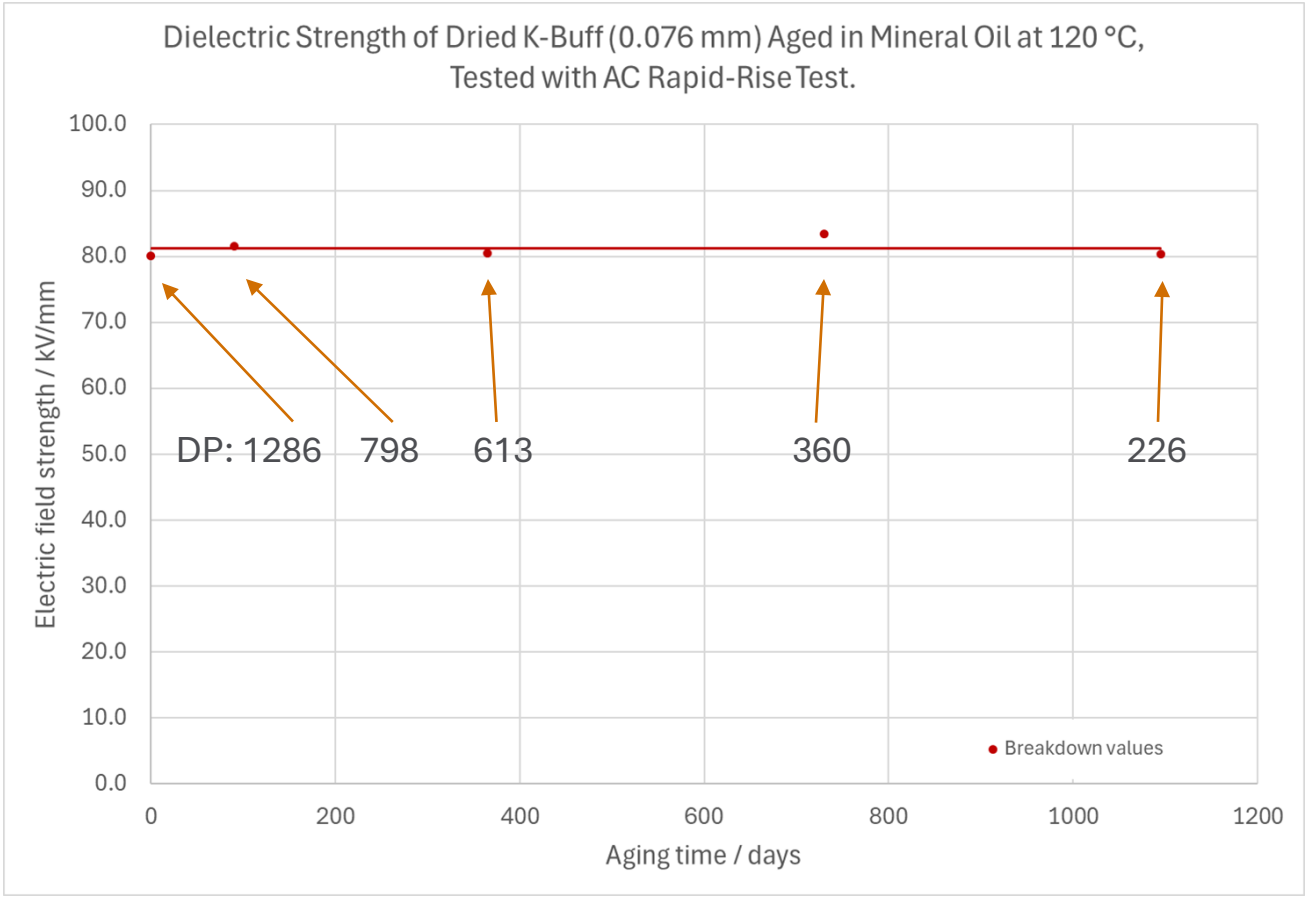
## IMPACT ON DIELECTRIC STRENGTH




Impulse withstand field strength of oil impregnated solid samples as a function of aging time. Between two spheres (d = 25 mm)

Aging of the oil together with:
——— TRANSFORMERBOARD T IV
– – – – – TRANSFORMERBOARD T III
Thermal stress: 90°C, 105°C, 120°C, 135°C, with thermal cycling

- No impact on the dielectric strength of dried aged K-Buff

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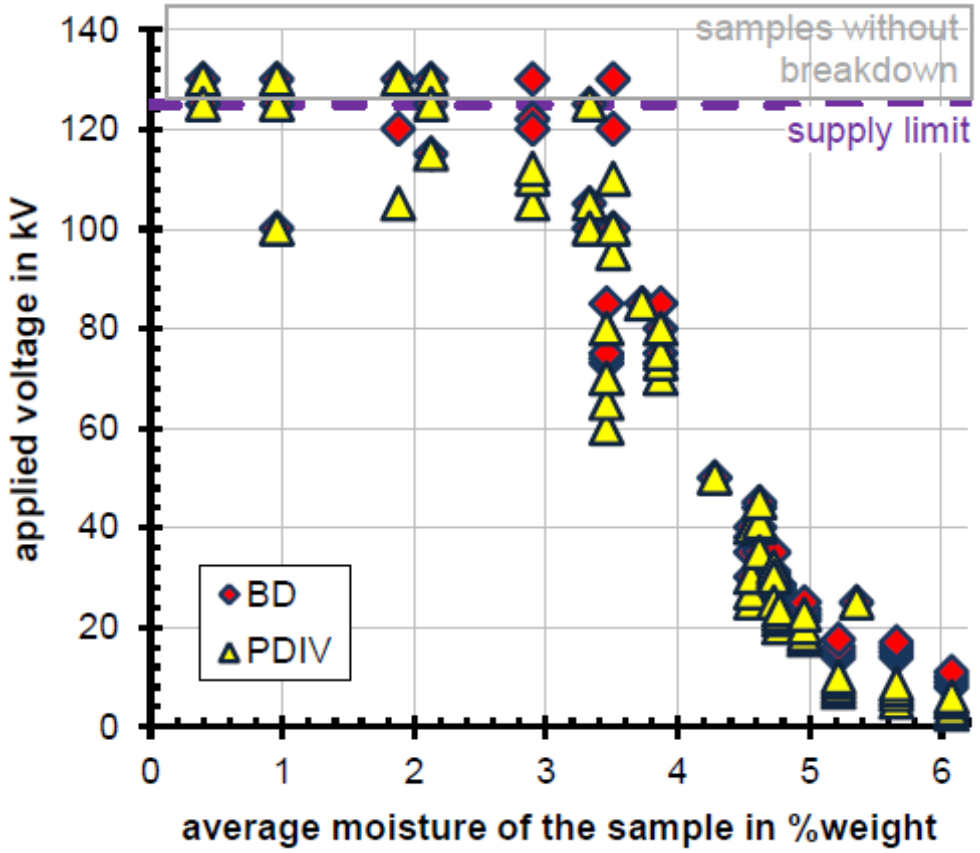
# IMPACT OF AGING ON DIELECTRIC PROPERTIES PRESSBOARD AND PAPER

## CONCLUSION




Tested were 10 mm height blocks of 8 mm board with step voltage (50 Hz, 1 min steps, 5 kV increase)

- As the Transformerboard ages, the loss factor tends to increase.
  - Due to the formation of ionic by-products (water) during the thermal aging
- Transformerboard and paper demonstrates remarkable stability in electrical strength.
- The paper and pressboard effectively manages the interaction between water, oxygen, and other degrading elements, preventing deterioration of its dielectric properties despite long-term exposure.
- The breakdown strength of the oil-solid insulation system is heavily influenced by water content.

Weidmann paper reference: Moisture Effects on the Electric Strength of Oil / Pressboard Insulation used in Power Transformers

# Thank you for your attention.
# We welcome any questions you may have.

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THANK YOU FOR YOUR ATTENTION.