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Moisture Cycle and Aging in Transformer Paper Insulation

MOISTURE ACCUMULATES OVER YEARS OF OPERATION

Moisture is always present and continuously increases from multiple sources.

SOURCES OF MOISTURE

1. MOISTURE IN NEW PAPER INSULATION

New transformers are meant to carry some moisture in the paper insulation as completely dry paper is too brittle and is not mechanically strong.

2. MOISTURE FROM THE ATMOSPHERE

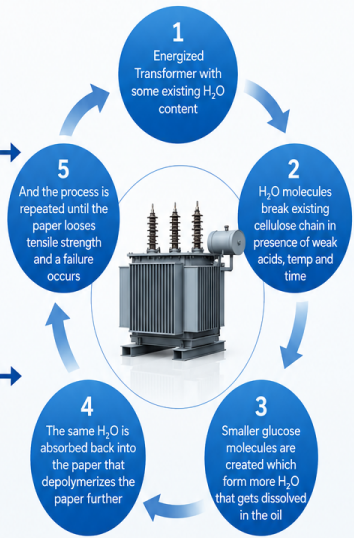
Free breathing transformers will add some moisture from the atmosphere through the conservator and through the breather.

3. MOISTURE CREATED INSIDE THE TRANSFORMER

Moisture is created inside the transformer paper insulation during normal operating conditions.

A never ending cycle that cannot be stopped

THE MOISTURE CYCLE



THE CYCLE IN ACTION

As the paper is subjected to heat, oxygen and starts to degrade, the cellulose chain breaks apart to form water which is then dissolved into the oil.

As the paper degrades further, more moisture is created and further degrades the paper creating moisture and so on.

CONSEQUENCES OF THE CYCLE

- Loss of paper tensile strength and mechanical integrity
- Reduced dielectric strength
- Increased risk of thermal runaway and failures
- Shorter transformer life and higher risk of unexpected outages

WHY THIS MATTERS

- Moisture is the primary driver of insulation aging and paper degradation.
- It is a continuous cycle that accelerates over time.
- The earlier it is detected and managed, the more asset life you preserve.
- Effective moisture management is the key to reliable and long-term transformer performance.

Moisture management is critical
to slow down the cycle, preserve paper insulation and extend transformer life.

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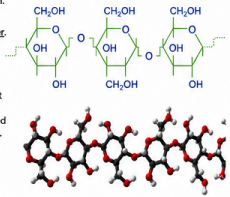
HOW MOISTURE BREAKS DOWN CELLULOSE AND ACCELERATES AGING

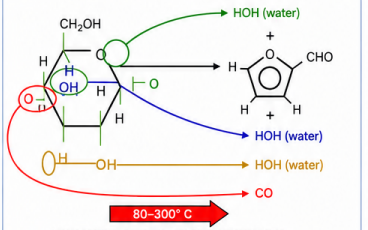
1. CELLULOSE – THE FOUNDATION OF PAPER INSULATION

- Kraft Paper or Thermally upgraded Kraft is used as Transformer winding insulation.
- Cellulose is mainly used to produce paperboard and paper.
- Kraft Paper or cardboard is produced from chemical pulp in the KRAFT process.
- Cellulose is the most abundant organic molecule in nature. It is a polysaccharide assembled from **glucose monomer units.**
- Average chain length: 1000 to 1300 units.
- Aging leads to shorter cellulose chains.

Cellulose Chain (Glucose Monomer Units)

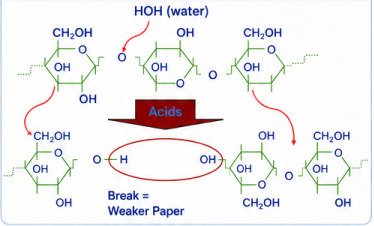


2. PAPER AGING = RUPTURE OF THE CELLULOSE CHAIN

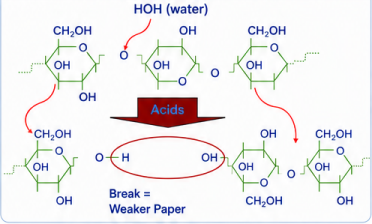


Assessing Water Content in Solid Transformer Insulation – Brian Sparling, SMIEEE – IEEE PEPS Seminar: April 2008

3. DEGRADATION OF PAPER LEADING TO FURAN FORMATION



4. DEGRADATION OF PAPER LEADING TO FURAN FORMATION



5. WHAT IT MEANS FOR YOUR TRANSFORMER

Water (HOH) in the insulation reacts with cellulose at elevated temperature (80–300 °C).

Cellulose chains break, forming **furan** compounds (**CHOH**) and releasing gases (CO, CO_2).

Chain rupture reduces paper tensile **strength** and mechanical integrity.

Acids accelerate the breakdown of cellulose.

More moisture → More aging → More moisture (continues the moisture cycle).

BUT TESTING ALONE IS NOT ENOUGH

To truly understand transformer behavior, utilities must also analyze:

- Temperature vs moisture relationship
- Load profile and thermal stress
- Moisture trend over time
- Oil–paper equilibrium behavior
- Moisture ingress sources (breathers, leakages)

FREQUENCY MATTERS

These tests should be performed every 6 months to 1 year across different climatic conditions.

Moisture migrates with temperature → Seasonal humidity affects equilibrium → Load cycles change insulation stress → A trend is the real story

THE REALITY

Most failures are not caused by sudden faults.

They are the result of slow insulation degradation driven by:

- Moisture
- Thermal stress
- Chemical aging

THE MISSING LINK

When moisture is identified as the dominant driver:

The strategy must shift from:

Periodic testing & filtration → TO → Continuous moisture management

FINAL THOUGHT

Transformer insulation health is not defined by one test — it is defined by the interaction of moisture, dielectric performance, and aging chemistry.

And once moisture becomes the driver… **managing it continuously is the only way to control insulation life.**

Control moisture. Protect insulation. Extend transformer life.

Measure Continuously | Analyze Trends | Act Proactively | Ensure Reliability

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