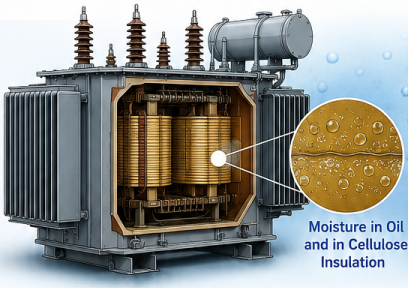
MOISTURE: THE HIDDEN DRIVER OF TRANSFORMER AGING AND FAILURE

WHAT IEC, IEEE AND CIGRÉ TELL US

KEY MESSAGE

International standards and transformer experts consistently identify **moisture** as one of the most influential factors affecting:

- Insulation aging
- Dielectric strength
- Bubble formation risk
- Remaining transformer life
- Reliability of critical assets



KEY FINDINGS FROM INTERNATIONAL STANDARDS

IEC 60422

Moisture significantly influences:

- Insulation performance
- Oil condition
- Dielectric strength
- Aging rate of cellulose
- Risk of bubble formation
- Transformer reliability

IEEE C57.91

Moisture accelerates the thermal aging of cellulose insulation and reduces insulation life.

CIGRÉ

Moisture is one of the primary drivers of insulation degradation and a major contributor to transformer failure risk.

HOW MOISTURE influences TRANSFORMER RELIABILITY

THERMAL STRESS
Increases hot-spot temperature and accelerates aging

OXIDATION
Promotes oil oxidation and sludge formation

MOISTURE

ELECTRICAL STRESS
Reduces dielectric strength and increases PD risk

MECHANICAL STRESS
Reduces insulation strength and increases failure risk

Moisture interacts with all other stress factors and accelerates insulation deterioration in every possible way.

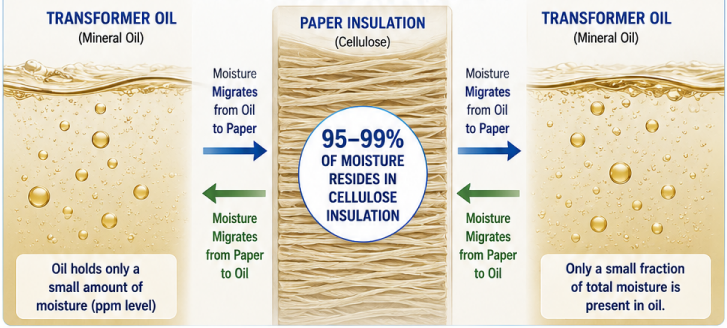
MOISTURE IS NOT SIMPLY AN OIL QUALITY ISSUE.
MOISTURE IS AN INSULATION LIFE ISSUE.

WHERE IS THE MOISTURE?

BASED ON OOMMEN'S MOISTURE EQUILIBRIUM THEORY

More than **95–99%** of transformer moisture is typically stored inside **cellulose insulation.**
Only a small fraction is visible in oil.

OIL – PAPER MOISTURE EQUILIBRIUM



WHAT HAPPENS?

- As **temperature** and **loading** change, moisture constantly migrates between oil and paper.
- During **heating**: moisture moves from paper to oil.
- During **cooling**: moisture moves from oil back into paper.
- Seasonal and load variations **continuously change** the moisture equilibrium.

A DYNAMIC MOISTURE CYCLE

FOUNDATIONAL WORK AND KEY EXPERT CONTRIBUTIONS

T. V. OOMMEN

Pioneered the moisture equilibrium theory for paper–oil insulation systems.

Established the basis for estimating paper moisture from oil moisture and temperature.

J. D. PIPER

Developed and validated improved moisture equilibrium models for practical transformer applications.

Provides widely used charts and equations.

MICHAEL KOCH

Advanced research on moisture assessment in cellulose insulation.

Highlighted the limitations of using oil moisture alone and the importance of accurate interpretation.

STEFAN TENBOHLEN

Pioneered dielectric response methods for moisture estimation in power transformers.

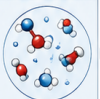
Introduced FDS (Frequency Domain Spectroscopy) techniques.

OIL MOISTURE IS ONLY THE VISIBLE PORTION OF THE PROBLEM.
PAPER INSULATION IS THE REAL MOISTURE RESERVOIR.

HOW MOISTURE DAMAGES TRANSFORMER INSULATION

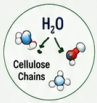
MOISTURE INITIATES A DEGRADATION CYCLE

1. MOISTURE



Moisture enters insulation system

2. HYDROLYSIS



Water reacts with cellulose molecules

3. DP REDUCTION

Degree of Polymerization (DP) reduces – paper weakens

4. LOSS OF MECHANICAL STRENGTH

Insulation becomes brittle, weaker and less flexible

5. INSULATION FAILURE

Increased risk of breakdown and failure

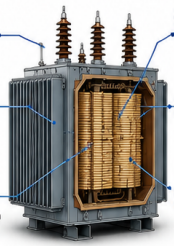
MOISTURE DOES NOT MERELY INDICATE AGING.
MOISTURE ACTIVELY DRIVES AGING.

HOW MOISTURE AFFECTS INSULATION

ACCELERATES CELLULOSE AGING
Moisture accelerates hydrolysis and reduces Degree of Polymerization (DP).

INCREASES FURAN GENERATION
Higher moisture leads to higher 2-FAL (furan) levels – a key aging indicator.

REDUCES MECHANICAL STRENGTH
Wet paper loses tensile strength and becomes brittle, increasing risk of deformation and failure.



REDUCES DIELECTRIC STRENGTH
Moisture lowers breakdown voltage (BDV) and overall dielectric withstand capability.

INCREASES DIELECTRIC LOSSES
Moisture increases dissipation factor (tan δ) and reduces resistivity.

INCREASES BUBBLE FORMATION RISK
Moisture lowers interfacial tension – increasing bubble formation under stress.

KEY INDUSTRY OBSERVATION

Transformer failures often occur after years of slow insulation deterioration rather than a single sudden event.

Insulation life is consumed gradually by
MOISTURE + HEAT + TIME

INTERNATIONAL FINDINGS

IEC 60422
Moisture has significant influence on dielectric strength, aging of cellulose insulation, dissipation factor and bubble formation in mineral oil.

IEEE C57.91
Moisture in cellulose insulation greatly accelerates aging. Even small increases in moisture content can significantly reduce insulation life.

CIGRÉ TB 761
Moisture is one of the primary contributors to insulation degradation and is strongly correlated with transformer failures.

EXPERT CONSENSUS

Controlling moisture is the most effective way to slow insulation aging and extend transformer life.

SUPPORTING INTERNATIONAL STANDARDS

IEC 60156
Standard for breakdown voltage testing.
Moisture reduces dielectric strength of oil.

IEC 60247
Standard for dissipation factor and resistivity.
Moisture increases dielectric losses and lowers resistivity.

IEC 61198
Standard for furan analysis.
Moisture drives cellulose degradation and furan formation.

IEC 60599
Guide for DGA interpretation.
Moisture and overheating are key indicators of insulation stress.

IEC 60567
Standard for DGA sampling and analysis.
Accurate detection of fault gases is essential.

IEC 60814
Standard method for water determination in oil.
Accurate moisture measurement is the foundation.

MOISTURE WEAKENS INSULATION IN MANY WAYS.
CONTROLLING MOISTURE IS CONTROLLING AGING, RISK AND FAILURE.

HOW MOISTURE DAMAGES TRANSFORMER INSULATION

— THE DEGRADATION CYCLE —

MOISTURE
enters and accumulates in the insulation system (mainly in cellulose paper)

SOURCES
- Breather ingress
- Oil leaks / seal leakage
- High humidity
- Maintenance activities
- Vacuum filling

MOISTURE

HYDROLYSIS
Moisture breaks down cellulose molecular chains

DP REDUCTION
Degree of Polymerization (DP) of cellulose decreases

LOSS OF MECHANICAL STRENGTH
Paper becomes weak, brittle and less resilient

INSULATION FAILURE
Increased risk of breakdown, partial discharge and short-circuit

A SILENT PROCESS THAT CONTINUES
24 x 7 x 365

EFFECTS OF MOISTURE

- **ACCELERATES CELLULOSE AGING** — Faster chemical degradation
- **INCREASES FURAN GENERATION** — Indicator of paper degradation
- **REDUCES DIELECTRIC STRENGTH** — Lower breakdown voltage
- **INCREASES DIELECTRIC LOSSES** — Higher dissipation factor (tan δ)
- **INCREASES BUBBLE FORMATION RISK** — Especially at high temperature
- **INCREASES PARTIAL DISCHARGE RISK** — Reduces insulation withstand capability

WHAT INTERNATIONAL STANDARDS AND EXPERTS CONFIRM

IEC 60156 Breakdown Voltage
Moisture reduces the dielectric strength of insulating oil and increases breakdown risk.

IEC 60247 Dielectric Properties
Moisture increases dissipation factor and reduces resistivity of insulation.

IEC 61198 Furan Analysis
Higher furan content indicates higher level of cellulose degradation driven by moisture.

IEEE C57.91 Loading Guide
Moisture significantly reduces insulation life and increases thermal aging rate.

CIGRÉ TB 761

IMPACT ON TRANSFORMER LIFE

DRY INSULATION LOW MOISTURE → LONG LIFE

WET INSULATION HIGH MOISTURE → SHORTENED LIFE

Moisture weakens paper insulation and increases the likelihood of failure.

EXPERT INSIGHT

> Most transformer failures are the result of slow insulation deterioration over time, not a sudden catastrophic event.

Controlling moisture is the most effective way to slow down insulation aging and extend transformer life.

MOISTURE DOES NOT MERELY INDICATE AGING.
MOISTURE ACTIVELY DRIVES AGING AND FAILURE.

WHAT INTERNATIONAL EXPERTS RECOMMEND

BEST PRACTICES FOR MOISTURE MANAGEMENT AND TRANSFORMER ASSET MANAGEMENT

A MODERN, RISK-BASED APPROACH

1. MONITOR WHAT MATTERS

- Moisture in Oil (ppm)
- Relative Saturation (%RS)
- Water Activity (a_w)
- Estimated Paper Moisture (%)
- Furan (2-FAL)
- Methanol
- Dissipation Factor (tan δ)
- Breakdown Voltage (BDV)
- DGA (H_2, CH_4, C_2H_2, etc.)
- Temperature & Load Profile

2. CONTROL WHAT YOU CAN

- Prevent moisture ingress through effective sealing
- Maintain breather performance
- Eliminate oil leaks
- Control internal moisture migration
- Maintain oil quality
- Ensure proper OLTC moisture and contamination management

3. ADOPT A CONTINUOUS APPROACH

CONTINUOUS MONITORING
Real-time visibility of moisture and insulation condition.

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CONDITION ASSESSMENT
Interpret data using standards, trends and expert methods.

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RISK-BASED DECISIONS
Prioritize assets and actions based on risk and remaining life.

↓

CONTINUOUS MOISTURE MANAGEMENT
Maintain low, stable moisture levels in oil and paper for long-term insulation life.

INDUSTRY EVOLUTION

PAST APPROACH

Periodic Testing → Periodic Filtration → Reactive Maintenance

MODERN APPROACH

Continuous Monitoring → Condition Assessment → Targeted Action & Care → Continuous Moisture Management → Extended Life, Lower Risk, Higher Reliability

KEY INTERNATIOINL REFERENCES

IEC STANDARDS

IEC 60422
Mineral insulating oils in electrical equipment – Supervision and maintenance guidance

IEC 60814
Determination of water by Karl Fischer titration

IEC 60156
Insulating liquids – Determination of breakdown voltage

IEC 60247
Measurement of relative permittivity, dielectric dissipation factor and d.c. resistivity

IEC 60567
Dissolved gas analysis – Sampling and analysis

IEC 60599
Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis

IEC 61198
Mineral oil – Determination of furans and related compounds

Other relevant IEC and ISO publications

IEEE STANDARDS & GUIDES

IEEE C57.91
Guide for Loading Mineral-Oil-Immersed Transformers

IEEE C57.143
Guide for the Application of Monitoring Equipment to Liquid-Immersed Power Transformers and Interpretation of Results

CIGRÉ PUBLICATIONS

CIGRÉ Technical Brochure 761
Condition Assessment of Power Transformers

CIGRÉ WG A2 Publications
Moisture in Transformers – Assessment, Impact and Management

CIGRÉ WG A2.49
Transformer Ageing and Life Management

KEY EXPERT PUBLICATIONS

T. V. OOMMEN
Moisture Equilibrium in Paper–Oil Insulation Systems (Foundational work on moisture equilibrium theory)

MICHAEL KOCH
Moisture Assessment of Power Transformers (Endorsed methods for paper moisture estimation)

STEFAN TENBOHLEN
Moisture Diagnostics Using Dielectric Response (Advanced FDS techniques for moisture evaluation)

J. D. PIPER
Moisture Equilibrium Models for Transformer Insulation Systems (Practical models and temperature dependent charts)

FINAL MESSAGE

IEC, IEEE, CIGRÉ and leading transformer researchers all recognize moisture **as one of the most influential and controllable factors affecting insulation aging, dielectric strength and transformer life.** A modern transformer asset management program must combine accurate diagnostics with continuous moisture management to ensure long-term reliability and value.

MANAGE MOISTURE TODAY – PROTECT INSULATION, EXTEND LIFE, REDUCE RISK.
THIS IS THE CONSENSUS OF INTERNATIONAL STANDARDS AND EXPERTS.