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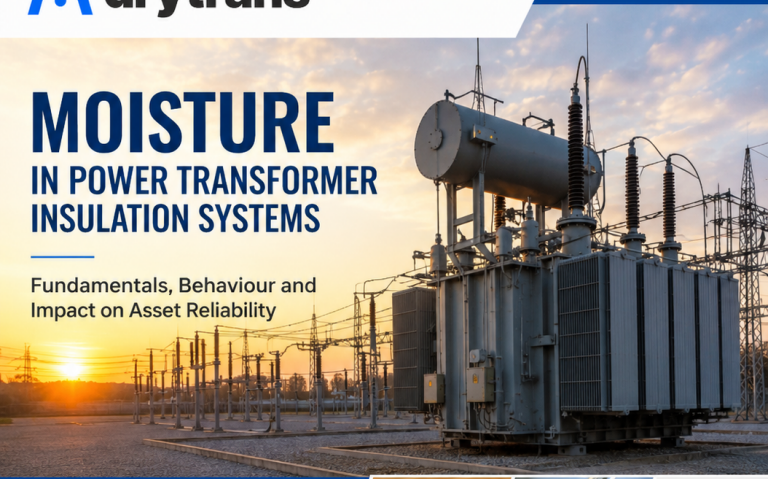
MOISTURE
IN POWER TRANSFORMER INSULATION SYSTEMS

Fundamentals, Behaviour and Impact on Asset Reliability



Moisture is one of the most influential factors affecting transformer performance, reliability and service life.

Understanding moisture behaviour is essential for accurate condition assessment, effective asset management and extending insulation life.

Cellulose Insulation

Transformer Oil

Moisture Analysis

KEY TAKEAWAYS

- Moisture is both a cause and a product of insulation ageing.
- Moisture continuously migrates between oil and cellulose with temperature changes.
- High moisture reduces dielectric strength and accelerates ageing.
- Excess moisture increases bubble formation risk under thermal stress.
- Effective moisture assessment improves reliability and extends asset life.

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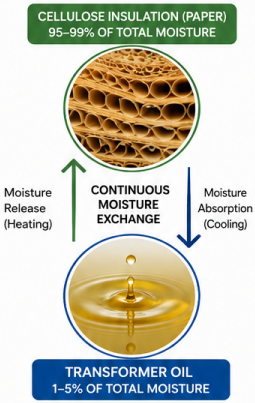
WHAT IS MOISTURE IN A TRANSFORMER?

A transformer insulation system is composed of insulating oil and cellulose (paper). Moisture exists in both, but the majority is stored in the cellulose insulation.

KEY FACT

95–99% of the total moisture in a transformer is contained in the cellulose insulation, not in the oil.

OIL–PAPER INSULATION SYSTEM



Oil acts as a transport medium that carries moisture between different parts of the transformer.

Understanding this balance is essential for accurate moisture assessment and effective asset management.

SOURCES OF MOISTURE

Residual Manufacturing Moisture
Moisture remaining in cellulose and oil even after drying processes.

Cellulose Ageing
Thermal degradation of cellulose generates water as a by-product.

External Ingress
Moisture enters through breathers, leaks, faulty gaskets and seals.

Maintenance Activities
Moisture may enter during oil handling, sampling and maintenance operations.

High Ambient Humidity
High humidity conditions increase the rate of moisture ingress.

WHY MOISTURE MATTERS

Accelerates Insulation Ageing
Moisture accelerates hydrolysis of cellulose, reducing Degree of Polymerization (DP) and mechanical strength.

Reduces Dielectric Strength
Higher moisture lowers breakdown voltage and increases dielectric losses.

Increases Bubble Formation Risk
Moisture in paper can vaporize at high temperatures, causing bubbles and partial discharges.

Degrades Overall Reliability
Moisture, in combination with thermal stress, significantly reduces insulation margin and service life.

Moisture is not a static parameter. It continuously migrates between oil and paper depending on temperature, load and environmental conditions.

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MOISTURE MIGRATION & EQUILIBRIUM

Moisture inside a transformer is dynamic. It continuously migrates between the oil and cellulose insulation, seeking equilibrium based on temperature, load and relative saturation.

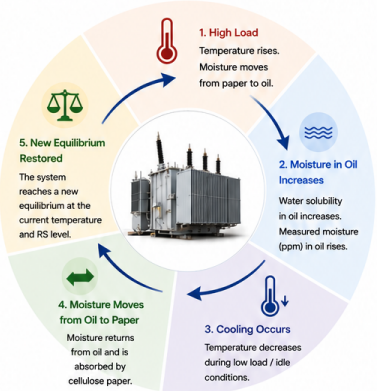
EQUILIBRIUM BETWEEN OIL AND PAPER

CELLULOSE INSULATION (PAPER)
95–99%
of total moisture

TRANSFORMER OIL
1–5%
of total moisture

The system tends to reach equilibrium at a given temperature and relative saturation level.

MOISTURE MIGRATION CYCLE



Oil moisture values vary throughout the day with load cycles, while total moisture in the transformer remains nearly constant.

FACTORS AFFECTING MOISTURE BEHAVIOUR

Temperature
Higher temperature increases water solubility in oil and drives moisture out of paper.

Load Profile
Load variations cause daily moisture exchange between oil and paper.

Relative Saturation (RS)
Higher RS indicates oil is closer to its moisture carrying capacity.

Ambient Conditions
High humidity and temperature increase the rate of moisture ingress.

Oil and Paper Condition
Aged oil or paper can change moisture solubility and adsorption characteristics.

KEY TAKEAWAYS

- Moisture is not static; it continuously migrates between oil and paper.
- Oil moisture is a dynamic indicator and depends on temperature and load conditions.
- A single measurement is only a snapshot; trends provide real insight.
- Understanding moisture migration is essential for accurate assessment and effective asset management.

REFERENCES

- **CIGRÉ** Technical Brochure 349 Moisture Equilibrium and Moisture Migration in Transformer Insulation Systems
- **CIGRÉ** Technical Brochure 741 Moisture Measurement and Assessment in Transformer Insulation
- **IEC 60422** – Mineral Insulating Oils in Electrical Equipment – Supervision and Maintenance Guidance
- **IEEE C57.91** – Guide for Loading Mineral-Oil-Immersed Transformers

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PPM VS RELATIVE SATURATION

WHY RELATIVE SATURATION MATTERS

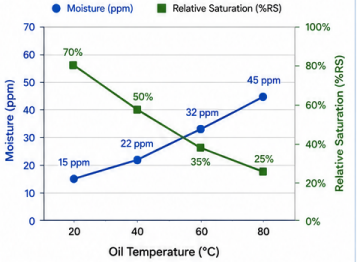
Water solubility in oil increases with temperature. Therefore, the same ppm value at different temperatures represents different moisture conditions. Relative Saturation (%RS) provides a better indication of moisture severity and insulation risk.

RELATIVE SATURATION (%RS)

$$RS = \frac{\text{Water Content (ppm)}}{\text{Water Solubility Limit at Temp (ppm)}} \times 100$$

%RS indicates how close the oil is to its saturation point. Values above ~80% increase the risk of insulation problems.

EXAMPLE: EFFECT OF TEMPERATURE ON PPM AND %RS



Illustrative example only. Actual values depend on oil type and condition.

PPM VS RELATIVE SATURATION (%RS)

Parameter	Moisture in Oil (ppm)	Relative Saturation (%RS)
Temperature Dependence	Highly Temperature Dependent	Less Temperature Dependent
Indicates Moisture Severity	Limited	Better Indicator of True Moisture Condition
Reflects Oil Saturation Condition	No	Yes
Correlation with Dielectric Strength	Weak	Stronger Correlation
Use in Online Monitoring	Yes	Yes (Recommended)
Recommended by Standards	IEC 60422 (as supporting parameter)	IEC 60422 (Key Parameter)

KEY TAKEAWAY

- PPM values alone can be misleading without oil temperature.
- %RS shows how close the oil is to its moisture carrying capacity.
- High %RS (>80%) indicates a higher risk of dielectric and ageing related issues.
- Always evaluate moisture using ppm, temperature and %RS together.

TYPICAL MOISTURE SEVERITY GUIDELINES (MINERAL OIL)

Relative Saturation (%RS)	Moisture Condition	Typical Interpretation	Recommended Action
0 – 30%	Very Dry	Healthy insulation condition	Continue monitoring
30 – 60%	Acceptable	Normal operation range	Continue routine monitoring
60 – 80%	Elevated	Moisture level increasing	Increase monitoring frequency, identify source
80 – 100%	High	Oil approaching saturation, risk of insulation problems	Investigate and take moisture control action
> 100%	Saturated	Oil is saturated – high risk	Immediate action required

IMPORTANT NOTE

These guidelines are general. Actual limits may vary depending on transformer design, loading, oil type (mineral or ester), condition and past operating history.

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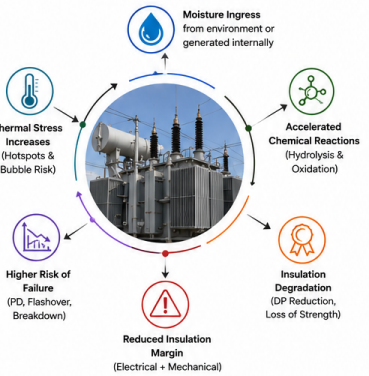
HOW MOISTURE AFFECTS TRANSFORMER INSULATION LIFE

Moisture is the primary driver of insulation degradation. Its impact extends across electrical, mechanical, thermal and reliability aspects of a transformer.



KEY IMPACT AREAS

1 CELLULOSE AGEING

- Moisture accelerates hydrolysis of cellulose.
- Degree of Polymerization (DP) decreases.
- Mechanical strength reduces.

2 ELECTRICAL PERFORMANCE

- Breakdown voltage (BDV) decreases.
- Dielectric loss (tan δ) increases.
- Resistivity of oil and paper decreases.

3 BUBBLE FORMATION RISK

- Moisture in paper can vaporize at high temperature.
- Causes gas bubbles in oil.
- Leads to partial discharges and breakdown risk.

4 OVERALL RELIABILITY IMPACT

- Insulation margin reduces significantly.
- Probability of failure increases.
- Service life of the transformer shortens.

MOISTURE DRIVEN AGEING MECHANISM

Moisture in Oil / Paper → Heat & Electrical Stress → Chemical Reactions (Hydrolysis) → Cellulose Chain Breakdown → DP Reduction & Strength Loss → Increased Failure Risk

Moisture accelerates ageing, reduces dielectric strength, and increases the likelihood of catastrophic failure.

INDUSTRY STANDARDS & REFERENCES

- **IEC 60422** – Mineral Insulating Oils in Electrical Equipment – Supervision and Maintenance Guidance
- **IEC 60814** – Determination of Water by Karl Fischer Titration
- **IEC 60156** – Breakdown Voltage of Insulating Liquids
- **IEC 60247** – Measurement of Dielectric Properties
- **IEEE C57.91** – Guide for Loading Mineral-Oil-Immersed Transformers
- **CIGRÉ TB 349** – Moisture Equilibrium and Moisture Migration in Transformer Insulation Systems
- **CIGRÉ TB 741** – Moisture Measurement and Assessment in Transformer Insulation

SUSTAINED INSULATION LIFE IMPROVEMENT REQUIRES:

- Maintain low moisture levels in both oil and paper.
- Control hot-spot temperature and loading.
- Monitor trends, not just single-point values.
- Ensure oil quality and system integrity.
- Implement moisture management as a continuous process.

Moisture may be invisible, but its impact is permanent.
Controlling moisture is controlling the life of your transformer.

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MOISTURE ASSESSMENT FRAMEWORK

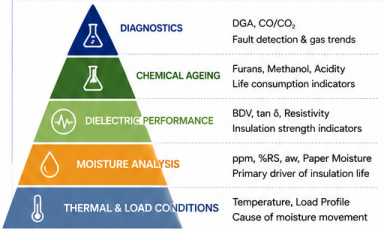
A HOLISTIC APPROACH TO TRANSFORMER HEALTH

No single test can define the true moisture condition of a transformer. A comprehensive evaluation using multiple parameters provides a complete picture of insulation health and helps in making the right decisions for asset management.

RECOMMENDED ASSESSMENT PARAMETERS

Category	Parameters
Moisture	• Moisture in Oil (ppm) • Relative Saturation (%RS) • Water Activity (aw) • Estimated Paper Moisture (%)
Electrical Performance	• Breakdown Voltage (BDV) • Dissipation Factor (tan δ) • Resistivity
Ageing Indicators	• Furan (2-FAL) • Methanol • Acidity (TAN) • Interfacial Tension (IFT)
Fault Diagnostics	• Dissolved Gas Analysis (DGA) • CO / CO_2
Operational Conditions	• Top Oil Temperature • Load Profile • Ambient Conditions

THE TRANSFORMER HEALTH PYRAMID



THE KEY: Combine measurements, understand the trends, and evaluate in the context of operating conditions.

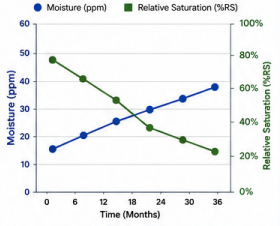
TREND ANALYSIS – THE REAL STORY

WHY TRENDS MATTER?

Moisture and other parameters change with time, load and climatic conditions.

- Identifies slow degradation
- Predicts future risk
- Supports maintenance planning
- Helps extend transformer life
- Reduces unplanned outages

EXAMPLE: MOISTURE & RELATIVE SATURATION TREND



Trend analysis provides early warning and guides proactive moisture management.

ESTIMATING PAPER MOISTURE FROM OIL MEASUREMENTS

- Oil moisture, temperature and Relative Saturation can be used with equilibrium models (Oommen, Fessler, IEC methods) to estimate paper moisture.
- These are engineering estimates, not direct measurements.
- Accuracy depends on thermal equilibrium, oil type, paper condition and operating history.
- Always interpret estimates with trend analysis and other diagnostic parameters.

LIMITATIONS & UNCERTAINTIES

Non-equilibrium operation
Most transformers are not in steady state. Daily load changes affect moisture distribution.

Temperature gradients
Oil temperature at one point may not reflect winding hot-spot temperature.

Aged insulation behavior
Older paper may adsorb and desorb moisture differently compared to new paper.

Oil chemistry effects
Oxidation products and contaminants can influence moisture behavior.

Method & sensor limitations
Sampling, calibration and sensor accuracy impact the reliability of results.

THE BOTTOM LINE

Understanding moisture is not just about measuring water in oil.
It is about understanding moisture behavior, its impact on insulation, and taking the right actions to protect transformer life.

Measure → Analyze → Act → Protect

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