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UNDERSTANDING BUBBLING RISK IN POWER TRANSFORMERS

When Moisture Becomes a Reliability Threat

WHAT IS BUBBLING?

Bubbling occurs when moisture contained within transformer cellulose insulation vaporizes due to elevated temperatures and forms water vapor bubbles inside the insulation system.

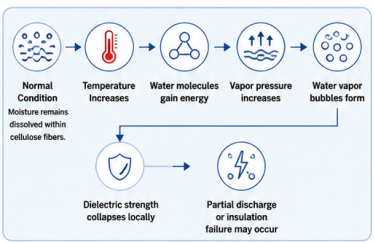
These bubbles can significantly reduce dielectric strength and may initiate:

- **Partial Discharge (PD)**
- **Insulation Breakdown**
- **Internal Flashover**
- **Catastrophic Transformer Failure**

The risk becomes particularly significant during:

- Overloading
- Emergency loading
- Generator transformer operation
- Rapid load increases
- Fault conditions

HOW BUBBLING DEVELOPS



KEY MESSAGE

Bubbling is not primarily a thermal problem.

Bubbling is a moisture-driven thermal failure mechanism.

THE HIDDEN PROBLEM

Many transformers operate with acceptable oil moisture levels while the paper insulation remains wet.

Since more than 95–99% of the total moisture resides inside the cellulose insulation, oil tests alone may not reveal the actual bubbling risk.

MOISTURE DISTRIBUTION IN A TRANSFORMER

COMPONENT	TYPICAL MOISTURE SHARE
Cellulose Insulation (Paper)	>95–99%
Transformer Oil	<1–5%

Therefore:

Bubbling risk is primarily determined by paper moisture, not oil moisture.

FACTORS INFLUENCING BUBBLING RISK

Moisture Content of Paper
The most important parameter. Higher paper moisture means lower bubbling temperature.

Hot Spot Temperature
Bubbles generally form in winding hot spots rather than bulk oil.

Transformer Age
Older insulation usually contains: more moisture, lower mechanical strength, higher degradation products.

Loading Conditions
Emergency overloads increase hotspot temperatures rapidly.

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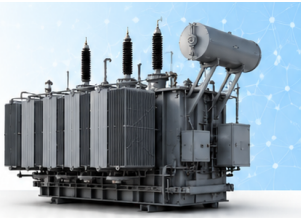
MOISTURE, TEMPERATURE AND BUBBLING RISK

How Moisture Inside the Insulation Determines the Safety Margin of Your Transformer



RELATIONSHIP BETWEEN PAPER MOISTURE AND BUBBLING TEMPERATURE

Bubbling (vapor bubble formation) occurs at lower temperatures as paper moisture increases.

PAPER MOISTURE (% by weight)	RELATIVE BUBBLING RISK	TYPICAL BUBBLING TEMPERATURE RANGE* (°C)
< 1%	Very Low	> 150
1 – 2%	Low	140 – 150
2 – 3%	Moderate	130 – 140
3 – 4%	Elevated	120 – 130
> 4%	High	110 – 120
> 5%	Very High	< 110

**Values depend on insulation condition, aging level, oil type, oxygen content and loading conditions.*

WHY MOISTURE MATTERS MORE THAN TEMPERATURE

Two transformers may operate at the same hot spot temperature. However, the one with higher paper moisture has a much lower bubbling margin.

EXAMPLE: SAME HOT SPOT TEMPERATURE = 120°C

TRANSFORMER A	TRANSFORMER B
Paper Moisture = 1%	Paper Moisture = 4%
Bubbling risk: LOW	Bubbling risk: HIGH
High safety margin	Low safety margin

Higher paper moisture means bubbles can form at significantly lower temperatures.

TYPICAL BUBBLING RISK SCENARIO

- Transformer: 25 years old
- Moisture in paper: 4 – 5%
- Emergency loading event
- Hot spot temperature rises above 130°C

RESULT

- Moisture migrates rapidly
- Vapor pressure increases
- Bubble generation begins
- Local dielectric strength decreases
- Partial discharge or insulation failure probability increases

HOW UTILITIES CAN REDUCE BUBBLING RISK

MONITOR MOISTURE CONTINUOUSLY
Use online moisture sensors measuring:
Relative Saturation (%RS) • Water Activity (aw) • Oil Temperature

ESTIMATE PAPER MOISTURE
Combine moisture measurements, oil temperature and equilibrium models to determine paper moisture and bubbling risk.

REDUCE MOISTURE BEFORE CRITICAL LOADING
Do not wait until overload or emergency conditions occur.

IMPLEMENT CONTINUOUS MOISTURE MANAGEMENT
Unlike periodic oil filtration, continuous moisture management addresses moisture migration from paper to oil over time.

THE DRYTRANS APPROACH

DryTrans systems continuously remove moisture from transformer oil while the transformer remains energized.

This gradually shifts the oil-paper equilibrium and reduces moisture inside the insulation, increasing the safety margin against bubble formation.

BENEFITS OF MOISTURE MANAGEMENT

- Reduces bubbling risk during overloads and transient events
- Reduces moisture in insulation (paper)
- Improves dielectric strength and insulation reliability
- Improves loading capability and thermal performance
- Extends insulation life and delays capital expenditure
- Improves overall asset reliability and availability

The safest transformer during overload conditions is not necessarily the coolest transformer. It is often the driest transformer.

KEY MESSAGE

Bubbling is a moisture-driven thermal failure mechanism. Continuous moisture management is the most effective way to reduce bubbling risk and ensure long-term transformer reliability.

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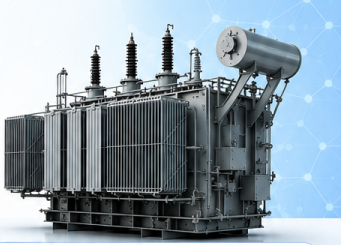
REFERENCES

The information presented in this flyer is based on internationally recognized transformer insulation research, standards and industry best practices.



INTERNATIONAL STANDARDS

IEC 60422
Mineral insulating oils in electrical equipment
Specifies test methods for mineral insulating oils including moisture, breakdown voltage and other key properties.

IEC 60076 Series
Power Transformers
Covers design, performance, testing and loading requirements for power transformers.

IEEE C57.91
Guide for Loading Mineral-Oil-Immersed Transformers
Provides guidance on safe loading, hot spot temperature rise and insulation life considerations.

IEEE C57.106
Acceptance and Maintenance of Insulating Oil
Defines practices for sampling, testing and maintaining insulating oil in service.

CIGRÉ PUBLICATIONS

Technical Brochure 349
Moisture Equilibrium and Moisture Migration in Transformer Insulation Systems
Describes moisture equilibrium, migration mechanisms and the impact of temperature and relative humidity.

Technical Brochure 741
Transformer Reliability and Condition Assessment
Covers reliability aspects, failure mechanisms and condition assessment of power transformers.

Working Group Publications
Insulation Aging, Moisture Assessment and Transformer Loading
Extensive research on moisture behavior, insulation aging, diagnostics and safe operating limits.

KEY TECHNICAL LITERATURE

T. V. Oommen
Moisture Equilibrium in Paper-Oil Insulation Systems
Fundamental research on moisture equilibrium models and their application in transformers.

M. Koch & S. Tenbohlen
Moisture Assessment Using Dielectric Response Measurements
Advanced techniques for moisture estimation using dielectric spectroscopy.

J. D. Piper
Moisture Equilibrium Models for Transformer Insulation
Comprehensive models for predicting moisture distribution and equilibrium behavior.

INDUSTRY CONSENSUS

- Moisture is one of the most significant accelerators of **insulation aging**.
- Elevated moisture reduces **dielectric strength** and increases **bubble formation risk**.
- Moisture management is essential for **maintaining transformer reliability** and **extending insulation life**.
- Online monitoring and continuous moisture control provide improved **visibility of insulation condition** and moisture migration behavior.

DISCLAIMER
Bubbling temperature and risk depend on numerous variables including paper moisture, insulation aging, oil type, oxygen content, loading profile and transformer design. Engineering assessment should always consider transformer-specific operating conditions.

DryTrans®
From Moisture Monitoring to Moisture Management
Improving Reliability. Extending Life.

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