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FUNDAMENTALS OF MOISTURE EQUILIBRIUM BETWEEN OIL AND PAPER

Understanding the Dynamic Relationship that Drives Moisture Migration

INTRODUCTION

The insulation system of an oil-filled transformer consists primarily of cellulose insulation (paper, pressboard, wood) and insulating oil.

Although transformer oil is often tested for moisture content, the majority of moisture in a transformer is not contained in the oil.

Under normal operating conditions:

- Approximately 95–99% of the total moisture resides within the cellulose insulation.
- Only a small percentage remains dissolved in the oil.

Because oil and paper are in constant contact, moisture continuously moves between them in an attempt to reach **moisture equilibrium.**

Understanding this relationship is essential for:

- Transformer condition assessment
- Moisture diagnostics
- Insulation life management
- Drying and dehydration strategies
- Failure risk reduction

WHAT IS MOISTURE EQUILIBRIUM?

Moisture equilibrium is the condition where:

> The water activity (chemical potential of water) in the oil equals the water activity in the cellulose insulation.

At equilibrium:

- Moisture continues to exist in both materials.
- There is no net migration of moisture from one material to the other.

The equilibrium condition depends on:

- Oil Temperature
- Paper Temperature
- Paper Moisture Content
- Oil Type
- Aging Condition of Insulation

WHY PAPER HOLDS MORE MOISTURE THAN OIL

Cellulose is a highly polar and hygroscopic material.
Its molecular structure contains hydroxyl (–OH) groups that attract and bind water molecules.

Transformer oil is largely non-polar and has limited ability to dissolve water.

As a result:

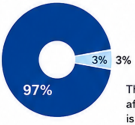
Material	Water Affinity
Cellulose Insulation	**Very High**
Mineral Oil	**Low**

Consequently:

- Paper acts as the primary moisture reservoir.
- Oil acts as the transport medium.

TYPICAL MOISTURE DISTRIBUTION

A transformer containing 100 units of total moisture may have:



- 97 units in paper insulation
- 3 units in transformer oil

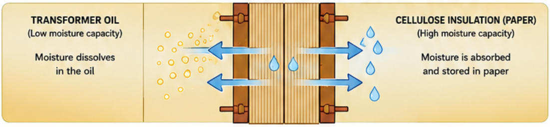
This explains why moisture often returns after oil processing. The moisture source is frequently the cellulose insulation rather than the oil itself.

KEY ENGINEERING PRINCIPLE

> Oil moisture is usually a symptom.
> **Paper moisture is the root cause.**

For this reason, insulation assessment should focus on understanding the oil–paper equilibrium relationship rather than oil moisture alone.

OIL–PAPER MOISTURE EQUILIBRIUM



EQUILIBRIUM POINT

Moisture continuously migrates between oil and paper until equilibrium is reached.

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MOISTURE MIGRATION AND EQUILIBRIUM IN OPERATING TRANSFORMERS

Transformer insulation is not static—moisture is continuously redistributed between oil and paper as operating and environmental conditions change.

FACTORS THAT DRIVE MIOISTURE MIGRATION

Temperature Changes
Affects oil solubility and paper moisture content.

Load Variations
Changes winding temperature and thermal gradients.

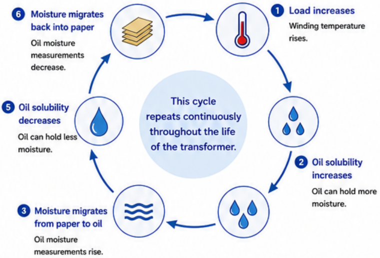
Ambient Conditions
Affect breathing air humidity and oil temperature.

Aging of Cellulose
Degradation products increase moisture affinity.

Insulation Condition
Impacts moisture diffusion and retention.

THE MOISTURE MIGRATION CYCLE

Moisture moves back and forth between paper and oil in response to temperature and load changes.



Moisture migration is a continuous, reversible process driven by temperature, load variations, and ambient conditions.

WHY ppm ALONE CAN BE MISLEADING

Moisture in oil is commonly reported in ppm, but ppm values are strongly temperature dependent. The same total moisture can show very different ppm values at different temperatures.

Example: Same Total Moisture, Different Temperatures

Oil Temperature (°C)	Oil Moisture (ppm)	Relative Saturation (%RS)
30	12 ppm	28%
45	18 ppm	28%
60	25 ppm	28%

ppm increases with temperature because warm oil can dissolve more water. Relative Saturation (%RS) gives a true picture of moisture stress.

RELATIVE SATURATION (%RS) – A BETTER INDICATOR

Relative Saturation is defined as the percentage of the maximum amount of water that oil can hold at a given temperature.

Benefits of using %RS:

- Temperature compensated
- Indicates free water risk
- Better indicator of dielectric stress
- Recommended for operational assessment

%RS

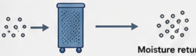
High %RS values indicate:

- Increased moisture stress
- Reduced dielectric strength
- Increased risk of bubble formation and breakdown

WHY CONTINUOUS MOISTURE MANAGEMENT WORKS

Traditional oil filtration removes moisture from the oil. However, once filtration stops, moisture stored in paper continues migrating back into the oil, and oil moisture levels can gradually increase again.

CONVENTIONAL APPROACH
Periodic oil filtration



Moisture returns from paper

CONTINUOUS MOISTURE MANAGEMENT
Maintain low moisture in oil continuously

- Low moisture concentration in oil
- Favorable equilibrium condition
- Encourages gradual moisture migration from paper
- Reduces overall insulation moisture and risk

Continuous moisture management shifts the equilibrium and gradually dries the entire insulation system.

KEY TAKEAWAY

Moisture equilibrium explains why moisture moves between oil and paper.
Oil moisture measurements represent only a small part of the insulation system.
Understanding equilibrium and moisture migration is fundamental to transformer moisture diagnostics, insulation life assessment, and long-term moisture management.

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REFERENCES

The following international standards, technical publications, and research works provide the scientific and engineering foundation for understanding moisture equilibrium and moisture dynamics in transformer insulation systems.

INTERNATIONAL STANDARDS

1. **IEC 60422**
Mineral Insulating Oils in Electrical Equipment – Supervision and Maintenance Guidance.
Provides comprehensive guidance on the maintenance of insulating oils, including moisture control, oil testing, and interpretation of test results.

2. **IEC 60814**
Insulating Liquids – Determination of Water by Automatic Coulometric Karl Fischer Titration.
Specifies the method for accurate determination of water content in insulating liquids using Karl Fischer titration.

3. **IEEE C57.106**
Guide for Acceptance and Maintenance of Insulating Oil in Equipment.
Covers acceptance criteria, maintenance testing, and recommended practices for insulating oil, including moisture limits and actions.

4. **IEEE C57.91**
Guide for Loading Mineral-Oil-Immersed Transformers.
Addresses thermal performance, loading guidelines, and the impact of moisture on insulation and transformer life.

CIGRÉ PUBLICATIONS

5. **CIGRÉ Technical Brochure 349**
Moisture Equilibrium and Moisture Migration in Transformer Insulation Systems.
Explains moisture equilibrium principles, migration mechanisms, and their effect on transformer insulation condition.

6. **CIGRÉ Technical Brochure 741**
Moisture Measurement and Assessment in Transformer Insulation.
Covers methods for moisture measurement, water activity, relative saturation, and moisture assessment techniques.

7. **CIGRÉ Technical Brochure 761**
Condition Assessment of Power Transformers.
Provides a framework for overall condition assessment, including the role of moisture in insulation aging and failure risk.

KEY TECHNICAL PAPERS

8. **T. V. Oommen**
Moisture Equilibrium in Paper-Oil Insulation Systems.
Pioneering research on the thermodynamics of moisture equilibrium between cellulose and insulating oil.

9. **M. Koch and S. Tenbohlen**
Moisture Assessment in Power Transformers Using Dielectric Response Methods.
Discusses advanced diagnostic techniques for moisture evaluation using dielectric response analysis.

10. **J. D. Piper**
Moisture Equilibrium Models for Transformer Insulation Systems.
Presents models and calculations for predicting moisture distribution and equilibrium in transformer insulation.

ADDITIONAL TECHNICAL REFERENCE

11. **United States Bureau of Reclamation (USBR)**
Facilities Instructions, Standards and Techniques (FIST) Volume 3-31 – Transformer Diagnostics.
Practical guidance on transformer diagnostics, including moisture measurement, oil testing, and condition evaluation.

12. **DryTrans Educational Reference**
Transformer Moisture Chart and equilibrium concepts used in DryTrans educational materials.
Practical reference chart illustrating the relationship between temperature, relative saturation (%RS), ppm, and water activity.[1]

WHY THESE REFERENCES MATTER

Moisture equilibrium and migration are complex, temperature-dependent phenomena that directly impact:

Insulation Reliability
Excess moisture accelerates aging and reduces dielectric strength.

Asset Life
Controlling moisture extends insulation life and improves transformer reliability.

Condition Assessment
Understanding equilibrium enables accurate diagnosis and trend analysis.

Moisture Management
Scientific understanding drives effective drying and moisture control strategies.

> “Moisture equilibrium is the fundamental mechanism governing moisture distribution inside oil-filled transformers.

Understanding this relationship is essential for accurate diagnostics, condition assessment, insulation life management, and effective moisture control strategies.

1 Refer to the DryTrans Transformer Moisture Chart for typical equilibrium values of %RS, ppm, and water activity (aw) at different temperatures.

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