Understanding Oil-Paper Equilibrium in Power Transformers

Moisture Migration, Temperature Effects, Relative Saturation, and Why Moisture Returns After Drying

Executive Summary

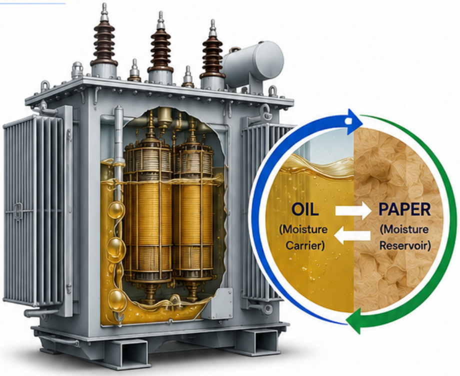
Moisture is the primary driver of insulation aging and one of the leading causes of transformer failure.

More than 95% of the moisture in a transformer insulation system is stored in the cellulose (paper), not in the oil.

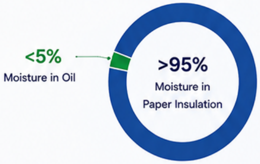
The oil and paper are in a dynamic relationship, continuously exchanging moisture until a state of equilibrium is reached at a given temperature.

Temperature changes, loading patterns, and environmental conditions constantly shift this equilibrium, causing moisture to migrate between oil and paper.

Understanding oil-paper equilibrium is essential to correctly interpret moisture test results, understand moisture rebound after drying, and implement effective moisture management strategies that extend insulation life.



Moisture Distribution in a Typical Power Transformer



- Cellulose (paper) acts as a moisture reservoir. It can hold large amounts of water.
- Oil acts as a moisture carrier. It holds only a small amount of water.
- Oil and paper continuously exchange moisture until equilibrium is reached.

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Executive Summary

Equilibrium is the Key to Understanding Transformer Moisture Behavior

Transformer insulation is a dynamic system in which moisture continuously moves between oil and paper until a state of thermodynamic equilibrium is reached at a given temperature.

Because more than 95% of the moisture in a transformer resides in the cellulose insulation (paper), any change in oil moisture is a reflection of moisture migration to or from the paper.

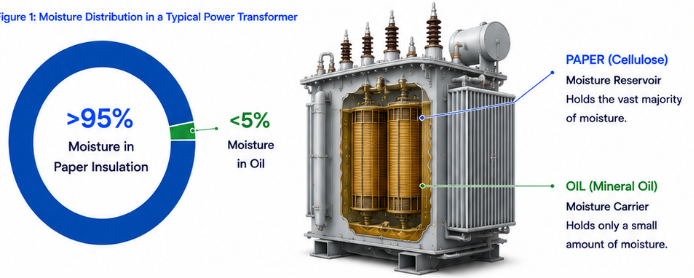
Temperature, loading, and environmental conditions constantly influence this equilibrium, causing oil moisture levels to rise or fall even when no external moisture ingress occurs.

Understanding oil–paper equilibrium is essential to correctly interpret moisture measurements, predict moisture rebound after drying, and implement effective moisture management strategies that extend insulation life and transformer reliability.

Key Takeaways

- More than 95% of transformer moisture is stored in the cellulose insulation, not in the oil.
- Oil and paper are in a continuous two-way exchange of moisture until equilibrium is reached.
- Temperature changes the equilibrium and causes moisture to move between oil and paper.
- Relative Saturation (RS) provides a truer picture of moisture stress than ppm alone.
- Moisture will return to the oil after drying unless the equilibrium is shifted through continuous moisture removal.

Figure 1: Moisture Distribution in a Typical Power Transformer



Why This Matters

Oil moisture measurements represent only a small fraction of the total moisture in the insulation system. To make informed decisions, we must understand the science of equilibrium and the factors that influence it.

Where Moisture Actually Lives

The Oil–Paper Insulation System

A power transformer insulation system is composed of cellulose (paper and pressboard) and insulating oil.

Cellulose is hygroscopic, meaning it has a natural affinity to absorb and hold water molecules within its fiber structure.

Mineral oil, on the other hand, has a very limited capacity to dissolve water.

As a result, the vast majority (>95%) of the moisture in a transformer is stored in the solid cellulose insulation, not in the oil.

The oil acts only as a moisture carrier, transporting small amounts of water to and from the paper surfaces.

This fundamental difference is the reason why oil moisture readings alone cannot indicate the true moisture condition of the insulation.

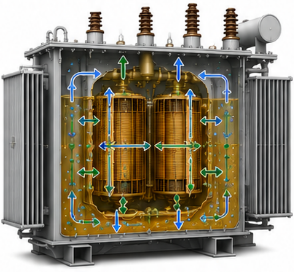
Figure 2: Moisture Storage Comparison

PAPER INSULATION (Cellulose)	OIL (Mineral Oil)
Holds a very large amount of moisture within its microscopic fiber structure.	Holds only a very small amount of moisture in solution.
	
Moisture Reservoir >95% of total moisture	**Moisture Carrier** <5% of total moisture

Figure 3: Moisture Movement Pathways in a Power Transformer

Moisture Sources

- **Ambient Air** – Breathing through conservator
- **Oil Ingress** – Moisture in new or contaminated oil
- **Water Ingress** – Through seals, gaskets, or leaks
- **High Humidity & Temperature Cycling** – Accelerates moisture ingress



Moisture Behavior

- **Constant Exchange** – Moisture continuously moves between oil and paper until equilibrium is reached.
- **Equilibrium State** – At equilibrium, the rate of moisture leaving the paper equals the rate entering it.
- **Dynamic Process** – Changes in temperature, loading, or oil moisture shift the equilibrium.

Key Message: Because paper holds the vast majority of moisture, any change in oil moisture is a reflection of moisture migration to or from the paper insulation.

What Is Oil-Paper Equilibrium?

The Foundation of Moisture Behavior

At any given temperature, moisture distributes itself between the oil and the paper insulation according to thermodynamic equilibrium.

This means the moisture activities (or chemical potentials) in the oil and the paper are equal, resulting in a stable condition where there is no net movement of moisture in either direction.

If the oil becomes drier than this equilibrium condition, moisture will migrate from the paper to the oil.

If the oil becomes wetter than the equilibrium condition, moisture will migrate from the oil into the paper.

This continuous two-way exchange is the reason why oil moisture changes over time even when no external moisture ingress occurs.

Key Concepts

- Equilibrium is the natural state where oil and paper are in balance.
- Moisture always moves from high activity (wetter) to low activity (drier).
- Temperature determines how much moisture the oil can hold, and therefore influences equilibrium.
- Equilibrium is dynamic, not static. It continuously responds to changes in temperature, loading, and moisture levels.
- Understanding equilibrium is essential for interpreting measurements and making the right moisture management decisions.

Figure 4: Oil-Paper Equilibrium Concept

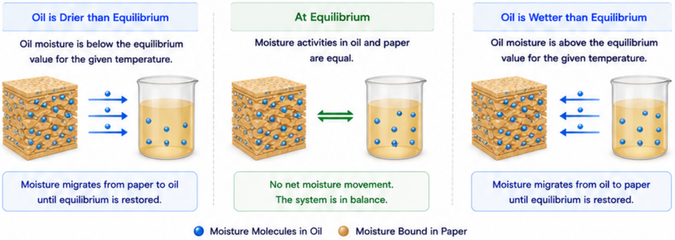
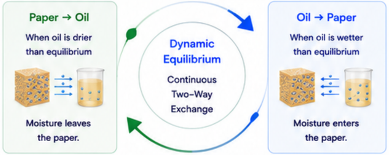


Figure 5: Dynamic Equilibrium



Key Message

Equilibrium is the driving force behind all moisture movement in a transformer.

To dry the paper, the oil must be kept consistently drier than the equilibrium value through continuous moisture removal.

Temperature Effects on Equilibrium

Why Moisture Readings Change

Temperature has a significant impact on the amount of moisture that mineral oil can hold.

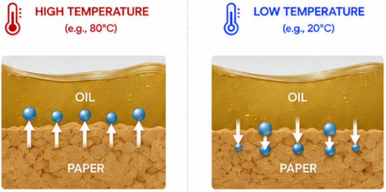
As temperature increases, the oil's capacity to dissolve water increases. To maintain equilibrium, moisture migrates from the paper insulation into the oil.

As temperature decreases, the oil's capacity decreases. Moisture then migrates from the oil back into the paper insulation.

This is why oil moisture (ppm) readings naturally rise when the transformer is hot and fall when it is cold—even if no external moisture ingress occurs.

Therefore, interpreting oil moisture without considering temperature can lead to incorrect conclusions about the actual moisture condition of the insulation.

Figure 6: Temperature Influence on Moisture Distribution



Moisture Moves from Paper to Oil

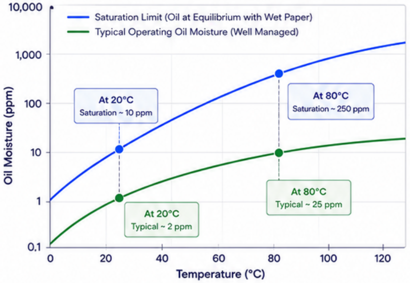
- Oil holds more moisture
- Oil ppm increases
- Paper moisture decreases

Moisture Moves from Oil to Paper

- Oil holds less moisture
- Oil ppm decreases
- Paper moisture increases

Oil moisture (ppm) varies with temperature, even when the insulation's actual moisture content remains unchanged.

Figure 7: Temperature Influence on Oil Moisture (Typical Mineral Oil)



Same oil, same insulation, different temperature → different oil moisture (ppm).

Key Takeaways

- Higher temperature → Oil holds more moisture → Oil ppm increases → Paper moisture decreases.
- Lower temperature → Oil holds less moisture → Oil ppm decreases → Paper moisture increases.
- Oil moisture (ppm) is temperature dependent and cannot be interpreted without temperature.
- Relative Saturation provides a more meaningful indication of moisture stress than ppm alone.
- Always evaluate oil moisture together with temperature and relative saturation.

Relative Saturation vs PPM

Why PPM Alone Can Be Misleading

PPM (parts per million) tells us how much moisture is in the oil, but not how close the oil-paper system is to moisture saturation at the given temperature.

Relative Saturation (RS) is the ratio of the actual moisture content to the maximum moisture the oil can hold at that temperature.

Relative Saturation indicates how much "moisture stress" exists in the insulation system.

Even a small ppm value can represent high moisture stress at low temperature, while a higher ppm value may represent low stress at elevated temperature.

Figure 8: Relative Saturation Concept

Water Present (PPM) ÷ **Water Solubility (PPM)** at Temperature = **Relative Saturation (%)**

Relative Saturation (RS) is a temperature-compensated indicator of moisture condition and is a better measure of insulation risk than ppm alone.

Figure 9: PPM vs Relative Saturation – Example

The same oil moisture (10 ppm) represents very different moisture stress levels at different temperatures.

Temperature (°C)	Saturation Limit* (ppm)	Oil Moisture (ppm)	Relative Saturation (%)	Moisture Stress Interpretation
20°C	85 ppm	10 ppm	12%	Dry Condition Low moisture stress
40°C	180 ppm	10 ppm	6%	Very Dry Condition Very low moisture stress
80°C	250 ppm	10 ppm	4%	Very Dry Condition Very low moisture stress
20°C	85 ppm	40 ppm	47%	Caution Moderate moisture stress
20°C	85 ppm	70 ppm	82%	High Risk High moisture stress

** Saturation limit values are typical for uninhibited mineral oil in equilibrium with wet paper.*

Relative Saturation provides a true picture of how close the insulation system is to moisture saturation, regardless of temperature.

Key Takeaways

- PPM is not sufficient to assess moisture condition because it does not account for temperature.
- Relative Saturation (RS) normalizes moisture content to temperature and provides a true indication of moisture stress.
- High RS indicates higher risk of insulation aging, reduced dielectric strength, and potential for failure.
- Industry practice recommends keeping RS below 40% under normal operating temperature.
- Always evaluate oil moisture using both temperature and relative saturation for accurate decision making.

Bottom Line

Use PPM to know *"how much"* moisture is in the oil.
Use Relative Saturation to understand *"how serious"* the moisture condition is.

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Equilibrium Curves and Paper Moisture Estimation

Using Equilibrium Models to Understand the True Moisture Condition

Equilibrium curves describe the relationship between oil moisture (ppm), paper moisture content (%), and temperature when the system is in thermodynamic equilibrium.

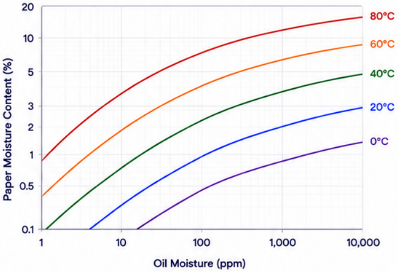
Several models exist; the most widely used are the Oommen and Koch curves, which are based on extensive laboratory and field data.

By measuring oil moisture and temperature, we can use these curves to estimate the moisture content in the paper, which represents the actual reservoir of moisture.

This estimation is essential for assessing insulation condition, predicting moisture rebound, and determining the effectiveness of drying.

Figure 10: Typical Oil–Paper Equilibrium Curve (Oommen Model)

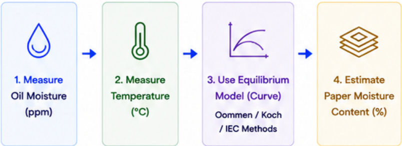
Paper Moisture Content (%) vs Oil Moisture (ppm) at Different Temperatures



At any given temperature, higher oil moisture (ppm) corresponds to higher paper moisture content at equilibrium.

Figure 11: How Moisture in Paper Is Estimated

By knowing two variables—oil moisture (ppm) and temperature—we can estimate the moisture content in the paper.



Accurate paper moisture estimation is the key to evaluating insulation condition and managing moisture risk effectively.

Common Equilibrium Models

Oommen Model
Most widely used; based on extensive data for mineral oil-paper systems.

Koch Model
Considered by many as more accurate in low moisture range.

IEC Interpretation
IEC 60422 and related standards provide guidance for moisture assessment using equilibrium data.

Different models may give slightly different results, but the trend and engineering decisions remain the same.

Key Message

Equilibrium curves are powerful tools that allow us to “see inside” the insulation. They convert simple oil measurements into meaningful insight about the true moisture condition of the cellulose insulation.

References

1. Oommen, T.V., “Moisture Equilibrium in Paper-Oil Insulation Systems,” IEEE Transactions on Power Delivery.
2. Koch, M., “Moisture Assessment of Transformer Insulation,” CIGRE Technical Brochure.
3. IEC 60422: Mineral insulating oils in electrical equipment – Supervision and maintenance guidance.
4. IEEE C57.143: Guide for the Application and Interpretation of Gases Generated in Oil-Immersed Transformers.

Why Moisture Returns After Drying

The Moisture Rebound Phenomenon

When a transformer is dried offline, the oil moisture content is reduced to a very low level, However, the paper insulation remains much wetter.

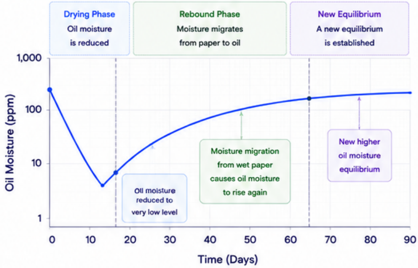
Because of the oil–paper equilibrium, this creates a strong moisture concentration gradient.

Moisture will naturally migrate from the wet paper into the dry oil until a new equilibrium is reached.

As a result, the oil moisture level increases again over time—this is known as moisture rebound.

The higher the initial paper moisture, the faster and higher the rebound.

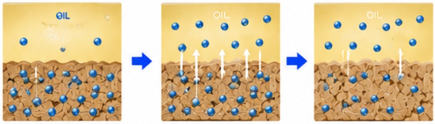
Figure 12: Moisture Rebound After Offline Drying



Moisture rebound is not a failure of drying equipment—it is a natural consequence of oil–paper equilibrium.

Figure 13: Moisture Rebound Mechanism

1. After Offline Drying	2. Moisture Migration	3. New Equilibrium
Oil is dry, paper is wet	Moisture moves from paper to oil	A new balance is established



Very low oil moisture (ppm) High paper moisture (%) Strong concentration gradient	Moisture migrates due to concentration gradient Oil moisture increases	Oil and paper reach a new equilibrium Oil moisture stabilizes

● Moisture Molecule

As long as the paper is wetter than the equilibrium value for the given oil moisture and temperature, moisture will continue to migrate into the oil.

Key Takeaways

- Offline drying removes moisture from the oil, but most of the moisture remains in the paper.
- A strong moisture gradient causes moisture to migrate from paper back to oil.
- Oil moisture will increase again until a new equilibrium is reached—this is moisture rebound.
- Rebound rate and final level depend on initial paper moisture, temperature, and system design.
- Continuous moisture management keeps oil moisture low, driving continuous migration from paper and gradually drying the insulation.

Key Message

Moisture rebound is inevitable after offline drying.
Only continuous moisture management can maintain a low oil moisture level and gradually dry the insulation over time.

Implications for Moisture Management

Why Continuous Drying Works

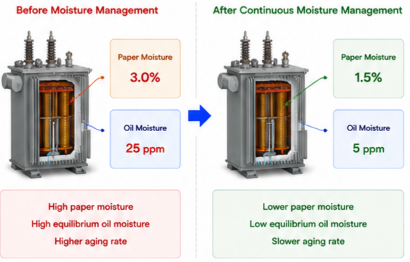
Offline drying can remove moisture from the oil, but the paper remains the primary moisture reservoir.

As long as the oil is kept drier than the equilibrium value for the given temperature, the equilibrium shifts—causing moisture to migrate from the paper into the oil.

Continuous moisture removal maintains this driving force, resulting in gradual and sustained drying of the paper insulation.

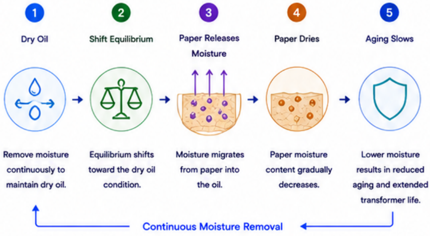
This approach reduces moisture stress, slows aging, and extends transformer life.

Figure 14: Equilibrium Shift Concept



Keeping oil moisture low continuously shifts equilibrium and encourages moisture to leave the paper over time.

Figure 15: Continuous Moisture Management Process



The process continues around the loop—maintaining dry oil drives continuous moisture migration and long-term insulation improvement.

Key Takeaways

- Oil is easy to dry; paper is harder to dry. Sustained low oil moisture is the key.
- Continuous moisture management maintains the equilibrium shift.
- Moisture continuously migrates from paper to oil.
- As paper dries, dielectric strength improves and aging slows.
- The result: higher reliability, fewer failures, and extended service life.

Key Message

Continuous moisture management leverages the science of oil–paper equilibrium.
By keeping oil moisture consistently low, we create a persistent driving force that dries the paper insulation over time—improving reliability and extending asset life.

Practical Guidelines for Moisture Management

What to Monitor and What to Control

Understanding oil–paper equilibrium helps us make better decisions about monitoring, target levels, and corrective actions.

1. Monitor Oil Moisture (ppm)
Regularly monitor oil moisture and temperature to assess the current condition of the system.

2. Calculate Relative Saturation (RS%)
Use RS% to understand the true moisture stress on the insulation, not just ppm.

3. Monitor Temperature
Always interpret ppm and RS% in the context of oil temperature.

4. Set Target Moisture Levels
Maintain RS% typically below 30–40% under normal operating temperature.

5. Apply Continuous Moisture Management
Use online solutions (e.g., DryTrans) to continuously remove moisture and maintain equilibrium shift.

6. Track Trends, Not Just Values
Trending data over time provides early indication of moisture ingress or system changes.

Figure 16: Recommended Moisture Control Strategy

Parameter	What It Indicates	Recommended Approach	Target / Guideline
Oil Moisture (ppm)	Current moisture in the oil	Monitor continuously	As low as practically achievable
Relative Saturation (RS%)	Moisture stress on insulation	Keep under control	< 30–40% (under normal temperature)
Temperature (°C)	Affects oil's ability to hold moisture	Monitor continuously	Record and analyze trends
Moisture Management	Ensures equilibrium is maintained	Apply continuously (online system)	Continuous operation
Trend Analysis	Early warning of moisture risk	Review trends regularly	Look for increasing trends

The goal is not zero moisture, but a stable equilibrium that minimizes insulation aging and failure risk.

Figure 17: Decision Framework for Moisture Management

1. **Measure Oil Moisture and Temperature** — Gain accurate current data.
2. **Calculate Relative Saturation (RS%)** — Understand true moisture stress.
3. **Evaluate Trends** — Identify rising or stable moisture trend.
4. **Decide Action** — Maintain, manage, or investigate.
5. **Implement Continuous Moisture Management** — Maintain equilibrium and reduce risk.

A data-driven approach ensures the right actions are taken at the right time to protect the insulation.

Key Takeaways

- Oil moisture (ppm) alone does not tell the full story—RS% and temperature matter.
- Keep RS% below 30–40% under normal operating temperature.
- Continuous online moisture management maintains equilibrium shift.
- Lower and stable moisture significantly reduces insulation aging and extends transformer life.
- Monitor, understand, act, and maintain—that is the key to moisture control.

Key Message

Understand the equilibrium. Monitor the right parameters.
Maintain the driving force. Protect the insulation.

Continuous moisture management is the most effective way to ensure long-term transformer reliability and performance.