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Moisture Under Control.
Reliability Assured.

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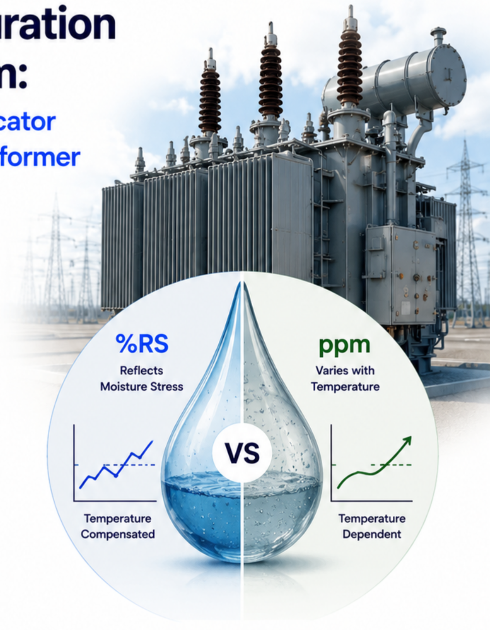
Relative Saturation (%RS) vs ppm:

Which Moisture Indicator Really Reflects Transformer Insulation Risk?



Moisture is the most critical and most manageable factor influencing transformer insulation health.

However, not all moisture indicators are created equal.

While oil moisture in ppm has traditionally been used for decades, Relative Saturation (%RS) provides a more accurate and consistent indication of the true moisture stress experienced by the insulation system.

This paper explains the differences, compares various moisture measurement approaches, and reveals which indicator best reflects insulation condition and risk.

- Understand Moisture Behavior
- Compare Moisture Indicators
- Improve Insulation Reliability
- Make Smarter Decisions
- Extend Asset Life and Value

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Executive Summary

The Moisture Measurement Challenge

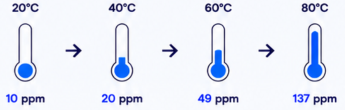
Moisture is one of the most influential factors affecting transformer insulation life, dielectric performance, and reliability. Yet despite decades of oil testing, many transformer maintenance decisions are still based solely on moisture concentration expressed in parts per million (ppm).

The challenge is that ppm does not directly represent insulation stress.

A transformer may show 10 ppm at 20°C, 50 ppm at 60°C, or 130 ppm at 80°C while the actual moisture content within the paper insulation remains nearly unchanged. This occurs because the water-holding capacity of oil increases significantly with temperature. As the transformer warms up, moisture migrates from paper into oil, causing ppm values to rise naturally.

Figure 1 – The Moisture Measurement Problem

Same Transformer
Same Total Moisture
Different Temperature



Has the transformer become wetter?

No.

The moisture has simply redistributed between paper and oil.

Why Relative Saturation Was Introduced

Relative Saturation (%RS) was developed to address the limitations of ppm measurements.

Instead of measuring only the amount of water present, %RS measures:
How close the oil is to its moisture carrying capacity at the current temperature.

This provides a direct indication of moisture stress and the likelihood of water-related insulation problems.

Figure 2 – PPM vs Relative Saturation

Parameter	ppm	%RS
Temperature Sensitive	✗ Very High	✓ Low
Indicates Moisture Stress	○ Limited	✓ Excellent
Suitable for Trending	○ Moderate	✓ Excellent
Reflects Water Activity	✗ No	✓ Yes
Better Correlation to Insulation Condition	○ Limited	✓ High

Key Questions This White Paper Answers

- Why does oil moisture increase with temperature?
- Why can a transformer show high ppm but still be relatively dry?
- Why is Relative Saturation often more meaningful than ppm?
- What are the strengths and limitations of moisture assessment methods?
- Which moisture indicator best reflects insulation risk?

Key Message

Moisture concentration (ppm) tells us how much water is dissolved in the oil.

Relative Saturation (%RS) tells us how close the insulation system is to moisture-related stress and failure mechanisms.

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Where Moisture Actually Lives

Most Moisture Is Hidden in the Paper Insulation

Understanding moisture distribution is essential before interpreting any moisture measurement.

One of the most common misconceptions in transformer maintenance is that moisture exists primarily in the oil.

In reality, the oil serves mainly as a transport medium, while the cellulose insulation acts as the primary moisture reservoir.

Studies and field experience show that:

- Oil may represent approximately 90% of the insulation system by volume.
- However, nearly all moisture is stored within the cellulose insulation.
- Typically, more than 95–99% of the total moisture inventory resides in paper and pressboard insulation.

This explains why significant changes in oil moisture can occur without substantial changes in paper moisture content.

Figure 3

Insulation Weight Distribution

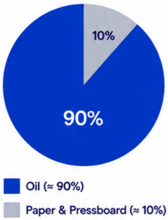
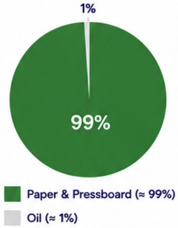


Figure 4

Moisture Distribution



Why This Matters

If a transformer contains:

- 15 kg of water in paper insulation
- 0.2 kg of water in oil

Removing moisture from the oil alone does not immediately dry the transformer.

As soon as oil becomes drier, moisture begins migrating from paper back into the oil until a new equilibrium is established.

This is the fundamental reason why:

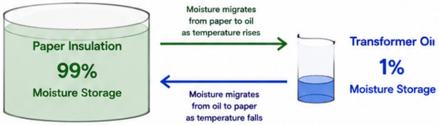
- Moisture rebounds after dehydration
- Oil ppm changes with temperature
- Long-term drying requires equilibrium management

Key Insight

Oil tells us what moisture is doing **now**.

Paper determines the **long-term** insulation condition.

Figure 5 Moisture Reservoir Concept



Bottom-Line Message

Moisture measurements taken in oil provide valuable information, but they **represent only a small fraction of the moisture actually present in the transformer insulation system.**

Why ppm Alone Can Be Misleading

Oil Moisture Varies Dramatically with Temperature

Oil can dissolve more water as temperature increases. As the transformer warms up, moisture migrates from the paper insulation into the oil. This natural behavior causes ppm values to rise significantly—even though the actual moisture content in the paper remains almost unchanged.

A single ppm value cannot indicate the true moisture stress on the insulation system without considering temperature.

The Reality

In the example shown, oil ppm increases more than 13 times as temperature rises from 20 °C to 80 °C, while the paper moisture remains essentially constant.

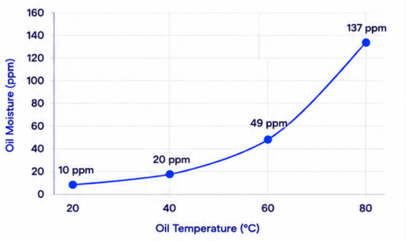
High ppm does not always mean the transformer is wet.
It may simply be the result of higher temperature and increased oil solubility.

Figure 4 – Example: Oil Moisture vs Temperature

Oil Temperature (°C)	Oil Moisture (ppm)	Relative Saturation (%RS)
20	10	18%
40	20	16%
60	49	20%
80	137	30%

Note: Paper moisture remains approximately constant while oil ppm increases with temperature.

Figure 5 – Oil Moisture (ppm) vs Temperature



As temperature increases, oil can hold more moisture. › Moisture moves from paper into oil to maintain equilibrium. › Result: Higher ppm, same paper moisture.

PPM follows temperature.
Relative Saturation (%RS) follows moisture stress.

For meaningful interpretation, moisture measurements must be evaluated in the context of temperature and expressed as Relative Saturation.

Key Tnsight

Look beyond ppm.
Understand moisture stress.
Use %RS for better decisions.

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What Is Relative Saturation (%RS)?

Relative Saturation (%RS) is a temperature-compensated moisture indicator that shows how close the oil is to its maximum water-holding capacity at a given temperature.

Instead of looking only at how much water is present (ppm), %RS tells us how much more water the oil can still hold before reaching saturation.

This provides a direct indication of moisture stress on the insulation system.

> %RS is not just about the quantity of water, it is about the potential for moisture-related problems.

Figure 6 – Relative Saturation (%RS) Formula

Relative Saturation (%RS)

$$\%RS = \frac{C_w}{C_{w,sat}} \times 100$$

Where:

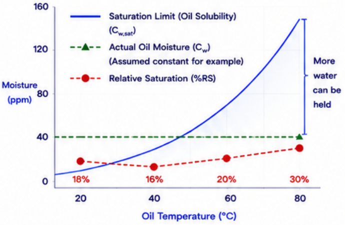
C_w = Actual water content in the oil (ppm)

$C_{w,sat}$ = Maximum water solubility of oil at that temperature (ppm)

> %RS is expressed as a percentage (0–100%). Higher %RS means the oil is closer to saturation and the insulation is under higher moisture stress.

Figure 7 – How %RS Works

Oil can hold more water as temperature increases.
%RS normalizes this effect.



> The same amount of water results in different ppm values at different temperatures, but %RS remains within a narrower and more meaningful range.

Figure 8 – Why %RS Is More Meaningful

Temperature Compensated
Removes the strong temperature dependency inherent in ppm measurements.

Indicates Moisture Stress
Shows how close the oil is to saturation, which drives moisture migration and risk.

Better for Trending
Provides consistent trends across seasons, loads and operating conditions.

Correlates with Insulation Condition
%RS correlates better with paper moisture, aging and dielectric performance.

Improves Decision Making
Helps utilities prioritize moisture management actions based on real insulation risk.

Key Takeaway

ppm tells us how much water is in the oil.
%RS tells us how close the system is to a moisture problem.

Use %RS to understand moisture stress.
Use ppm to understand moisture quantity.

Why %RS Is More Meaningful Than ppm

%RS Follows Moisture Stress. ppm Follows Temperature.

Oil moisture in ppm can change dramatically with temperature even when the actual moisture content in the insulation remains nearly unchanged.

Relative Saturation (%RS) compensates for temperature by comparing the actual water content to the oil's maximum water solubility at that temperature.

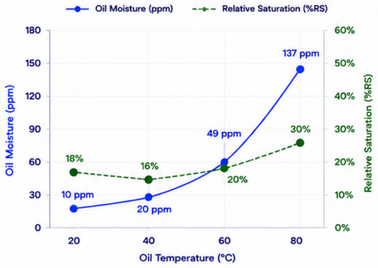
As a result, %RS remains relatively stable and provides a truer indication of moisture stress on the insulation.

Figure 7 – %RS vs ppm Across Temperature

Oil Temperature (°C)	Oil Moisture (ppm)	Relative Saturation (%RS)	Interpretation
20	10	18%	Normal moisture stress
40	20	16%	Normal moisture stress
60	49	20%	Normal moisture stress
80	137	30%	Approaching moisture stress

While ppm increases more than 13 times from 20°C to 80°C, %RS changes only modestly.
%RS reflects insulation stress; ppm reflects temperature.

Figure 8 – Comparison: ppm vs %RS



ppm is highly temperature dependent.
%RS normalizes this effect and is a better indicator of moisture stress.

Key Advantages of Using %RS

Temperature Compensated
%RS accounts for temperature's effect on oil's water solubility, removing a major source of misinterpretation.

Reflects True Moisture Stress
Indicates how close the oil and insulation system is to saturation, which drives moisture migration and related risks.

Better for Trending
Provides consistent trends across seasons, loads, and operating conditions.

Correlates with Insulation Condition
Better correlation with paper moisture, aging rate, dielectric strength, and failure mechanisms.

Improves Decision Making
Helps utilities prioritize moisture management actions based on real risk, not temperature influence.

Key Takeaway

ppm tells you how much water is in the oil.
%RS tells you how close the system is to moisture-related problems.

Use %RS to assess moisture stress.
Use ppm to assess moisture quantity.

Comparing Moisture Assessment Methods

Different Methods, Different Answers

Moisture in transformer insulation can be assessed using several methods. Each method has its own principles, strengths, and limitations.

Understanding the differences helps in selecting the right approach and interpreting results correctly.

> **There is no single number for moisture.**
> Different methods answer different questions.

> The right interpretation comes from using the right method for the right purpose.

Figure 9 – Moisture Assessment Methods

Method	What It Measures	How It Works	Key Strength	Limitations
1 Oil ppm + Equilibrium Charts	Moisture in oil (ppm)	Compares oil ppm with equilibrium charts to estimate paper moisture	Simple, widely used	Highly dependent on temperature, assumes equilibrium
2 Relative Saturation (%RS)	Moisture stress (% of saturation)	Temperature-compensated indicator of moisture stress	Accounts for temperature, better indicator of stress	Requires accurate temperature measurement
3 FDS / PDC	Dielectric response	Measures polarization currents to infer moisture in paper	On-line capability (with sensors)	Influenced by temperature, oil conductivity
4 Direct Paper Sampling (Karl Fischer)	Actual moisture in paper (%)	Laboratory measurement of water in paper	Most direct and accurate	Off-line, intrusive, not always practical
5 DFR (Frequency Response)	Insulation frequency response	Analyzes frequency response to estimate moisture in paper	Good for trending and condition assessment	Requires baseline and advanced analysis

Figure 10 – Accuracy Ranking vs Direct Paper Moisture (Karl Fischer)

Based on comparative studies and field experience, the following ranking shows how closely each method correlates with actual paper moisture measured by Karl Fischer analysis.

(1 = Closest correlation)

Ranking	Method	Correlation with KF Paper Moisture	
1	Relative Saturation (%RS)	Closest	★★★★★
2	FDS / PDC	Very Good	★★★★☆
3	Oil ppm + Equilibrium Charts	Good	★★★☆☆
4	DFR (Frequency Response)	Fair	★★☆☆☆
5	Oil ppm (ppm Only)	Lowest	★☆☆☆☆

Relative Saturation (%RS) shows the closest correlation with actual paper moisture because it compensates for temperature and reflects true moisture stress in the insulation system.

Key Takeaway

- Each method views moisture from a different perspective.
- Temperature compensation is critical for meaningful results.
- Methods are complementary, not competitive.
- Interpretation is as important as measurement.

Best Practice

- Use %RS as the primary moisture stress indicator.
- Confirm trends with FDS/PDC or DFR.
- Use equilibrium charts with caution.
- Validate periodically with paper sampling when possible.

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Interpreting Results
ppm vs %RS

Understanding the difference in what ppm and %RS represent is essential for accurate assessment of insulation condition and risk.

The table alongside illustrates how the same transformer can show very different ppm values with temperature, while %RS provides a consistent view of moisture stress.

Figure 11 – Interpreting Moisture Results: ppm vs %RS

Oil Temperature (°C)	Oil Moisture (ppm)	Relative Saturation (%RS)	Moisture Stress	Interpretation
20	10	18%	Low	Dry condition
40	20	16%	Low	Dry condition
60	49	20%	Low	Dry condition
80	137	30%	Moderate	Approaching moisture stress

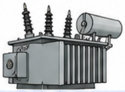
ppm increases with temperature because oil can hold more water.
%RS changes only when moisture stress on the insulation changes.

Key Takeaway

Use ppm to understand moisture quantity in oil.

Use %RS to understand moisture stress on the insulation system.

Figure 12 – Same Transformer, Different Temperature

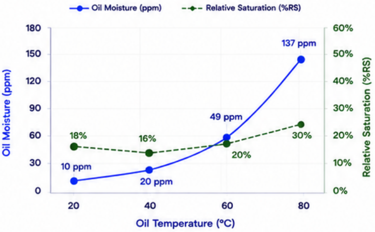


Same Transformer
Same Total Moisture
Different Temperature

Temperature (°C)	Oil Moisture (ppm)	Relative Saturation (%RS)
20	10	18%
40	20	16%
60	49	20%
80	137	30%

Oil moisture (ppm) varies significantly.
%RS remains within a narrow range until moisture stress begins to increase.

Figure 13 – Oil Moisture (ppm) and %RS vs Temperature



ppm rises sharply with temperature.
%RS stays relatively stable and shows true moisture stress.

Conclusion

To make informed decisions about transformer insulation health, both ppm and %RS should be measured and evaluated together.

ppm shows how much moisture is present.
%RS shows how serious the moisture problem is.

Best Practice

- Measure ppm and %RS together.
- Always consider temperature.
- Track trends, not single readings.
- Use %RS to assess moisture stress and risk.
- Validate with other tests and condition assessment.

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Oil–Paper Equilibrium: The Key to Understanding Moisture Behavior

Transformer insulation is a dynamic system. Moisture continuously migrates between the paper and the oil until equilibrium is reached at a given temperature and moisture stress.

Oil moisture reflects the current condition, but paper moisture determines the long-term insulation health.

Key Takeaway

- Oil can only hold a small amount of moisture compared to paper.
- When oil is dried, moisture moves from paper to oil until a new equilibrium is established.
- Sustained drying requires lowering the overall moisture content in the paper.

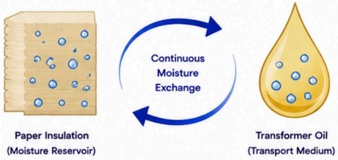
What Drives Moisture Migration?

Temperature Change
Higher temperature reduces oil's ability to hold moisture, causing moisture to move from paper to oil.

Humidity Ingress
Moisture entering through breathers or leakages increases the overall moisture content.

Change in Moisture Gradient
Moisture always moves from high concentration (paper) to low concentration (oil).

Figure 14 – Oil–Paper Equilibrium Concept



At equilibrium, the oil holds the maximum moisture it can dissolve at that temperature, and the paper holds the remaining moisture.

Implications for Transformer Reliability

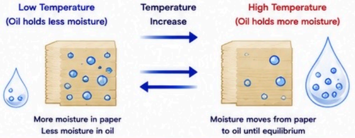
Moisture Rebound
After oil drying, moisture can quickly return from paper to oil if equilibrium is not managed.

Dynamic with Operating Conditions
Load, temperature, and environment constantly shift the equilibrium point.

Paper Moisture is the Long-Term Indicator
Oil readings alone cannot reveal the true moisture content stored in the paper.

Equilibrium Must Be Managed Continuously
Effective moisture control focuses on reducing paper moisture over time.

Figure 15 – Moisture Migration with Temperature Increase



Why %RS Is Critical in Equilibrium Analysis

- %RS accounts for the oil's water-holding capacity at the actual operating temperature.
- It indicates how close the system is to moisture-related stress, not just how much water is present.
- It helps detect early signs of stress before moisture reaches critical levels.
- It enables better decisions for drying, loading, and life management.

Bottom Line

Transformer insulation is a moisture balance system.
Understanding and managing oil–paper equilibrium is essential for accurate assessment, effective drying strategies, and long-term transformer reliability.

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Moisture and Insulation Life: The Real Connection

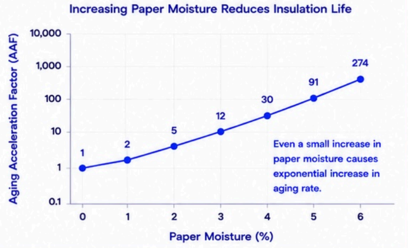
Moisture is the primary driver of insulation aging. Even a small increase in paper moisture can dramatically accelerate the aging rate and reduce the expected insulation life.

Controlling moisture is the most effective way to extend transformer life and improve reliability.

Key Takeaway

- Moisture and temperature multiply the aging rate.
- Higher moisture = faster aging.
- Lowering moisture significantly extends insulation life.

Figure 16 – Aging Acceleration Factor vs Paper Moisture



At 3% paper moisture, aging is 12 times faster.
At 5% paper moisture, aging is 91 times faster.

Figure 17 – Estimated Insulation Life vs Paper Moisture (At 90°C Hot-Spot Temperature)

Paper Moisture (%)	Aging Acceleration Factor (AAF)	Estimated Insulation Life (Relative to Dry Paper)
0 (Dry)	1	100% (Baseline)
1%	2	50%
2%	5	20%
3%	12	8%
4%	30	3% %
5%	91	1.1%
6%	274	34 0.4%

Insulation life reduces exponentially as paper moisture increases. Controlling moisture is the most effective way to extend life.

Factors That Increase Aging Rate

Higher Moisture Content	More water in paper accelerates cellulose hydrolysis.
Higher Temperature	Every 6°C increase approximately doubles the aging rate.
Higher Load	Increased load raises hot-spot temperature and speeds aging.
Oxygen Presence	Oxygen reacts with oil and paper, accelerating degradation.
Acidity & By-products	Acids and by-products from aging further degrade insulation.

Best Practice

- Keep paper moisture as low as practical.
- Maintain oil-paper equilibrium at safe levels.
- Control temperature and loading.
- Use continuous moisture management.
- Monitor trends, not just single test results.

Bottom Line

Moisture is the single biggest factor that determines insulation life.
Lower moisture = lower aging rate.
Lower aging rate = longer life, higher reliability, lower life-cycle cost.

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