drytrans

QUICK FACTS

MOISTURE IN TRANSFORMER OIL & PAPER INSULATION

Moisture is the primary driver of insulation aging and failure risk in power transformers. Understanding moisture behavior is essential for reliable operation, life extension and asset protection.

30 ESSENTIAL QUICK FACTS

1 Moisture is the primary aging accelerator.

Moisture, together with temperature and oxygen, significantly accelerates cellulose hydrolysis and reduces insulation life.

Ref: IEEE C57.91; EPRI; Oommen

2 Most moisture resides in paper insulation.

Typically more than 95–99% of total transformer moisture is contained within the cellulose insulation system.

Ref: Oommen, IEEE Electrical Insulation Magazine; CIGRÉ TB 349

3 Oil moisture measurements represent only a small portion of total moisture.

Oil acts primarily as a transport medium for moisture moving to and from the paper insulation.

Ref: Oommen; Koch & Tenbohlen

4 Relative Saturation (%RS) is more meaningful than ppm.

The same oil moisture level (ppm) can represent very different moisture risks depending on oil temperature.

Ref: IEC 60422; Vaisala

5 Water solubility in oil increases with temperature.

As oil temperature rises, oil can dissolve significantly more moisture.

Ref: IEC 60422; USBR 3-31; Lewand

6 Moisture migrates continuously between paper and oil.

Transformer insulation is a dynamic moisture equilibrium system.

Ref: Oommen; CIGRÉ TB 349

7 Drying oil does not immediately dry paper.

Moisture removal from cellulose is a slow diffusion-controlled process.

Ref: CIGRÉ TB 741; Koch & Tenbohlen

8 Moisture reduces dielectric strength.

Increasing moisture reduces Breakdown Voltage (BDV) and insulation withstand capability.

Ref: IEC 60156; IEC 60422

9 Moisture increases dielectric losses.

High moisture contributes to increased dissipation factor (tan δ) and reduced resistivity.

Ref: IEC 60247

10 Moisture accelerates paper depolymerization.

Cellulose chain scission occurs more rapidly in the presence of moisture.

Ref: IEEE C57.91; EPRI

vishal@drytrans.com | +971506790417 | www.drytrans.com

drytrans

30 ESSENTIAL QUICK FACTS

Moisture in Transformer Oil & Paper Insulation

FACTS 11–20 | FAILURE MECHANISMS & IMPACTS

11

Every increase in moisture significantly reduces insulation life.

Aging studies demonstrate that increasing paper moisture substantially accelerates aging rate and shortens remaining life.

Ref: EPRI Transformer Aging Studies; IEEE C57.91; Oommen

12

Moisture and oxygen together create a destructive aging cycle.

Oxidation products generate acids which attack cellulose and further accelerate degradation.

Ref: IEC 61125; CIGRÉ Aging Studies

13

Moisture contributes to sludge formation.

Oxidation by-products from wet insulation form acids, sludge and varnish which impair cooling and insulation performance.

Ref: IEC 61125; IEC 60422

14

Moisture is one of the most significant contributors to transformer failures.

Moisture related insulation degradation is a leading cause of dielectric failure and loss of reliability.

Ref: CIGRÉ TB 761; IEEE C57.143

15

Free water is extremely dangerous.

When oil approaches saturation, free water can precipitate or form emulsions, causing severe reduction in dielectric strength.

Ref: IEC 60422; Vaisala Technical Papers

16

Moisture increases partial discharge susceptibility.

Wet insulation exhibits higher PD activity, lower inception voltage and higher risk of insulation breakdown.

Ref: CIGRÉ TB 444; IEEE Electrical Insulation Magazine

17

Moisture increases bubbling risk.

Wet cellulose can generate vapor bubbles during overloads, faults or rapid temperature rise causing mechanical damage and failure.

Ref: IEEE C57.91; CIGRÉ TB 324

18

Bubble formation can occur well below oil boiling temperature.

Localized hot spots and wet paper insulation can initiate vapor bubble generation at much lower temperatures.

Ref: IEEE C57.91 Loading Guide

19

Transformer insulation life is controlled by paper condition.

Cellulose insulation is generally the life-limiting component in power transformers.

Ref: IEEE C57.91; CIGRÉ TB 761

20

Furan analysis is an indirect indicator of paper degradation.

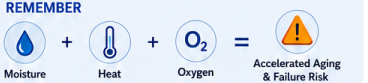
Furans are generated from cellulose decomposition and correlate with insulation aging and remaining life.

Ref: IEC 61198

KEY MESSAGE

Moisture is not just water in oil.
It is the primary driver of insulation aging, dielectric weakness and transformer failures.

REMEMBER



vishal@drytrans.com | +971506790417 | www.drytrans.com

drytrans

30 ESSENTIAL QUICK FACTS

Moisture in Transformer Oil & Paper Insulation

FACTS 21–30 | DIAGNOSTICS & ASSET MANAGEMENT

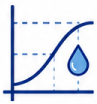
21

Methanol is an early indicator of cellulose degradation.

Methanol generation can occur before significant furan levels are produced.

Ref: CIGRÉ WG D1 Studies; Jalbert et al.

22



DFR/FDS is one of the best methods for estimating paper moisture.

Dielectric Frequency Response directly evaluates moisture in cellulose insulation.

Ref: CIGRÉ TB 414; Koch & Tenbohlen

23

Karl Fischer Titration remains the laboratory reference method.

Karl Fischer titration is the internationally accepted reference method for water determination in transformer oil.

Ref: IEC 60814

24

Online capacitive sensors provide continuous moisture trending.

Online sensors enable real-time monitoring of moisture migration, Relative Saturation and temperature.

Ref: CIGRÉ Moisture Measurement Webinar; Vaisala MHT Guide

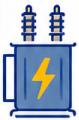
25

Natural ester fluids dissolve significantly more moisture than mineral oil.

PPM values cannot be directly compared between ester and mineral oil transformers.

Ref: IEEE C57.147

26



Moisture limits should be interpreted according to voltage class and criticality.

Higher-voltage transformers require stricter moisture management because dielectric margins are lower.

Ref: IEC 60422; IEEE C57.106

27

Paper moisture classification guides insulation condition.

Paper moisture level is the best indicator of actual insulation wetness and aging risk.

Ref: Oommen; CIGRÉ TB 349; IEEE Industry Guidance

28

Relative Saturation (%RS) classification guides risk level.

%RS indicates how close the oil is to saturation and the risk of free water formation.

Ref: IEC 60422; Vaisala; Lewand

29

Practical moisture targets (ppm) depend on voltage class.

Lower ppm targets are required for higher voltage and more critical transformers.

Ref: Doble Engineering Moisture Guidelines; Lewand; Utility Practice Documents

30

Continuous moisture management is more effective than periodic drying.

It controls moisture migration from paper insulation throughout the year and extends insulation life.

Ref: Oommen Equilibrium Theory; CIGRÉ Moisture Management Studies

EXECUTIVE SUMMARY

Moisture is the single most important factor affecting transformer insulation life. It drives aging, reduces dielectric strength and increases failure risk.

Measure it, understand it, manage it – continuously.

- Know your **moisture**
- Understand **the trend**
- Control **the source**
- Extend **the life of your asset**

vishal@drytrans.com | +971506790417 | www.drytrans.com

drytrans

30 ESSENTIAL QUICK FACTS

Moisture in Transformer Oil & Paper Insulation

MOISTURE REFERENCE & INTERPRETATION GUIDE

PAPER MOISTURE CLASSIFICATION [1]

Paper Moisture (%)	Interpretation
< 1%	Very Dry
1 – 2%	Dry
2 – 3%	Acceptable
3 – 4%	Wet
> 4%	Very Wet

Paper moisture is strongly temperature dependent and should be based on temperature-corrected estimation (DFR/FDS or equilibrium methods).

RELATIVE SATURATION (%RS) CLASSIFICATION [2]

Relative Saturation (%RS)	Interpretation
< 10%	Very Dry
10 – 20%	Good
20 – 30%	Monitor
30 – 50%	Elevated Risk
50 – 80%	High Risk
> 80%	Very High Risk

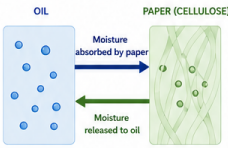
RS > 30% generally indicates elevated risk of free water formation and reduced dielectric performance.

PRACTICAL MOISTURE TARGETS (MINERAL OIL) [3]

Voltage Class	Moisture in Oil (ppm) at Operating Temp.
Distribution (≤ 33 kV)	< 20 ppm
69 – 132 kV	< 15 ppm
230 kV	< 12 ppm
345 – 500 kV	< 10 ppm
765 kV and above	< 10 ppm

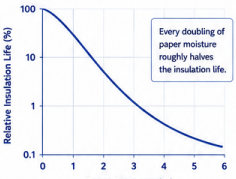
Targets are practical field guidance and must be evaluated with transformer temperature, loading, age, oil type and criticality.

OIL–PAPER MOISTURE EQUILIBRIUM



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

EFFECT OF MOISTURE ON INSULATION LIFE [4]



Ref: EPRI; IEEE C57.91; Oommen

TYPICAL OIL MOISTURE SOLUBILITY INCREASES WITH TEMPERATURE [5]

Temperature (°C)	Max. Water Solubility (ppm) in Mineral Oil
20	18
40	36
60	72
80	129

As temperature increases, oil can dissolve significantly more water. Therefore, ppm values must always be interpreted at operating temperature.

REFERENCES

1. **IEC 60422**: Mineral insulating oils in electrical equipment
2. **IEC 60814**: Determination of water by Karl Fischer titration
3. **IEC 60156**: Insulating liquids – Determination of breakdown voltage
4. **IEC 60247**: Measurement of relative permittivity, dissipation factor and resistivity
5. **IEC 61198**: Mineral insulating oils – Determination of furanic compounds
6. **IEEE C57.91**: Guide for Loading Mineral-Oil-Immersed Transformers
7. **IEEE C57.106**: Guide for Acceptance and Maintenance of Insulating Oil in Equipment
8. **IEEE C57.143**: Guide for Transformer Condition Assessment
9. **IEEE C57.147**: Guide for Acceptance and Maintenance of Natural Ester Fluids
10. **CIGRÉ TB 349**: Moisture Equilibrium and Moisture Assessment in Transformers
11. **CIGRÉ TB 414**: Dielectric Response Methods for Moisture in Power Transformers
12. **CIGRÉ TB 444**: Partial Discharges in Power Transformers
13. **CIGRÉ TB 761**: Condition Assessment of Power Transformers
14. **T.V. Oommen**: Moisture Equilibrium in Paper-Oil Insulation Systems
15. **Koch & Tenbohlen**: Moisture Assessment in Power Transformers Using Dielectric Response
16. **Lance Lewand**: Understanding Water in Transformer Systems
17. **EPRI**: Transformer Life Management and Aging Studies
18. **Vaisala**: Moisture in Transformer Oil – Technical Guide
19. **Jalbert et al.**: Methanol as an Early Indicator of Cellulose Aging

KEY TAKEAWAYS

- Moisture is the primary driver of insulation aging and failure.
- Control moisture to maintain dielectric strength, reliability and asset life.
- Use trends, not single readings. Understand the behavior.
- Moisture behavior depends on temperature, load and environment.
- Continuous moisture management is the most effective strategy for long-term insulation health.

IMPORTANT: All moisture limits and interpretations must be evaluated with transformer temperature, loading, age, oil type, design, insulation system and criticality. This guide provides general industry guidance and is not intended to replace manufacturer recommendations or engineering judgment.

Know your moisture. Manage it. Extend life.

vishal@drytrans.com | +971506790417 | www.drytrans.com