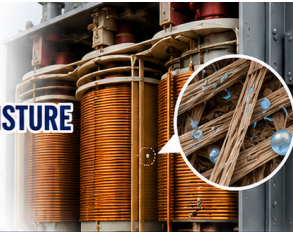


AGING AND DEGRADATION OF TRANSFORMER INSULATION DUE TO MOISTURE

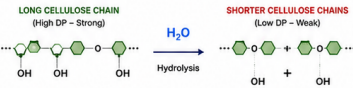
HOW MOISTURE AGES CELLULOSE INSULATION

Cellulose insulation (paper and pressboard) forms the backbone of transformer insulation. When moisture is present, it reacts with cellulose at the molecular level, causing irreversible chemical changes that reduce mechanical strength and shorten insulation life.



1. HYDROLYSIS OF CELLULOSE – THE PRIMARY AGING MECHANISM

Water molecules attack the β -1,4-glycosidic bonds in cellulose chains. This hydrolysis reaction breaks the long polymer chains into shorter fragments, reducing the Degree of Polymerization (DP).



Hydrolysis is the dominant chemical reaction responsible for cellulose aging in transformers.

2. FACTORS THAT ACCELERATE CELLULOSE AGING

The rate of hydrolysis increases exponentially with:

- MOISTURE** (Water drop icon): More moisture = faster hydrolysis (most critical factor)
 - TEMPERATURE** (Thermometer icon): Rule of thumb: Every 6°C rise approximately doubles the aging rate.
 - OXYGEN** (O₂ icon): Promotes oxidation, acid formation and further cellulose degradation.
- Moisture + Heat + Oxygen = Accelerated Aging** (Target icon)

3. REDUCTION IN DEGREE OF POLYMERIZATION (DP)

DP is the most widely used indicator of cellulose insulation aging. As DP decreases, the mechanical strength of paper deteriorates.

DP VALUE	INSULATION CONDITION	INSULATION LIFE
> 1000	New (Un-aged)	
800 – 1000	Good / Healthy	
500 – 800	Moderate Aging	
300 – 500	End-of-Life Approaching	
< 300	High Risk of Failure	

4. CHEMICAL BY-PRODUCTS OF AGING

Moisture accelerates the formation of acidic and furanic compounds, which further catalyze insulation degradation.



ACID FORMATION

Increases acidity (TAN), promoting hydrolysis and corrosion.



FURAN FORMATION

2-FAL and other furans indicate paper deterioration and life consumption.



SLUDGE FORMATION

Degraded cellulose produces sludge, reducing cooling efficiency.



GAS FORMATION

CO, CO₂ and other gases are released as cellulose degrades.



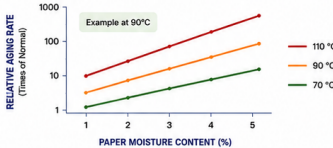
These by-products create a self-accelerating aging cycle.

5. MOISTURE-AGING RELATIONSHIP (EXAMPLE)

Below is a typical relationship between paper moisture content, temperature and relative aging rate.



Even a small increase in paper moisture content can dramatically increase the aging rate. Controlling moisture is controlling aging.



KEY FACT

Once cellulose chains are broken, the lost DP and strength cannot be regenerated. Therefore, preventing moisture ingress and managing moisture is the only way to preserve insulation life and reliability.



KEY TAKEAWAY

Moisture initiates hydrolysis, reduces DP, weakens cellulose and accelerates chemical degradation. This cumulative effect leads to loss of insulation integrity and premature transformer failure.



MOISTURE-INDUCED HYDROLYSIS AND CELLULOSE AGING

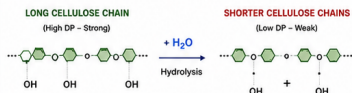
How water molecules break cellulose chains and reduce insulation life

The cellulose insulation in transformers (paper and pressboard) is a long-chain polymer. Moisture acts as a catalyst for hydrolysis, breaking these chains and reducing the Degree of Polymerization (DP). This reduces mechanical strength, increases brittleness and shortens insulation life.



1. HYDROLYSIS MECHANISM – THE ROOT CAUSE

Water molecules attack the β -1,4-glycosidic bonds in cellulose chains. This hydrolysis reaction breaks the long polymer chains into shorter fragments.



Hydrolysis is the dominant chemical reaction responsible for cellulose aging in transformers.

2. FACTORS THAT ACCELERATE HYDROLYSIS AND AGING

The rate of cellulose hydrolysis increases exponentially with the following factors.

- MOISTURE**
 - More moisture = faster hydrolysis
 - Most critical factor
 - TEMPERATURE**
 - Every 6 °C rise approximately doubles the aging rate
 - High hot-spot temperature greatly accelerates aging
 - OXYGEN**
 - Promotes oxidation
 - Increases acid and sludge formation, further accelerating aging
- Moisture + Heat + Oxygen = Accelerated Cellulose Aging

3. REDUCTION IN DEGREE OF POLYMERIZATION (DP)

DP indicates the average length of cellulose chains. As DP decreases, insulation strength deteriorates.

DP VALUE	INSULATION CONDITION	INSULATION LIFE
> 1000	New (Un-aged)	 Long Life Short Life
800 – 1000	Good / Healthy	
500 – 800	Moderate Aging	
300 – 500	End-of-Life Approaching	
< 300	High Risk of Failure	



Once DP is lost, it cannot be restored. Aging is irreversible.

4. CHEMICAL BY-PRODUCTS OF CELLULOSE AGING

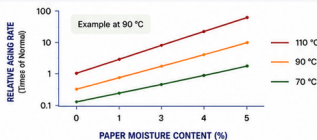
Moisture-accelerated reactions produce by-products that further degrade insulation.

- FURAN FORMATION**
2-FAL and related furans indicate paper deterioration and life consumption.
- ACID FORMATION**
Increases acidity (TAN), leading to corrosion and catalyzing further hydrolysis.
- SLUDGE FORMATION**
Degraded cellulose produces sludge, reducing cooling efficiency.
- GAS FORMATION**
CO, CO₂, and other gases are released as cellulose degrades.



These by-products create a self-accelerating aging cycle that continuously weakens insulation.

5. MOISTURE CONTENT AND AGING RATE – TYPICAL RELATIONSHIP



Even a small increase in paper moisture content can dramatically increase the aging rate.

Controlling moisture is controlling aging.

KEY TAKEAWAY

- Moisture causes hydrolysis, breaking cellulose chains.
- Lower DP = lower strength and shorter insulation life.
- Heat and oxygen multiply the damage.
- Controlling moisture is the most effective way to slow insulation aging.



Moisture is the primary driver of cellulose aging and transformer life.



Understand Moisture



Monitor Continuously



Manage Proactively

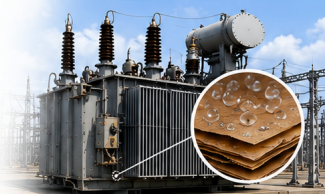


Extend Transformer Life

OPERATIONAL CONSEQUENCES OF MOISTURE IN TRANSFORMER INSULATION

How moisture compromises performance, increases risk and leads to premature failures.

Moisture affects both the dielectric performance and the mechanical integrity of insulation. It also increases the risk of electrical failures and reduces overall reliability.



1. MOISTURE MIGRATION IN THE OIL-PAPER SYSTEM

Moisture continuously moves between paper and oil depending on temperature, load and humidity.

MOISTURE (H₂O)

PAPER / CELLULOSE (Major moisture reservoir) ↔ OIL (Minor moisture reservoir)

→ Moisture migration
--> Influencing factors

Temperature Load Humidity Time

i Therefore, a single oil test is only a snapshot. Trend analysis is the real indicator of insulation condition.

2. BUBBLE FORMATION RISK

At high temperature, moisture in paper vaporizes and can form bubbles in the insulation system.

Moisture in paper → Vaporization (High temperature) → Bubble in insulation → Possible consequences

Flashover
Dielectric failure
Catastrophic outage

! Moisture + High temperature = Bubble risk
One of the leading causes of catastrophic transformer failures.

3. PARTIAL DISCHARGE (PD) RISK

Moisture reduces the inception voltage of partial discharge and accelerates insulation deterioration.

DRY INSULATION: High PD Inception Voltage, Low Risk

WET INSULATION: Low PD Inception Voltage, High Risk

! Increased PD activity leads to carbonization, tracking and accelerated breakdown of insulation.

4. DETERIORATION OF DIELECTRIC PERFORMANCE

As moisture content increases, dielectric performance deteriorates significantly.

PARAMETER	EFFECT OF INCREASING MOISTURE
⚡ Breakdown Voltage (BDV)	↓ Decreases
⚡ Dissipation Factor (tan δ)	↑ Increases
⚡ Resistivity	↓ Decreases
ε Relative Permittivity (ε _r)	↑ Increases

i Reduced dielectric margin increases the probability of electrical failure under stress.

5. REDUCTION IN MECHANICAL STRENGTH

Moisture causes cellulose chains to break (hydrolysis), reducing the mechanical strength of paper and pressboard.

STRONG (DRY) → WEAK (WET / AGED)

! Wet or aged paper cannot withstand short-circuit forces, vibration and thermal stress.

6. OIL-PAPER EQUILIBRIUM AND RELATIVE SATURATION (%RS)

Moisture equilibrium depends on temperature and oil moisture. Relative Saturation (%RS) indicates how close the insulation is to saturation.

%RS RANGE	INSULATION CONDITION	RISK LEVEL
< 60%	Dry / Good	Low
60 – 80%	Moderate	Medium
80 – 95%	High	High
> 95%	Near Saturation	Very High

! Keeping %RS below 60–70% significantly reduces aging rate and failure risk.

KEY MESSAGE

Moisture weakens insulation from every angle—electrical, mechanical and thermal. Controlling moisture is essential to maintain reliability and prevent catastrophic failures.

Understand Moisture

Monitor Continuously

Manage Proactively

Extend Transformer Life

drytrans
Continuous Moisture Management for Transformer Insulation Systems

drytrans

FROM MOISTURE MONITORING TO MOISTURE MANAGEMENT

Controlling the primary driver of insulation aging

Monitoring tells you the current condition.
Managing moisture continuously protects the insulation
and extends transformer life.



1. MOISTURE DIAGNOSTIC TOOLS

A combination of tests provides the most reliable moisture assessment.



**Karl Fischer
(Oil Moisture)**

Direct measurement
of moisture in oil
(ppm)



**Dielectric
Response (FDS/RVM)**

Estimates moisture
in paper using
equilibrium models



**Paper Moisture
(Lab)**

Direct measurement
of moisture in
cellulose (%)



**DGA + Key
Oil Tests**

Support overall
condition and
failure risk
assessment

i No single test is enough.
Use multiple diagnostic methods and trend them over time.

2. MOISTURE ASSESSMENT – OIL PAPER EQUILIBRIUM

Moisture in paper and oil
are in dynamic equilibrium,
influenced by temperature.

Relative Saturation (%RS)
indicates how close the
insulation is to saturation.

$$\%RS = \frac{\text{Actual Oil Moisture (ppm)}}{\text{Saturation Oil Moisture (ppm) at Temp}} \times 100$$

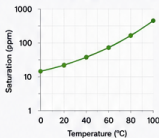
RELATIVE SATURATION (%RS)

%RS < 60%	60 – 80%	80 – 95%	> 95%
Dry / Good	Moderate	High	Near Saturation (Very High Risk)

Saturation Oil Moisture (ppm)
(Typical Mineral Oil)

Temperature (°C)	Saturation (ppm)
20	8.6
30	12.8
40	18.7
50	27.1
60	39.0
70	55.0
80	76.0
90	103.0

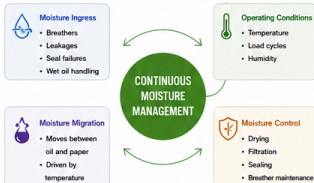
Saturation Oil Moisture vs Temperature



Keeping %RS in the
safe zone (< 60-70%)
significantly reduces
insulation aging
and failure risk.

3. CONTINUOUS MOISTURE MANAGEMENT

Moisture is always trying to enter the transformer.
Continuous management keeps it under control.



✓ Continuous control breaks the aging cycle and preserves insulation life.

4. THE DRYTRANS SOLUTION

Continuous, automatic and intelligent moisture management
for transformer insulation systems.



Continuous Online Drying
Maintains low and stable
moisture levels.

Preserves Insulation Life
Slows aging and extends
transformer life.

Real-time Monitoring
Live data on moisture
and system status.

Automatic Operation
No manual intervention,
24/7 protection.

Lower Risk, Lower Cost
Reduces failures, outages
and maintenance.

☹ DryTrans does not just remove moisture.
It keeps moisture low, all the time.

5. KEY ENGINEERING RECOMMENDATIONS

Test Regularly

- Every 6 months to 1 year
- In different climatic conditions

Track Trends

- Analyze trends, not just snapshots
- Watch %RS, not only ppm

Identify Root Cause

- Find moisture ingress sources
- Fix leaks and seal failures

Maintain Low %RS

- Target < 60-70% %RS
- Lower is better for life

Manage Continuously

- Use online drying solutions
- Make moisture management a continuous process

Protect the Asset

- Moisture control = Life extension
- Reliability starts with dry insulation



Monitoring gives you **visibility**. Management gives you **control**.
Continuous moisture management is the most effective way
to protect transformer insulation and **maximize asset life and reliability**.



REFERENCES AND TECHNICAL SOURCES

TECHNICAL FOUNDATION FOR UNDERSTANDING MOISTURE AND INSULATION AGING IN TRANSFORMERS

The mechanisms, data and recommendations presented in this flyer are based on international standards, technical guides and peer-reviewed literature from leading organizations and industry experts.







These references provide the scientific and engineering foundation for moisture assessment, aging evaluation and moisture management strategies.



1. STANDARDS AND TECHNICAL GUIDES

	IEEE Std C57.106™-2015 IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment	Guidelines for oil testing, moisture limits, and maintenance of insulating oil.
	IEEE Std C57.137™-2017 IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers	Interpretation of dissolved gases analysis (DGA) for fault diagnosis.
	IEC 60422:2013 Mineral insulating oils in electrical equipment – Supervision and maintenance guidance	Guidance on the maintenance of insulating oils including moisture control.
	IEC 60076-14:2018 Power transformers – Part 14: Liquid-immersed power transformers using mineral insulating liquids	Design and performance requirements including insulation and moisture considerations.
	IEC 62899:2015 Mineral insulating oils in electrical equipment – Measurement of water saturation point	Standard method to determine water saturation in insulating oils.
	ASTM D1533 Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration	Standard method for precise measurement of water (ppm) in insulating oils.
	ASTM D2500 Standard Test Method for Insulation Resistance of Insulating Liquids	Measures resistivity of insulating liquids as an indicator of insulation condition.
	CIGRE Technical Brochure 761 (2019) Moisture Equilibrium in Transformer Insulation Systems	Comprehensive treatment of moisture equilibrium in oil–paper insulation systems.
	CIGRE Technical Brochure 349 (2008) Ageing of Cellulose in Mineral-Oil Insulated Transformers	Detailed discussion of cellulose aging mechanisms, including the role of moisture, heat and oxygen.

2. KEY TECHNICAL PUBLICATIONS AND BOOKS

-  Duval, M. (2005)
The Transformer: Aging, Condition Monitoring, Diagnosis and Life Extension – 2nd Edition, CRC Press.
-  Basse, C., Briant, Y., Descloux, J., & Jaya Prakash, O. (2012)
Transformer Insulation Aging – Part I: Accelerated Ageing Tests, IEEE Electrical Insulation Magazine.
-  Liao, R., Ekanayake, C., & Ma, H. (2014)
Review of moisture equilibrium in transformer insulation and evaluation methods, IEEE Transactions on Dielectrics and Electrical Insulation.
-  Tenbohlen, S. (2018)
Moisture in Transformer Insulation: Measurement, Interpretation and Management, CIGRE Workshop.

3. ADDITIONAL RECOMMENDED READING

-  IEC 60599:2021 – Mineral insulating oils in electrical equipment – Measurement of relative permittivity, dielectric dissipation factor (tan δ) and DC resistivity.
-  IEC 61198:2017 – Method for determination of 2-furfural and related compounds in insulating liquids.
-  IEEE C57.92™-2011 – IEEE Guide for Loading Mineral-Oil-Immersed Transformers.
-  EPRI Technical Update: Moisture Control in Power Transformers – Best Practices for Reliability.
-  National Grid ESO – Transformer Moisture Guidance Notes.



Reliable data. Sound standards. Smarter decisions.

Understanding moisture and its impact on insulation aging is the first step.

Managing it effectively is the key to a longer, safer and more reliable transformer life.