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TRANSFORMER FAILURE MECHANISMS

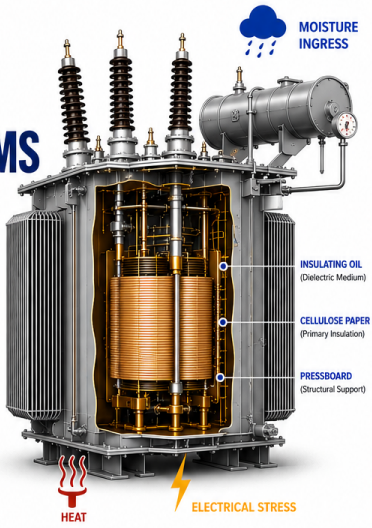
DUE TO INSULATION SYSTEM

IN COMPARISON WITH OTHER FACTORS DUE TO MOISTURE

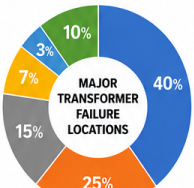
Transformer reliability depends primarily on the health of its insulation system—cellulose paper, pressboard and insulating oil. Although failures can occur for many reasons, international surveys consistently show that components related to insulation and insulation performance are among the most significant contributors to transformer outages.

Moisture does not act alone. It accelerates almost every major degradation mechanism in the insulation system—reducing life expectancy and increasing the risk of failure.

> **Moisture is not always the root cause, but it is the most influential accelerator** of transformer insulation failure.



TYPICAL MAJOR FAILURE LOCATIONS*
(BASED ON INTERNATIONAL SURVEYS)

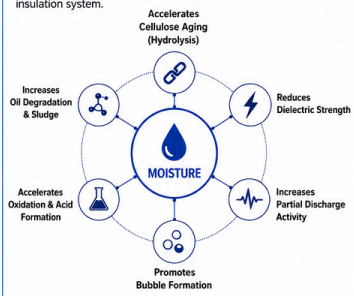


* Source: CIGRÉ Reliability Survey and related reports (ISH/2017/598, CIGRÉ TB 761, and other utility studies).
Percentages vary with design, voltage class, age and operating conditions.

Windings & insulation system related failures represent the single largest contributor to major transformer outages.

WHY MOISTURE IS THE MOST INFLUENTIAL ACCELERATOR

Moisture interacts with heat, oxygen and electrical stress to accelerate nearly every degradation mechanism in the insulation system.



KEY MESSAGE

Moisture is one of the few factors that simultaneously accelerates chemical, electrical, thermal and mechanical degradation mechanisms. Controlling moisture is therefore one of the most effective ways to preserve insulation health and extend transformer life.

IN THIS ARTICLE

- Detailed insulation failure mechanisms due to moisture
- Comparison with other failure drivers
- Impact on transformer life and reliability
- Monitoring, diagnostics and moisture management
- International standards and references

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HOW MOISTURE DAMAGES TRANSFORMER INSULATION

Moisture, even in small quantities, initiates and accelerates multiple degradation processes in the insulation system. The impact is not limited to one phenomenon—it affects chemical, electrical, thermal and mechanical performance simultaneously.

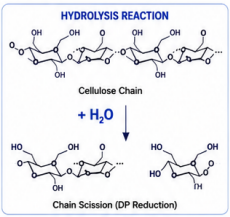
1 CELLULOSE HYDROLYSIS – THE PRIMARY AGING MECHANISM

Water molecules break the long cellulose polymer chains through hydrolysis reactions, reducing the degree of polymerization (DP). This leads to irreversible loss of mechanical strength and short-circuit withstand capability.

TYPICAL DP RANGE IN PAPER INSULATION

Condition	Degree of Polymerization (DP)
New Transformer	1000 – 1200
Healthy	> 700
Aged	300 – 700
End of Life	< 200

HYDROLYSIS REACTION



CONSEQUENCES

- Reduced DP
- Loss of tensile strength
- Brittle paper insulation
- Reduced short-circuit withstand capability
- Accelerated aging and end of life

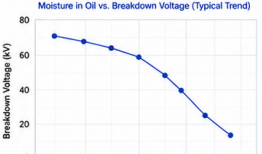
Even a small increase in paper moisture significantly accelerates hydrolysis, especially at higher temperatures.
Temperature + Moisture = Exponential aging.

2 REDUCTION OF DIELECTRIC STRENGTH

Moisture increases the electrical conductivity of oil and paper, reducing the dielectric strength of the insulation system.

IMPACT OF MOISTURE ON DIELECTRIC PROPERTIES

Breakdown Voltage (BDV)	↓
Dissipation Factor (tan δ)	↑
Resistivity	↓
Insulation Resistance	↓
Leakage Current	↑



POTENTIAL RESULT

- Flashover
- Internal insulation failure
- Electrical tracking
- Partial Discharge inception
- Reduced dielectric margin

Wet insulation has less ability to withstand electrical stress, making the transformer more vulnerable to both operating and transient overvoltages.

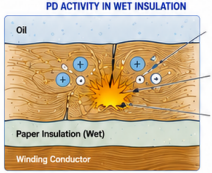
3 INCREASED PARTIAL DISCHARGE ACTIVITY

Moisture creates localized weak dielectric regions and increases conductivity. These conditions promote partial discharge (PD) and accelerate insulation deterioration.

WHY MOISTURE PROMOTES PD

- Higher electrical conductivity
- Local field enhancement
- Microvoids and gas bubbles
- Surface conductivity increase
- Lower PD inception voltage

PD ACTIVITY IN WET INSULATION



RESULT

- Insulation erosion
- Surface tracking
- Internal arcing risk
- Faster aging
- Catastrophic failure potential

Moisture impacts the insulation system in multiple ways—chemically, electrically and physically. It accelerates aging and increases the probability of failure.

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MOISTURE INTERACTION WITH OTHER FAILURE MECHANISMS

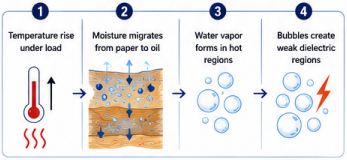
Moisture does not act alone. It interacts with other stresses and processes inside the transformer, significantly accelerating insulation deterioration and increasing the risk of failure.

1. BUBBLE FORMATION DURING LOADING

When transformer temperature rises during loading, moisture migrates from paper to oil and forms water vapor. In high-temperature regions, bubbles may develop.

Since water vapor has much lower dielectric strength than oil, it creates ideal conditions for partial discharge initiation and possible insulation breakdown.

THE BUBBLE FORMATION PROCESS



RISKS

- Partial discharge initiation
- Insulation breakdown
- Catastrophic failure

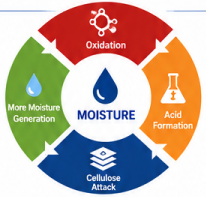
Moisture + Heat = Bubble risk → PD activity → Insulation failure

2. MOISTURE AND OXIDATION

Moisture accelerates the oxidation of oil, increasing the formation of acids and sludge. These by-products attack cellulose, reduce oil quality and impair heat transfer.

DEGRADATION CYCLE

Moisture → Oxidation → Acid Formation → Cellulose Attack → More Moisture Generation



CONSEQUENCES

- Reduced heat transfer
- Higher hotspot temperatures
- Faster insulation aging
- Reduced transformer life

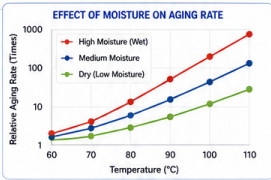
3. MOISTURE AND THERMAL AGING

Temperature accelerates insulation aging. When moisture is present, the rate of aging increases exponentially compared to dry conditions.

KEY TAKEAWAY

The combined effect of heat and moisture is the primary reason for rapid insulation deterioration in aging transformers.

EFFECT OF MOISTURE ON AGING RATE



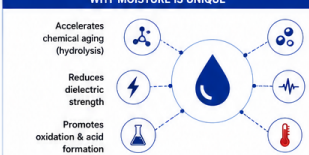
OBSERVATIONS

- Higher moisture content dramatically increases aging rate at all temperatures.
- At 90 °C, wet insulation can age 10–20 times faster than dry insulation.
- At 110 °C, the aging rate can be more than 100 times higher in wet conditions.

RELATIVE IMPACT ON INSULATION LIFE

Moisture	VERY HIGH
Temperature (Heat)	VERY HIGH
Electrical Stress (PD)	HIGH
Oxidation & Acidity	HIGH
Mechanical Stress	MEDIUM
Manufacturing Defects	MEDIUM
Contamination	MEDIUM

WHY MOISTURE IS UNIQUE



Moisture interacts with multiple failure mechanisms simultaneously, making it one of the most influential accelerators of insulation degradation and transformer failure risk.

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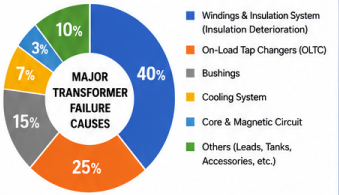
COMPARISON: FAILURE DRIVERS AND THE ROLE OF MOISTURE

While multiple factors contribute to transformer failures, moisture is the most pervasive and influential driver as it accelerates nearly every degradation mechanism in the insulation system.

TYPICAL DISTRIBUTION OF MAJOR TRANSFORMER FAILURE CAUSES*
(Based on International Surveys and Utility Data)



Insulation system related failures (windings, insulation, leads) represent the single largest contributor to major transformer outages.

* Source: CIGRÉ Reliability Survey (TB 761), IEEE, EPRI and other utility studies. Percentages vary with design, voltage class, age and operating conditions.

HOW MOISTURE CONTRIBUTES TO INSULATION FAILURE MECHANISMS

Insulation Failure Mechanism	Moisture Influence	How Moisture Accelerates the Mechanism
Cellulose Hydrolysis (Primary Aging)	VERY HIGH	Breaks cellulose polymer chains, reducing DP and mechanical strength.
Reduction in Dielectric Strength	HIGH	Increases conductivity and reduces breakdown voltage and dielectric margin.
Oxidation & Acid Formation	HIGH	Promotes oil oxidation, acid formation and sludge; increases corrosion and reduces insulation quality.
Bubble Formation (Under Load)	HIGH	Water vapor forms bubbles in hot spots, causing partial discharges and possible insulation breakdown.
Partial Discharge Activity	HIGH	Creates low dielectric regions and increases PD inception and severity.
Thermal Aging Acceleration	HIGH	Moisture + Heat act together to exponentially increase aging rate.
Mechanical Degradation of Paper	MEDIUM	Reduces paper toughness, increases brittleness and risk of mechanical failure.
Facilitation of Other Stress Factors	HIGH	Magnifies the impact of electrical, thermal and mechanical stresses.

Moslatire is not always the root cause, but it is the most influential accelerator of transformer insulation failure.

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

FROM TEST DATA TO ACTIONABLE INSIGHTS

Raw test data is useful, but actionable insights drive better decisions and longer transformer life.

Comprehensive Testing (All Four Domains)	→	Complete Health Assessment
Trend Analysis Over Time	→	Early Warning & Risk Prediction
Correlation of Moisture with Temperature & Load	→	Root Cause Understanding
Actionable Insights	→	Targeted Interventions
Continuous Moisture Management	→	Sustained Life Improvement

TESTING IS ONLY THE FIRST STEP. UNDERSTANDING, ACTING AND MANAGING MOISTURE IS WHAT EXTENDS TRANSFORMER LIFE.

BEST PRACTICES FOR MOISTURE MANAGEMENT

Keep Insulation as Dry as Practical
- Maintain moisture at optimal levels (as per IEEE/IEC guidelines) for maximum dielectric strength and life.

Maintain Oil Filtration & Dehydration Systems
- Ensure efficient removal of free and dissolved moisture.

Maintain Transformer Temperature
- Operate within recommended temperature limits to control aging rate.

Ensure Breather & Sealing Integrity
- Prevent moisture ingress through breathers, gaskets, flanges and conservator leaks.

Monitor Continuously
- Track moisture, temperature, load and key oil/insulation parameters regularly.

Act on Insights
- Implement corrective actions early to prevent irreversible damage.

Periodic Review & Trending
- Review data across seasons and years to validate insulation life and risk.

KEY TAKEAWAY

Moisture influences almost every major degradation mechanism in a transformer's insulation system. By understanding its impact, monitoring it continuously and managing it effectively, utilities can significantly reduce failure risk, extend transformer life and improve asset reliability.

SUSTAINED INSULATION LIFE IMPROVEMENT REQUIRES:

Low Moisture (Content) + Controlled Temperature + Healthy Oil (Chemistry) + Strong Dielectric Performance = Longer Life & Higher Reliability

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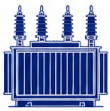
MOISTURE: THE ROOT CAUSE ENABLER
HOW IT TRIGGERS AND ACCELERATES FAILURE

Moisture rarely acts alone, but it enables and accelerates nearly every failure mechanism inside the transformer. It is the common denominator behind most insulation failures.

MOISTURE (PRESENT IN INSULATION SYSTEM)

Cellulose Hydrolysis (Aging)	Breaks cellulose chains, reduces DP and strength.
Reduced Dielectric Strength	Increases conductivity, reduces breakdown voltage and dielectric margin.
Oxidation & Acid Formation	Forms acids and sludge, accelerates cellulose degradation and corrosion.
Bubble Formation (Under Load)	Water vapor forms bubbles in hot spots, causing PD and possible breakdown.
Partial Discharge Activity	Creates weak dielectric regions, leading to insulation erosion and eventual failure.
Thermal Aging Acceleration	Moisture + heat exponentially increases aging rate and reduces life.

OUTCOME



- Insulatioe deterioration
- Loss of dielectric strength
- Increased failure risk
- Reduced transformer life
- Unplanned outages

RESULTING IMPACT

- Higher probability of catastrophic failure
- Shorter asset life
- Higher maintenance and replacement cost
- Lower reliability and availability

Moisture is not always the direct cause of failure, but it is the primary enabler that makes every other stress more damaging.

MOISTURE LEVELS AND RISK OF INSULATION FAILURE

Relative Saturation (RS %)*	Water Activity (aw)	Estimated Paper Moisture (%)	Risk Level	Impact on Insulation & Life
0 – 20	0 – 0.20	< 1.0	LOW	Insulation in good condition. Slow aging.
20 – 40	0.20 – 0.40	1.0 – 2.0	MODERATE	Aging rate increases. Monitor closely.
40 – 60	0.40 – 0.60	2.0 – 3.0	HIGH	Significant aging acceleration. Action required.
> 60	> 0.60	> 3.0	VERY HIGH	Rapid degradation. High risk of failure.

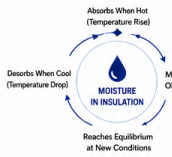
* RS% at in-service oil temperature.

MOISTURE BEHAVIOR IS DYNAMIC

Key Influencing Factors

- Ambient & Top Oil Temperature
- Relative Humidity
- Load Profile (Thermal Stress)
- Seasonal Variations
- Breather Condition & Moisture Ingress

Effect on Moisture



Moisture is continuously moving and changing. That is why single-point testing is not enough.

EFFECTIVE MOISTURE MANAGEMENT: THE KEY TO RELIABILITY

Sustained insulation life improvement requires continuous moisture management — not just periodic testing.

STANDARDS AND GUIDELINES

Global standards recognize the critical role of moisture in transformer insulation and provide methods for assessment and management.

cigre	CIGRÉ TB 349	Moisture Equilibrium and Moisture Assessment in Transformer Insulation
cigre	CIGRÉ TB 761	Condition Assessment of Power Transformers
IEEE	IEEE Std C57.106™	Guide for Acceptance and Maintenance of Insulating Oil in Equipment
IEEE	IEEE Std C57.91™	Guide for Loading Mineral-Oil-Immersed Transformers
IEC	IEC 60422	Mineral insulating oils in electrical equipment – Supervision and maintenance guidance
IEC	IEC 60076 Series	Power Transformers

Following standards-based practices ensures accurate assessment, effective moisture control and extended transformer life.

Moisture is the most pervasive driver of insulation degradation.
Understanding its behavior and managing it continuously is the only proven way to extend transformer life and ensure reliability.

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REFERENCES & INTERNATIONAL STANDARDS

A number of international standards, technical reports and research publications highlight the critical role of moisture in transformer insulation and provide guidance for assessment, management and best practices.

> Standards provide the foundation.
> Understanding provides the insight.
> Action provides the reliability.

IEC STANDARDS

IEC 60422	Mineral insulating oils in electrical equipment – Supervision and maintenance guidance
IEC 60814	Insulating liquids – Determination of water by coulometric Karl Fischer titration
IEC 60156	Insulating liquids – Determination of breakdown voltage at power frequency
IEC 60247	Measurement of relative permittivity, dielectric dissipation factor (tan δ) and d.c. resistivity
IEC 60567	Oil-impregnated paper and pressboard – Determination of 2-furaldehyde (2-FAL)
IEC 60599	Mineral insulating oils – Determination of acidity
IEC 61198	Guide for the application and interpretation of dissolved and free gases analysis

IEEE STANDARDS

IEEE C57.91™	Guide for Loading Mineral-Oil-Immersed Transformers
IEEE C57.106™	Guide for Acceptance and Maintenance of Insulating Oil in Equipment
IEEE C57.143™	Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers

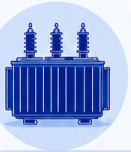
CIGRÉ PUBLICATIONS

CIGRÉ TB 349	Moisture Equilibrium and Moisture Assessment in Transformer Insulation
CIGRÉ TB 761	Condition Assessment of Power Transformers
CIGRÉ WG A2.49	Moisture in Transformer Insulation
CIGRÉ Reliability Survey Reports	International Survey on Transformer Failures and Reliability

KEY TECHNICAL PAPERS & PUBLICATIONS

Oommen, T.V.	"Moisture Equilibrium in Paper-Oil Insulation Systems" IEEE Electrical Insulation Magazine
Koch, M. & Tenbohlen, S.	"Moisture Assessment in Power Transformers Using Dielectric Response"
EPRI Technical Reports	Transformer Reliability and Failure Analysis United States
USBR FIST Program (Volume 3-31)	Transformer Diagnostics and Condition Assessment Handbook
Birtwhistle, R.G.	"Moisture in Transformers – Sources, Effects and Control"
Werne, T.	"Dynamic Moisture Behavior in Power Transformer Insulation"
Powertech Labs Reports	Impact of Moisture on Transformer Aging and Dielectric Performance
Doble Engineering Reports	Failure Case Studies Related to Moisture and Insulation Degradation

FINAL CONCLUSION



Moisture is **not always the direct root cause** of transformer failure, but it is one of the few factors that **simultaneously accelerates:**

- **Chemical Degradation** (Hydrolysis, Oxidation & Acid Formation)
- **Electrical Degradation** (Reduced Dielectric Strength & PD)
- **Thermal Degradation** (Increased Aging Rate)
- **Mechanical Degradation** (Loss of Strength & Toughness)

Effective moisture management therefore represents **one of the most powerful tools available** to extend transformer life and improve reliability.

KEY TAKEAWAYS

- Moisture is the most pervasive driver of insulation degradation.
- It accelerates aging, reduces dielectric strength and increases failure risk.
- Continuous monitoring and management are essential.
- Standards and best practices provide a proven framework.
- Action today ensures reliability tomorrow.

The goal is simple:

KEEP INSULATION DRY, HEALTHY & STRONG – ALL THE TIME.

That is the foundation of transformer reliability and asset sustainability.

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