

# Why Oil & Paper Insulation Characteristics Deteriorate as Moisture Increases in Power Transformers

THE CHEMISTRY BEHIND INSULATION DEGRADATION



## EXECUTIVE SUMMARY

Moisture is the most pervasive and damaging contaminant in power transformer insulation systems. Even small increases in moisture content trigger a series of chemical reactions and electrical changes that degrade both mineral oil and cellulose paper. These reactions are accelerated by the presence of oxygen, elevated temperature, and catalytic metals (e.g., copper). The combined effect leads to deterioration in dielectric performance, chemical stability, mechanical strength, and ultimately a reduction in transformer life and reliability.

## WHY MOISTURE IS UNIQUE

Water (H<sub>2</sub>O) is not an inert contaminant. It is a highly polar molecule that actively participates in both electrical and chemical processes inside the transformer.

- **Electrical Reactivity** – Water molecules increase conductivity, distort electric fields and raise dielectric losses.
- **Chemical Reactivity** – Water reacts with hydrocarbons, oxygen, and cellulose, initiating or accelerating degradation reactions.
- **Mobility** – Moisture migrates between oil and paper with temperature and load changes.
- **Self-Perpetuating** – Aging of cellulose generates water, which in turn accelerates further aging.

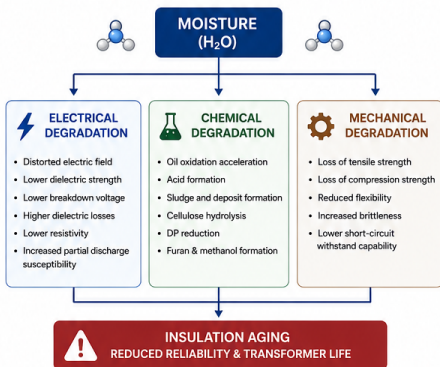
## SOURCES OF MOISTURE

- Ingress from atmosphere through breathers, seals, gaskets and leaks.
- Moisture introduced during manufacturing, installation, maintenance or oil handling.
- High ambient temperature and load cycles increase moisture solubility and migration.
- Moisture generated internally from cellulose degradation and oil oxidation.
- Catalytic action of copper and other metals promotes moisture-driven reactions.

## MOISTURE EFFECTS AT A GLANCE

In Mineral Oil	In Cellulose Paper
<ul style="list-style-type: none"> <li>• Accelerates oxidation</li> <li>• Increases acidity</li> <li>• Lowers interfacial tension</li> <li>• Reduces breakdown voltage</li> <li>• Increases dielectric losses (tan δ)</li> <li>• Lowers resistivity</li> <li>• Causes color darkening</li> <li>• Promotes sludge formation</li> </ul>	<ul style="list-style-type: none"> <li>• Causes hydrolysis of cellulose</li> <li>• Reduces degree of polymerization (DP)</li> <li>• Lowers mechanical strength</li> <li>• Generates furans (2-FAL, 5-HMF)</li> <li>• Generates methanol and other by-products</li> <li>• Causes color darkening</li> <li>• Shortens insulation life</li> </ul>

## MOISTURE: THE ROOT CAUSE OF INSULATION DEGRADATION



## KEY TAKEAWAY

Moisture acts simultaneously through electrical, chemical, and mechanical pathways. It increases the rate of oil oxidation, produces acids, breaks down cellulose chains, reduces dielectric strength, and weakens the mechanical structure of paper insulation. Controlling moisture is therefore the most effective strategy to preserve transformer insulation and maximize asset life.

## Moisture–Mineral Oil Chemistry

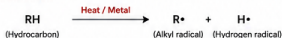
### HOW MOISTURE ACCELERATES OIL OXIDATION AND DETERIORATES OIL CHARACTERISTICS

Mineral oil is composed of complex mixtures of paraffinic, naphthenic and aromatic hydrocarbons. In the presence of oxygen, elevated temperature and catalysts (e.g., copper, iron), moisture accelerates oxidation and leads to the formation of acids, polar compounds and sludge. These chemical changes directly deteriorate the electrical and physical properties of the oil.

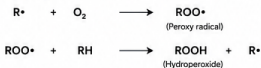
#### 1. OXIDATION MECHANISM OF MINERAL OIL

Oil oxidation proceeds through a free-radical chain mechanism.

##### A. INITIATION



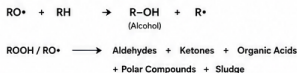
##### B. PROPAGATION



##### C. HYDROPEROXIDE DECOMPOSITION



##### D. FORMATION OF SECONDARY PRODUCTS



Water (H<sub>2</sub>O) accelerates both the decomposition of hydroperoxides and the formation of acids and sludge.









#### 3. KEY CHEMICAL REACTION PATHWAY




##### Overall Effect:


Moisture + Oxygen + Heat + Metal → Accelerated Oxidation  
→ Acid Formation + Sludge → Oil Degradation


#### 4. EFFECT OF MOISTURE ON IMPORTANT OIL CHARACTERISTICS

Property / Test	Effect as Moisture Increases	Chemical Reason	Test Method
 Breakdown Voltage (BDV)	↓ Decreases	Water forms conductive pathways and promotes ionization.	IEC 60156
 Dielectric Strength	↓ Decreases	Lower molecular cohesion; higher permittivity and charge mobility.	IEC 60156
 Dissipation Factor (Tan δ)	↑ Increases	Polar water molecules align with AC field and create dielectric losses.	IEC 60247
 Resistivity	↓ Decreases	Increased ionic conductivity due to water and dissolved polar species.	IEC 60247
 Interfacial Tension (IFT)	↓ Decreases	Oxidation products and acids are surface active; they accumulate at the oil-water interface.	ISO 6295
 Acidity (TAN)	↑ Increases	Oxidation produces carboxylic acids; moisture accelerates their formation.	IEC 62021
 Colour	↑ Darkens	Formation of oxidized aromatics, resins and sludge precursors.	ASTM D1500
 DGA (CO / CO <sub>2</sub> )	↑ Increases	Cellulose and oil oxidation produce CO and CO <sub>2</sub> .	IEC 60567
 Sediments / Sludge	↑ Increases	Polymerization of oxidation products in the presence of water.	Visual / Gravimetric


#### 2. ROLE OF MOISTURE IN OIL OXIDATION

 **Increases hydroperoxide decomposition**  
Water facilitates the breakdown of ROOH into radicals, accelerating the oxidation chain reaction.

 **Increases acid formation**  
Moisture promotes further oxidation, generating carboxylic acids.

 **Enhances metal-catalyzed reactions**  
Water increases the mobility of metal ions (Cu, Fe), which catalyze oxidation.

 **Promotes sludge and deposit formation**  
Polar oxidation products polymerize in the presence of moisture, forming sludge and varnish.

 **Lowers oxidation stability**  
The induction period of oil decreases as moisture content increases.

#### 5. FACTORS THAT INFLUENCE MOISTURE-INDUCED OIL DEGRADATION



##### TEMPERATURE

Higher temperature increases reaction rate exponentially (Arrhenius law).



##### OXYGEN

Oxygen is essential for oxidation; higher oxygen availability accelerates aging.



##### METAL CATALYSTS

Copper and iron catalyze hydroperoxide decomposition and radical formation.



##### MOISTURE

Accelerates all chemical steps and increases conductivity.



##### ELECTRIC FIELD

High electric stress enhances oxidation and PO activity in wet oil.

#### KEY TAKEAWAY

Moisture is not an inert contaminant in mineral oil. It actively participates in and accelerates oxidation chemistry, leading to the formation of acids, polar compounds and sludge. These chemical by-products cause a systematic deterioration in dielectric, chemical and physical properties of oil, ultimately compromising transformer insulation and reliability.

## Moisture-Cellulose Paper Chemistry

### HOW MOISTURE BREAKS DOWN CELLULOSE AND ACCELERATES PAPER AGING

Cellulose paper is the structural backbone of transformer insulation. It is highly sensitive to moisture, temperature, oxygen and acids. Moisture participates directly in hydrolysis reactions that break the long cellulose polymer chains, reducing the Degree of Polymerization (DP), mechanical strength and dielectric performance.



#### 1. CELLULOSE STRUCTURE

Cellulose is a linear polymer composed of β-D-glucose units linked by β-1,4-glycosidic bonds.

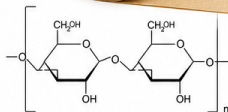
Typical DP of New Paper: 1000 – 1200

End of Life Paper: < 200

#### WHERE DOES MOISTURE RESIDE?

≈ 99% In Paper (Cellulose)      ≈ 1% In Oil

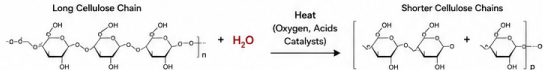
Paper acts as the primary reservoir for moisture in the insulation system.



Cellulose repeating unit  
(C<sub>6</sub>H<sub>10</sub>O<sub>5</sub>)<sub>n</sub>

#### 2. HYDROLYSIS: THE CORE MOISTURE-DRIVEN REACTION

Water molecules attack the glycosidic bonds in cellulose, causing chain scission.

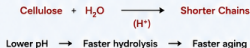


#### Result

- ↓ Degree of Polymerization (DP)
- ↓ Mechanical Strength
- ↓ Dielectric Strength
- ↓ Insulation Life

#### 3. ACID-CATALYZED HYDROLYSIS

Organic acids generated from oil oxidation (see Page 2) lower the pH inside the paper and act as catalysts, dramatically accelerating the hydrolysis reaction.



#### 4. BY-PRODUCTS OF CELLULOSE DEGRADATION

As cellulose breaks down, various compounds are formed. These by-products are excellent indicators of moisture-induced aging.

By-Product	Chemical Formula	Formation Pathway	Indication
2-Furfural (2-FAL)	C <sub>5</sub> H <sub>4</sub> O <sub>2</sub>	Advanced cellulose decomposition	Strong indicator of paper aging
5-Hydroxymethylfurfural (5-HMF)	C <sub>6</sub> H <sub>8</sub> O <sub>3</sub>	Further degradation of sugars	Severe aging
Methanol	CH <sub>3</sub> OH	Early stage cellulose degradation	Early indicator
Ethanol	C <sub>2</sub> H <sub>5</sub> OH	Decomposition of side groups	Aging indicator
Carbon Monoxide (CO)	CO	Decomposition of carbonyl groups	Aging & oxidation by-product
Carbon Dioxide (CO <sub>2</sub> )	CO <sub>2</sub>	Oxidation of cellulose and by-products	Aging & oxidation by-product

#### 5. DEGREE OF POLYMERIZATION (DP)

DP is the average length of cellulose polymer chains. It decreases as moisture and temperature increase.

Condition	Typical DP Range	Insulation State
New Paper	1000 – 1200	Excellent
Moderately Aged	500 – 700	Good / Acceptable
Heavily Aged	200 – 500	Poor
End of Life	< 200	Unreliable



DP correlates directly with mechanical strength and remaining life. A DP below 200 is generally considered end of life.

#### 6. PAPER COLOR CHANGE

Moisture accelerates the formation of chromophoric compounds (oxidation products, furans, carbonyls) which darken cellulose paper.



Color change is a simple visual indicator of chemical degradation and moisture exposure over time.

#### 7. FACTORS THAT ACCELERATE MOISTURE-INDUCED CELLULOSE DEGRADATION

<p><b>TEMPERATURE</b></p> <ul style="list-style-type: none"> <li>Higher temperature increases reaction rates (Arrhenius law).</li> <li>Every 5–8 °C rise roughly doubles the aging rate.</li> </ul>	<p><b>MOISTURE</b></p> <ul style="list-style-type: none"> <li>Direct reactant in hydrolysis.</li> <li>Higher moisture = more chain scission.</li> <li>Above 3–4% in paper, aging accelerates sharply.</li> </ul>	<p><b>OXYGEN</b></p> <ul style="list-style-type: none"> <li>Essential for oxidation.</li> <li>Produces acids and carbonyls that catalyze hydrolysis.</li> </ul>	<p><b>METAL CATALYSTS</b></p> <ul style="list-style-type: none"> <li>Copper, iron and other metals decompose peroxides.</li> <li>Generate radicals and accelerate reactions.</li> </ul>	<p><b>ACIDITY</b></p> <ul style="list-style-type: none"> <li>Organic acids lower pH.</li> <li>Acid-catalyzed hydrolysis is far more destructive than neutral hydrolysis.</li> </ul>	<p><b>ELECTRIC FIELD &amp; STRESS</b></p> <ul style="list-style-type: none"> <li>Enhanced electric stress in wet insulation.</li> <li>Increases PD activity and local heating.</li> </ul>
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#### KEY TAKEAWAY

Moisture is not a passive contaminant in cellulose paper. It is an active reactant that, especially in the presence of heat, oxygen and acids, breaks down cellulose polymer chains, generates furans and other by-products, reduces DP and mechanical strength, darkens the paper and shortens transformer life.

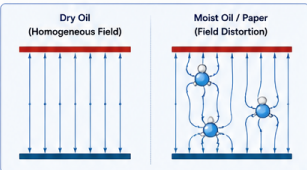
## How Moisture Changes Electrical & Dielectric Properties

### THE PHYSICS BEHIND MOISTURE-INDUCED DETERIORATION

Water molecules have a very high polarity and relative permittivity compared to mineral oil. Their presence in oil and paper insulation distorts electric fields, increases polarization losses, enhances ionic conduction and lowers the overall dielectric withstand capability of the insulation system.

#### 1. POLAR NATURE OF WATER & FIELD DISTORTION

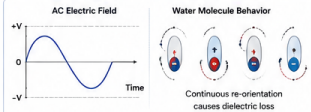
Water ( $\epsilon_r \approx 80$ ) has a much higher relative permittivity than mineral oil ( $\epsilon_r \approx 2.2$ ). Even small amounts of water cause significant electric field distortion.



Water molecules and micro-droplets create regions of enhanced electric stress, reducing the dielectric strength and PD inception voltage.

#### 3. DIELECTRIC LOSS MECHANISM (TAN $\delta$ )

In an AC electric field, polar water molecules attempt to align with the field. They lag behind due to molecular friction, causing energy dissipation as heat.



Higher  $\tan \delta$  indicates higher dielectric losses and deterioration of insulation.

#### 5. MOISTURE IN PAPER: EFFECT ON DIELECTRIC PERFORMANCE

Moisture in cellulose increases its relative permittivity and dielectric losses, and reduces its breakdown strength.

Paper Moisture (%)	Relative Permittivity ( $\epsilon_r$ )	Dielectric Strength (kV/mm)	Tan $\delta$ (at 50 Hz)
0.5	~3.2	~70 - 90	~0.4%
1.0	~3.6	~50 - 60	~0.6%
2.0	~4.2	~30 - 40	~0.9%
3.0	~4.8	~20 - 30	~1.2%
4.0	~5.4	~12 - 20	~1.6%

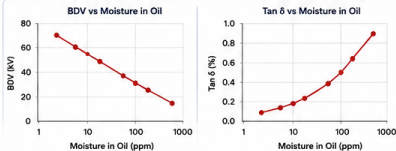


As moisture increases in paper, dielectric strength drops sharply and losses increase significantly.

#### 2. EFFECT OF MOISTURE ON KEY ELECTRICAL PROPERTIES

Property	What Moisture Does	Why It Happens	Consequence
Breakdown Voltage (BDV)	↓ Decreases	Water reduces dielectric strength and promotes electrical avalanches.	Lower insulation margin and higher flashover risk.
Dielectric Strength	↓ Decreases	Local field enhancement and easier charge accumulation.	Reduced ability to withstand overvoltages and transients.
Dissipation Factor (Tan $\delta$ )	↑ Increases	Polar water molecules continuously orient in AC field, causing energy loss.	Higher dielectric losses, heating and reduced insulation quality.
Resistivity	↓ Decreases	Water provides paths for ionic conduction and dissolves ionic species.	Higher leakage current and reduced insulation resistance.
Partial Discharge Resistance	↓ Decreases	Water drops and moisture pockets initiate PD at lower stress.	Accelerated insulation erosion and aging.
Relative Permittivity ( $\epsilon_r$ )	↑ Increases	Water ( $\epsilon_r \approx 80$ ) is much higher than oil ( $\epsilon_r \approx 2.2$ ) or paper ( $\epsilon_r \approx 3-4$ ).	Field distortion and lower dielectric withstand capability.

#### 4. TYPICAL RELATIONSHIP: MOISTURE vs DIELECTRAL PROPERTIES



Even small increases in moisture cause significant deterioration in dielectric strength and increase in dielectric losses.

#### 6. KEY FACTORS THAT INFLUENCE MOISTURE EFFECTS



**Temperature**  
Higher temperature increases molecular motion, accelerates chemical reactions and reduces moisture solubility in oil.



**Moisture Level**  
Above critical levels, properties deteriorate rapidly and non-linearly.



**Oxygen**  
Essential for oxidation reactions in oil and aging of cellulose.



**Electric Field Stress**  
Higher stress enhances PD activity in the presence of moisture.



**Metal Catalysts**  
Copper, iron and other metals catalyze oxidation and hydrolysis reactions.



**Acidity**  
Acids further accelerate cellulose hydrolysis.



**Oil Quality**  
Naphthenic oils oxidize faster than paraffinic oils.



**Load & Thermal Cycling**  
Repeated heating and cooling drives moisture movement and stresses insulation.



#### KEY TAKEAWAY

Moisture changes the fundamental electrical behavior of both oil and paper by increasing polarity, conductivity and molecular activity. This leads to lower dielectric strength, higher losses and accelerated insulation aging.

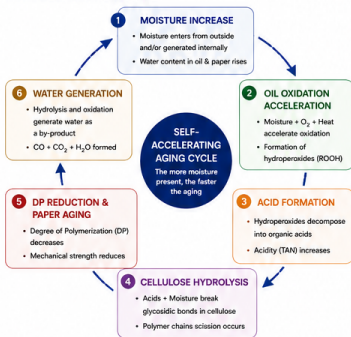


# The Moisture–Oxidation–Hydrolysis Feedback Loop

## THE SELF-ACCELERATING MECHANISM OF INSULATION AGING

Moisture does not act in isolation. It creates a self-accelerating chemical cycle in the transformer insulation system. This cycle continuously generates more water and degradation by-products, even if external moisture ingress is controlled.

### 1. THE DEGRADATION CYCLE



This cycle continues as long as moisture, oxygen and temperature are present. It is the fundamental reason why old transformers deteriorate faster with time.

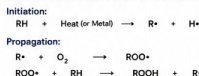
### 3. MAJOR BY-PRODUCTS INDICATING THE CYCLE

By-Product	Origin	Indicates
Furfural (2-FAL)	Cellulose hydrolysis	Advanced paper aging
5-Hydroxymethylfurfural (5-HMF)	Further cellulose degradation	Severe aging
Methanol	Early cellulose degradation	Initial aging
CO / CO <sub>2</sub>	Oxidation of oil & cellulose	Thermal + chemical aging
Acidity (TAN)	Oxidation (oil)	Oxidation severity
Sludge / Deposits	Polymerization of oxidation products	Severe oxidation

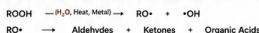
Tracking these by-products provides a window into the ongoing chemical reactions inside the transformer.

### 2. KEY CHEMICAL REACTIONS INVOLVED

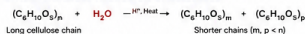
#### A. OIL OXIDATION (INITIATION & PROPAGATION)



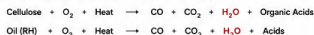
#### B. HYDROPEROXIDE DECOMPOSITION (MOISTURE ACCELERATED)



#### C. ACID-CATALYZED HYDROLYSIS OF CELLULOSE



#### D. INTERNAL WATER GENERATION (FROM AGING)

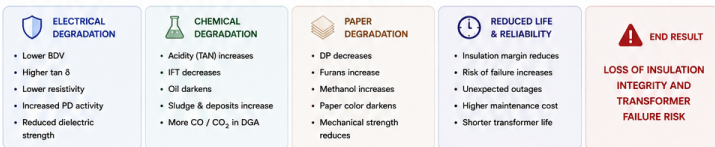


Water is both a reactant and a product in these reactions. Therefore, once the cycle starts, it sustains and accelerates.

### 4. FACTORS THAT ACCELERATE THE FEEDBACK LOOP

- High Temperature**  
Increases reaction rates exponentially (Arrhenius law). Every 6–8 °C rise approximately doubles the aging rate.
- High Moisture**  
Provides reactant for hydrolysis and promotes hydroperoxide decomposition.
- Oxygen Availability**  
Essential for oxidation reactions in both oil and cellulose.
- Metal Catalysts (Cu, Fe, etc.)**  
Promote decomposition of hydroperoxides into free radicals and acids.
- Electric Stress**  
Increases partial discharge activity which further decomposes oil and cellulose locally.

### 5. CONSEQUENCES OF THE FEEDBACK LOOP ON TRANSFORMER INSULATION



### KEY TAKEAWAY

Moisture triggers and sustains a self-accelerating chemical cycle involving oxidation and hydrolysis. This cycle continuously generates more water and destructive by-products, rapidly deteriorating both oil and cellulose insulation, reducing dielectric and mechanical performance, and shortening transformer life.

# Diagnostic Tests Affected by Moisture

## TEST INTERPRETATION, MOISTURE INFLUENCE AND ACCEPTABLE LIMITS FOR IN-SERVICE TRANSFORMERS

Moisture influences nearly every diagnostic test used to assess transformer insulation condition. The table below summarizes how moisture affects each test, the chemical/electrical reason, and typical acceptable limits for in-service transformers (IEC/IEEE/CIGRÉ guidance and industry practice).



### HOW MOISTURE AFFECTS INSULATION TESTS

#### MOISTURE INGRESS

- Enters oil and paper from atmosphere, leaks, breathers, seal deterioration, etc.
- Paper absorbs ~99% of moisture.



#### CHEMICAL EFFECTS

- Accelerates oil oxidation and acid formation.
- Promotes cellulose hydrolysis.
- Generates by-products (furans, methanol, CO, CO<sub>2</sub>).



#### ELECTRICAL EFFECTS

- Lowers dielectric strength and BDV.
- Increases dielectric losses (tan δ).
- Reduces resistivity and increases conductivity.
- Increases PD activity.



#### PHYSICAL EFFECTS

- Paper strength reduces.
- Oil color darkens.
- Sludge and deposits form.
- Reduced insulation reliability and life.

#### ★ KEY MESSAGE

No single test tells the whole story. Trend analysis of multiple tests is essential to understand moisture impact and insulation health.

### DIAGNOSTIC TESTS: MOISTURE INFLUENCE, REASON AND ACCEPTABLE LIMITS

#	TEST / PARAMETER	MOISTURE INFLUENCE	WHY MOISTURE AFFECTS THIS TEST	TEST METHOD (REFERENCE)	ACCEPTABLE LIMITS FOR IN-SERVICE TRANSFORMERS	
					NORMAL SERVICE (≤ 69 kV)	HIGH VOLTAGE (≥ 69 kV)
1	Moisture in Oil (ppm)	↑ Increases	Direct measurement of water present in the oil.	IEC 60814	≤ 20 ppm (Preferably < 15 ppm)	≤ 15 ppm (Preferably < 10 ppm)
2	Relative Saturation (%RS)	↑ Increases	Moisture relative to oil temperature and saturation point.	IEC 60814	≤ 60 %RS (Preferably < 40 %RS)	≤ 50 %RS (Preferably < 30 %RS)
3	Water Activity (a <sub>w</sub> )	↑ Increases	Indicates availability of water for chemical reactions.	IEC 61810	≤ 0.50 (Preferably < 0.40)	≤ 0.40 (Preferably < 0.30)
4	Breakdown Voltage (BDV)	↓ Decreases	Water lowers dielectric strength and promotes discharge.	IEC 60156	≥ 50 kV (Preferably ≥ 60 kV)	≥ 60 kV (Preferably ≥ 70 kV)
5	Dissipation Factor (tan δ) @ 90 °C	↓ Increases	Polar water molecules cause higher dielectric losses.	IEC 60247	≤ 0.50 %	≤ 0.30 %
6	Resistivity @ 90 °C	↓ Decreases	Water increases ionic content, lowering resistivity.	IEC 60247	≥ 1 × 10 <sup>11</sup> Ω·m	≥ 5 × 10 <sup>11</sup> Ω·m
7	Interfacial Tension (IFT)	↓ Decreases	Oxidation products and acids (accelerated by moisture) reduce IFT.	ISO 6295	≥ 25 mN/m (Preferably ≥ 30 mN/m)	≥ 30 mN/m (Preferably ≥ 35 mN/m)
8	Acidity (TAN)	↑ Increases	Moisture accelerates oxidation and acid formation.	IEC 62021	≤ 0.20 mg KOH/g (Preferably < 0.10)	≤ 0.10 mg KOH/g (Preferably < 0.05)
9	Colour (ASTM)	↑ Darkens	Oxidation and sludge formation darken the oil.	ASTM D1500	≤ 2.5	≤ 2.0
10	2-Furfural (2-FAL)	↓ Increases	Formed from cellulose hydrolysis accelerated by moisture.	IEC 61198	≤ 0.25 mg/kg (Preferably < 0.10)	≤ 0.10 mg/kg (Preferably < 0.05)
11	Methanol	↓ Increases	Early indicator of cellulose degradation.	IEC 61198 / GC	≤ 0.30 mg/kg	≤ 0.20 mg/kg
12	CO in Oil	↓ Increases	Cellulose and oil oxidation generate CO.	IEC 60567	≤ 350 ppm	≤ 250 ppm
13	CO <sub>2</sub> in Oil	↓ Increases	Oxidation and paper degradation produce CO <sub>2</sub> .	IEC 60567	≤ 2500 ppm	≤ 1500 ppm
14	DGA (Key Gases)	↑ Increases	Moisture accelerates insulation degradation, generating gases.	IEC 60567	Within IEEE C57.104 & IEC 60599 normal range	Within IEEE C57.104 & IEC 60599 normal range
15	Degree of Polymerization (DP)	↓ Decreases	Hydrolysis shortens cellulose chains.	IEC 60450	≥ 600 (Good)	≥ 600 (Good)

Note: Limits shown are general guidelines for in-service transformers operating under normal conditions. Stricter limits may be applied based on criticality, age, loading, temperature and manufacturer recommendation.

#### INTERPRETATION GUIDELINES

- Evaluate trends, not just single values.
- Correlate moisture with temperature, load and aging indicators.
- Investigate increasing moisture even if values are within limits.
- Combine oil tests with paper tests for complete assessment.
- Take corrective action early to prevent irreversible aging.

#### ✓ BOTTOM LINE

Moisture drives both electrical and chemical deterioration in oil and paper insulation. Keeping moisture within acceptable limits is fundamental to maintaining dielectric strength, mechanical integrity and long transformer life.

**CONTROL MOISTURE – CONTROL AGING – EXTEND LIFE**

## 7. CONCLUSION

This technical paper has demonstrated that moisture is not merely a contaminant in transformer insulation; it is an active chemical reactant and a powerful catalyst that drives multiple interconnected degradation mechanisms in both mineral oil and cellulose paper.

### Key findings from this study are:

- Moisture accelerates mineral oil oxidation, leading to the formation of hydroperoxides, acids, polar compounds and sludge. These products deteriorate electrical properties and increase the risk of faults.
- Moisture causes hydrolysis of cellulose by breaking the glycosidic bonds in the polymer chain. This reduces the Degree of Polymerization (DP), mechanical strength and dielectric performance of paper.
- The acids and by-products formed in oil further accelerate paper aging, creating a self-accelerating moisture-oxidation-hydrolysis feedback loop.
- Moisture significantly affects all critical diagnostic parameters including BDV,  $\tan \delta$ , resistivity, IFT, acidity, furans, methanol, CO/CO<sub>2</sub> and DGA gases.
- Controlling moisture through effective sealing, drying, filtration, breather maintenance and continuous monitoring is the most effective strategy to preserve insulation integrity and extend transformer service life.



In conclusion, moisture is the root cause that initiates and accelerates chemical, electrical and mechanical degradation of transformer insulation. Understanding its chemistry and managing it continuously is essential for reliable, safe and economical operation of power transformers.

## REFERENCES

### A. INTERNATIONAL STANDARDS

- IEC 60422:2013, *Mineral insulating oils in electrical equipment – Supervision and maintenance guidance.*
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The chemical reaction mechanisms and degradation pathways presented in this paper are derived from the above standards, technical brochures, peer-reviewed publications and industry references. The equations and reaction sequences are reproduced as per the original sources cited.