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Moisture Under Control

Knowledge. Reliability. Performance.
Moisture Under Control.

DRYTRANS KNOWLEDGE SERIES

THE COMPLETE TRANSFORMER MOISTURE GUIDE

51
SECTIONS
THE ULTIMATE MOISTURE RESOURCE

51 SECTIONS. ONE COMPLETE KNOWLEDGE LIBRARY.

From moisture fundamentals to advanced diagnostics, from best practices to technical references—everything you need to master transformer moisture and ensure reliable power for decades.

- **UNDERSTAND** Moisture Science
- **MEASURE** Accurately & Reliably
- **MONITOR** Continuously
- **MANAGE** Proactively
- **EXTEND** Transformer Life
- **OPTIMIZE** Performance & Cost

FOUNDATION SECTIONS 1–10	MOISTURE SCIENCE SECTIONS 11–20	ADVANCED ENGINEERING SECTIONS 21–30	ASSET MANAGEMENT SECTIONS 31–40	PRACTICAL IMPLEMENTATION SECTIONS 41–50	REFERENCE & RESOURCES SECTION 51
Understand the Basics	Science, Behavior & Measurement	Diagnostics, Degradation & Chemistry	Monitoring, Assessment & Life Extension	Best Practices, Protection & Reliability	Standards, Research & References

51 COMPREHENSIVE SECTIONS

100% FOCUSED ON MOISTURE

PRACTICAL ACTIONABLE RELIABLE

FOR ENGINEERS BY ENGINEERS FOR RELIABILITY

SCAN TO EXPLORE THE SERIES

KNOWLEDGE IS POWER.
MOISTURE MANAGEMENT IS TRANSFORMER PROTECTION.
PROTECT TODAY. POWER TOMORROW.

DRY TODAY.
RELIABLE TOMORROW.
POWER FOR YEARS.

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The Complete Transformer Moisture Knowledge Resource

CONTENT PAGE
ALL SECTIONS
SECTION 1 TO 51

COMPLETE CONTENT OVERVIEW

51 SECTIONS. ONE COMPLETE KNOWLEDGE LIBRARY.

From fundamentals to advanced diagnostics, from moisture science to asset management, from best practices to technical references—everything you need to master transformer moisture and ensure reliable power.

KEY TAKEAWAY

- Understand moisture.
- Measure it accurately.
- Monitor continuously.
- Manage proactively.
- Extend transformer life.
- Control moisture.

Control your transformer future.

FOUNDATION (1–10)
Understanding the Basics

1. Why Moisture is the #1 Enemy of Transformers
2. Transformer Insulation System Explained
3. The Moisture Problem – An Overview
4. Moisture in Transformer Oil
5. Moisture in Transformer Paper
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9. Effects of Moisture on Paper Insulation
10. Moisture and Transformer Aging

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REFERENCE & RESOURCES (51)
Standards, Research & References

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    - International Standards (IEC)
    - IEEE References
    - CIGRE Technical Brochures
    - Transformer Textbooks
    - Research Papers
    - Bubbling, PD, Methanol, Oxidation References
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    - Most Frequently Used References

SERIES ROADMAP

FOUNDATION
Build your understanding
↓
MOISTURE SCIENCE
Learn the science
↓
ADVANCED ENGINEERING
Understand effects & diagnostics
↓
ASSET MANAGEMENT
Manage risk & extend life
↓
PRACTICAL IMPLEMENTATION
Apply best practices
↓
REFERENCE & RESOURCES
Use trusted references

WHAT YOU WILL ACHIEVE WITH THIS SERIES

DEEP KNOWLEDGE
Understand moisture in oil, paper and the insulation system comprehensively.

ACCURATE MEASUREMENT
Measure the right way using the right methods and tools.

SMART MONITORING
Monitor trends and detect issues early.

EFFECTIVE MANAGEMENT
Implement proven strategies to control moisture.

EXTENDED LIFE
Extend transformer life, reduce failures and improve reliability.

LOWER COST
Reduce unplanned outages, repairs and replacement cost.

ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protcict your investment. Our solutions are proven in utilities, industries and critical infrastructure around the world.

MMS90
Moisture Monitoring System

TR50
Online Moisture Removal System

TRAM90
Dual Cylinder Moisture Management System

SCAN TO EXPLORE DRYTRANS KNOWLEDGE SERIES

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DRYTRANS SOLUTIONS
- TR5 / TR50 – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management
- Training & Technical Support

Knowledge is power.
Moisture management is transformer protection.
Protect today. Power tomorrow.

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SECTION 1

FUNDAMENTALS OF TRANSFORMER MOISTURE

Understanding the Invisible Threat to Transformer Life

Small amounts of moisture can have a very large impact on transformer performance and life.

Moisture is one of the most important factors affecting transformer reliability, insulation life, and asset performance. Unlike electrical faults that occur suddenly, moisture acts slowly and continuously. It accelerates insulation aging, reduces dielectric strength, increases bubble formation risk, and ultimately shortens transformer life.

01 WHAT IS MOISTURE IN A TRANSFORMER?

Answer:
Moisture refers to water present within the transformer insulation system.

It can exist in:

- Transformer oil
- Cellulose paper insulation
- Pressboard insulation
- Wood and insulating structures
- Free water droplets (in severe cases)

KEY MESSAGE
Moisture is invisible, but its impact is real and unavoidable.

02 WHERE DOES MOISTURE EXIST INSIDE A TRANSFORMER?

Answer:
Moisture is not evenly distributed.

Typical distribution:

Location	Moisture Distribution
Cellulose Insulation (Paper)	95–99%
Transformer Oil	1–5%
Free Water	Normally 0%

KEY MESSAGE
Oil is where moisture is measured.
Paper is where moisture is stored.

03 WHY DO UTILITIES MONITOR MOISTURE?

Answer:
Moisture directly affects:

- Transformer life
- Dielectric strength
- Loading capability
- Bubble formation risk
- Failure probability
- Overall asset reliability

DRYTRANS INSIGHT
Most transformer failures are linked directly or indirectly to insulation degradation, and moisture is one of the primary drivers of that degradation.

04 HOW MUCH MOISTURE IS NORMALLY STORED IN OIL?

Answer:

Condition	Moisture in Oil (ppm)
Very Dry	< 10 ppm
Dry	10 – 20 ppm
Moderate	20 – 30 ppm
Wet	30 – 40 ppm
Very Wet	> 40 ppm

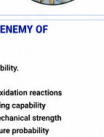
05 HOW MUCH MOISTURE IS NORMALLY STORED IN PAPER INSULATION?

Answer:

Condition	Moisture in Paper (%)
Very Dry	< 1%
Dry	1 – 2%
Moderate	2 – 3%
Wet	3 – 4%
Very Wet	> 4%

06 WHY DOES PAPER HOLD MUCH MORE MOISTURE THAN OIL?

Answer:
Cellulose contains hydroxyl (–OH) groups that attract water molecules.



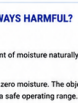
As a result:

- Paper behaves like a sponge
- Water bonds strongly to cellulose
- Moisture remains trapped inside insulation

07 WHAT IS THE DIFFERENCE BETWEEN DISSOLVED WATER AND FREE WATER?

DISSOLVED WATER

- Invisible
- Normal operating condition
- Measured in ppm
- Participates in oil–paper equilibrium



FREE WATER

- Visible droplets
- Dangerous condition
- Severe dielectric risk
- Indicates excessive moisture contamination

KEY MESSAGE
Dissolved water is part of normal operation. Free water is never acceptable.

08 WHY IS MOISTURE CONSIDERED THE ENEMY OF TRANSFORMER INSULATION?

Answer:
Moisture affects almost every aspect of transformer reliability.

It can:

- Accelerate cellulose aging
- Reduce dielectric strength
- Increase dielectric losses
- Promote partial discharge
- Increase bubble formation risk
- Accelerate oxidation reactions
- Reduce loading capability
- Decrease mechanical strength
- Increase failure probability

DRYTRANS INSIGHT
Moisture is unique because it affects both aging (long term) and dielectric performance (short term).

09 IS MOISTURE ALWAYS HARMFUL?

Answer:
Not necessarily. A small amount of moisture naturally exists in cellulose insulation.

The objective is not to achieve zero moisture. The objective is to maintain moisture within a safe operating range.

10 WHAT HAPPENS IF INSULATION BECOMES COMPLETELY DRY?

Answer:
Extremely dry cellulose may become:

- **Brittle**
- **Less flexible**
- **Mechanically weaker**

In practice, completely dry insulation is rarely achieved.

11 WHAT IS THE OPTIMUM MOISTURE RANGE?

Answer:

Moisture in Paper (%)	Condition
< 1%	Very Dry
1 – 2%	Preferred Range
2 – 3%	Acceptable
3 – 4%	Elevated Risk
> 4%	High Risk

KEY TAKEAWAYS

- Moisture is one of the primary drivers of transformer insulation aging.
- Approximately 95–99% of transformer moisture resides in cellulose insulation.
- Oil moisture measurements represent only a small portion of total moisture.
- Cellulose acts as a moisture reservoir while oil acts as a transport medium.
- Excessive moisture accelerates aging and increases dielectric risk.
- Effective transformer life management requires understanding and controlling moisture.

DRYTRANS INSIGHT

Moisture is not a one-time contamination event. It is a continuous process of ingress, storage, migration and generation. Therefore, moisture management should also be continuous.

REFERENCES

- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEC 60814 – Determination of Water by Karl Fischer Titration
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- IEEE C57.91 – Moisture Equilibrium Models for Transformer Insulation
- CIGRÉ TB 349 – Moisture Equilibrium and [illegible]
- CIGRÉ TB 741 – Moisture Measurement to Equilibrium in Paper-Oil Insulation Systems
- Koch & Tenbohlm – Moisture Assessment Using Dielectric Response Methods

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SECTION 2

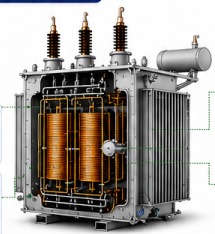
SOURCES AND GENERATION OF TRANSFORMER MOISTURE

Moisture is Always Finding Its Way In and Being Generated From Within

Understanding where moisture comes from is essential to control it effectively. Moisture enters a transformer from external sources and is also generated internally during normal operation and insulation aging.

1. ATMOSPHERIC MOISTURE INGRESS
Breather, seals and tank breathing

2. OIL HANDLING & MAINTENANCE
During filling, sampling, servicing and maintenance



3. INSULATING MATERIALS & COMPONENTS
Paper, pressboard, wood, gaskets, sealing materials

4. INTERNAL GENERATION OF MOISTURE
Aging, chemical reactions and electrical stress

Moisture is continuously entering and being generated.
Continuous management is the only long-term solution.

Q1 What are the main sources of moisture in transformers?

Answer:
Transformer moisture originates from both external and internal sources.

External sources:
- Atmospheric humidity
- Breather issues
- Seal leakage
- Maintenance activities

Internal sources:
- Cellulose aging
- Hydrolysis
- Oxidation processes

KEY MESSAGE
Moisture is continuously entering and being generated throughout transformer life.

Q2 Can moisture remain inside a transformer from manufacturing?

Answer:
Yes.
Even after factory drying, a small amount of residual moisture remains in cellulose insulation.

Reasons include:
- Manufacturing processes
- Transportation
- Storage
- Cellulose moisture retention

TYPICAL CONDITION
New transformers normally contain less than 1% paper moisture.

Q3 Can insulation aging generate moisture?

Answer:
Yes.
Cellulose degradation continuously produces water throughout transformer life.

IMPORTANT
Older transformers generate moisture even when no external ingress exists.

Q4 Why does insulation aging create water?

Answer:
Cellulose undergoes hydrolysis and oxidation. These reactions break polymer chains and release water molecules.

This creates a self-accelerating cycle:

Moisture
↓
Faster Aging
↓
More Water Generation
↓
More Moisture

Q5 Can transformer oil generate moisture?

Answer:
Not significantly.
The primary source of internally generated moisture is cellulose degradation rather than oil degradation.

Oil oxidation mainly produces:
- Acids
- Sludge
- Polar compounds

Q6 How does moisture enter through the atmosphere?

Answer:
Transformers continuously breathe.
As temperature changes:
- Air enters
- Air exits
- Moisture enters with incoming air

Without proper moisture control, humidity gradually accumulates inside the transformer.

Q7 What role does the breather play?

Answer:
The breather removes moisture from incoming air.

A healthy silica gel breather:
- ✓ Reduces moisture ingress
- ✓ Protects insulation
- ✓ Extends oil life

A saturated breather loses effectiveness.

Q8 Can leaking seals allow moisture ingress?

Answer:
Yes.
Common locations include:
- Conservator gaskets
- Bushings
- Valve assemblies
- Inspection covers

Even small leaks can introduce moisture over many years.

Q9 Can maintenance activities introduce moisture?

Answer:
Yes.
Typical activities include:
- Oil filling
- Oil sampling
- Internal inspections
- Repairs
- Oil processing

Proper procedures are essential to prevent contamination.

Q10 Which source contributes the most moisture?

Answer:
It depends on transformer age.

Transformer Age	Dominant Moisture Source
New	Residual moisture from manufacturing
Mid-life	Atmospheric moisture ingress
Aged	Cellulose degradation (internal generation)

KEY TAKEAWAYS

- Moisture originates from both external and internal sources.
- Cellulose aging continuously generates water.
- Breathers and seals play a critical role in moisture control.
- Maintenance activities can introduce moisture.
- The dominant source of moisture changes with transformer age.
- Understanding moisture sources is the first step toward effective moisture management.

DRYTRANS INSIGHT

Moisture is not a one-time contamination event.
It is a continuous process of:

Ingress (External) + Generation (Internal) + Migration (Inside Transformer)

Therefore, moisture management should also be continuous.

REFERENCES

- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEC 60814 – Determination of Water by Karl Fischer Titration
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- IEEE C57.91 – Moisture Equilibrium Models for Transformer Insulation
- CIGRÉ TB 349 – Moisture Equilibrium and Moisture Assessment
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- T.V. Oommen – Moisture Equilibrium in Paper-Oil Insulation Systems
- Koch & Tenbohlen – Moisture Assessment Using Dielectric Response Methods

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SECTION 3

INSULATING MATERIALS & MOISTURE BEHAVIOR

How Different Materials Store, Hold and Release Moisture

The insulation system of a transformer is made of different materials. Each material interacts with moisture differently. Understanding their moisture behavior is essential for accurate assessment and effective moisture management.

INSULATION SYSTEM

KEY MESSAGE

Different materials have different moisture capacities, water affinities, and release characteristics.

Moisture is stored mostly in solid insulation, while oil acts as the transport medium.

Q1 What are the main insulating materials in a transformer?

Answer:
The major insulating materials are:

- Cellulose paper (windings, insulation)
- Pressboard (barriers, spacers)
- Wood (structural parts)
- Transformer oil (liquid insulation)
- Gaskets and sealing materials

These materials form the complete insulation system and determine the moisture behavior of the transformer.

Q2 Which material holds the most moisture?

Answer:
Cellulose paper holds the most moisture.

Typical moisture holding capacity (at equilibrium with oil):

Material	Moisture Holding Capability
Cellulose Paper	High (3 – 6% or more)
Pressboard	Moderate (2 – 4%)
Wood	Moderate (varies with type)
Transformer Oil	Low (ppm level)

Approximately 95–99% of the total moisture in a transformer is stored in cellulose insulation.

Q3 Why does cellulose paper hold so much moisture?

Answer:
Cellulose has hydroxyl (–OH) groups that attract water molecules through hydrogen bonding.

As a result:

- ✓ It behaves like a sponge
- ✓ It absorbs moisture rapidly
- ✓ It holds moisture strongly
- ✓ It releases moisture slowly

Hydrogen bonding between cellulose and water molecules

Q4 How does pressboard store moisture?

Answer:
Pressboard is also cellulose based, but with a denser structure.

It absorbs less moisture than paper, but still holds significant amounts.

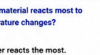
Typical equilibrium moisture:
2% – 4%

Q5 How does wood behave with moisture?

Answer:
Wood is hygroscopic.
It absorbs or releases moisture based on relative humidity.

Moisture content varies with:

- Wood type
- Temperature
- Relative Humidity (RH)

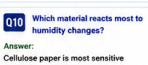


Q6 Why does oil hold very little moisture?

Answer:
Oil is non-polar and has low affinity for water.

It can dissolve only a small amount of water.

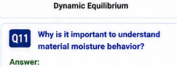
Moisture in oil is expressed in ppm (parts per million).



Q7 How does moisture move between oil and solid insulation?

Answer:
Moisture continuously migrates between oil and cellulose based on:

- Temperature
- Relative Humidity
- Moisture concentration gradient

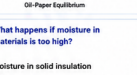


Dynamic Equilibrium

Q8 What is moisture equilibrium?

Answer:
Moisture equilibrium is the condition where moisture in oil and moisture in paper are in balance.

At this point, there is no net movement of moisture between oil and paper.



Oil–Paper Equilibrium

Q9 Which material reacts most to temperature changes?

Answer:
Cellulose paper reacts the most.

As temperature increases:
- It releases moisture to oil

As temperature decreases:
- It absorbs moisture from oil

Q10 Which material reacts most to humidity changes?

Answer:
Cellulose paper is most sensitive to humidity changes.

Higher RH → absorbs more moisture

Lower RH → releases moisture

Q11 Why is it important to understand material moisture behavior?

Answer:
Because:

- ✓ It helps interpret test results correctly
- ✓ It helps estimate true paper moisture
- ✓ It helps in risk assessment
- ✓ It helps plan effective moisture control strategies

Q12 What happens if moisture in materials is too high?

Answer:
Excess moisture in solid insulation can cause:

- Accelerated aging
- Loss of mechanical strength
- Reduced dielectric strength
- Increased risk of bubble formation
- Higher failure probability

MOISTURE CHARACTERISTICS OF INSULATING MATERIALS

Material	Moisture Affinity	Moisture Capacity (at Equilibrium)	Moisture Release Rate	Role in Transformer
Cellulose Paper	Very High	3 – 6% or more	Slow	Main moisture reservoir
Pressboard	High	2 – 4%	Moderate	Structural & insulation
Wood	Moderate	Varies (depends on RH)	Moderate	Structural support
Transformer Oil	Very Low	ppm level	Fast	Moisture transport medium
Gaskets / Seals	Low to Moderate	Varies	Moderate	Sealing & containment

KEY TAKEAWAYS

- Cellulose paper holds the most moisture.
- Oil holds very little moisture.
- Moisture is in dynamic equilibrium between oil and solid insulation.
- Temperature and humidity strongly influence moisture movement.
- Understanding material behavior is essential for accurate assessment and effective moisture management.

MOISTURE CYCLE IN INSULATION SYSTEM

DRYTRANS INSIGHT

Testing gives a snapshot of oil moisture. Understanding material behavior reveals the true story of insulation moisture.

SUSTAINED INSULATION LIFE IMPROVEMENT REQUIRES:

- Understand Materials
- Monitor Moisture Continuously
- Control Ingress Sources
- Maintain Equilibrium Conditions

REFERENCES

- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEC 60814 – Determination of Water by Karl Fischer Titration
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- CIGRE TB 349 – Moisture Equilibrium and Moisture Assessment
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SECTION 4

MOISTURE MEASUREMENT & INTERPRETATION

Measuring the Invisible to Understand the Critical

Accurate moisture measurement is the foundation of effective transformer insulation life management. Understanding measurement methods, parameters and interpretation is essential for correct decisions and reliable asset management.

KEY MESSAGE

What you measure in oil is only a small part of the total moisture in the insulation system.

Correct measurement + Correct interpretation = Correct decision + Longer life

Q1 WHAT IS PPM?

Answer:
PPM (parts per million) is the unit used to express moisture content in oil.

1 ppm = 1 mg of water per kg of oil

1,000 ppm = 0.1% water in oil

PPM indicates how much water is dissolved in the transformer oil.

Q2 WHAT IS RELATIVE SATURATION (RS%)?

Answer:
Relative Saturation (RS%) indicates how close the oil is to its maximum water holding capacity at the measured temperature.

RS% = (Actual moisture in oil + Saturation limit) × 100

RS%	Interpretation
0 – 20%	Very Dry
20 – 40%	Dry
40 – 60%	Moderate
60 – 80%	Wet
80 – 100%	Very Wet (Risky)
> 100%	Supersaturated (Free water risk)

Q3 WHY IS %RS MORE IMPORTANT THAN PPM?

Answer:
- PPM changes with temperature.
- %RS considers temperature.
- %RS shows how close the oil is to saturation.
- High %RS means high risk of moisture transfer to paper.
- %RS is a better indicator of the true moisture condition.

KEY POINT
%RS tells you the risk. PPM alone does not.

Q4 WHAT IS KARL FISCHER (KF) TITRATION?

Answer:
Karl Fischer titration is the most accurate method for measuring moisture in transformer oil.

Types:
- Coulometric Karl Fischer (For < 200 ppm)
- Volumetric Karl Fischer (For > 200 ppm)

- KF is the reference method as per IEC 60814 and ASTM D1533/D6304.

Q5 CAN OIL MOISTURE INDICATE PAPER MOISTURE?

Answer:
Yes. Oil and paper are in equilibrium.

If oil moisture is high, paper moisture will also be high.

However, the reverse is not always immediate because:
- Paper holds much more moisture than oil.
- Moisture transfer from paper to oil is slower.

Q6 WHY CAN MOISTURE READINGS CHANGE DAILY?

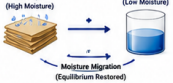
Answer:
Moisture in oil changes due to:
- Temperature fluctuations (day/night)
- Load changes
- Breathing of the transformer
- Humidity variations
- Moisture migration between oil and paper

FACT
Daily or weekly variations are normal. Trend is more important than a single reading.

Q7 WHY DOES MOISTURE RETURN AFTER FILTRATION?

Answer:
Because the moisture comes from the paper (insulation) and not only from oil.

After filtration:
- Oil becomes dry
- Moisture migrates from paper to oil
- Oil gets wet again until equilibrium is re-established



Q8 WHAT IS THE BEST MEASUREMENT STRATEGY?

Answer:
Use a combination of parameters for accurate assessment:
- Moisture in Oil (ppm)
- Relative Saturation (%RS)
- Temperature
- Paper Moisture (Estimated)
- DGA (to rule out faults)
- Furan (to assess aging)

BEST PRACTICE
Do not rely on a single parameter. Use multiple parameters and trends.

Q9 WHAT IS THE RECOMMENDED MEASUREMENT FREQUENCY?

Answer:
- Routine testing: Every 6 – 12 months
- For critical transformers: Every 3 – 6 months
- After major events:
  - Overloads
  - Faults
  - Oil handling
  - Maintenance

Q10 WHAT FACTORS AFFECT MOISTURE MEASUREMENT ACCURACY?

Answer:
- Sampling method
- Sample handling & storage
- Temperature at the time of measurement
- Type and calibration of instrument
- Contamination during sampling
- Air exposure

Q11 WHAT IS CONSIDERED A SAFE MOISTURE CONDITION?

Answer:

Moisture in Oil (@ 20–30 °C)

Condition	ppm	%RS
Very Dry	< 10	< 20%
Dry	10 – 20	20 – 40%
Moderate	20 – 30	40 – 60%
Wet	30 – 40	60 – 80%
Very Wet	> 40	> 80%

Estimated Paper Moisture (%)

Condition	%
Very Dry	< 1%
Dry	1 – 2%
Moderate	2 – 3%
Wet	3 – 4%
Very Wet	> 4%

⚠ Higher %RS and higher paper moisture = Higher Risk

Q12 WHAT IS THE GOAL OF MOISTURE MEASUREMENT?

Answer:
- Know the true moisture condition
- Understand the risk
- Track trends
- Take timely action
- Extend insulation life

REMEMBER
Measurement without interpretation is just data. Interpretation converts data into life extension.

KEY TAKEAWAYS

- PPM is the amount of moisture in oil.
- %RS is the risk of the oil (temperature compensated).
- KF titration is the most accurate method.
- Oil moisture and paper moisture are in equilibrium.
- Moisture readings change with time and conditions.
- Moisture returns from paper after filtration.
- Use multiple parameters and trends for correct decisions.
- Accurate measurement + correct interpretation = longer transformer life.

DRYTRANS INSIGHT

Oil testing gives a snapshot.
Trends reveal the story.
Trends drive the strategy.
Strategy extends the life.

OUR PHILOSOPHY

Measure accurately.
Interpret correctly.
Manage continuously.

REFERENCES

- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEC 60814 – Determination of Water by Karl Fischer Titration
- IEC 61550 – Determination of Relative Permittivity, Dissipation Factor and D.C. Resistivity
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- CIGRÉ TB 349 – Moisture Equilibrium and Moisture Assessment
- CIGRÉ TB 741 – Moisture Measurement and Interpretation
- T.V. Oommen – Moisture Equilibrium in Paper–Oil Systems
- Koch & Tenbohlen – Moisture Assessment Using Dielectric Response Methods

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SECTION 5

MOISTURE MEASUREMENT METHODS FOR TRANSFORMER OIL

Choosing the Right Method for Accurate Results

Accurate moisture measurement is critical for assessing transformer insulation condition and making informed decisions. Different methods are available, each with its own principle, advantages, limitations and suitable applications.

KEY MESSAGE

No single method is best for all conditions. Understanding the principles, limitations and proper use of each method ensures reliable moisture assessment and longer transformer life.

Q1 WHAT ARE THE COMMON METHODS TO MEASURE MOISTURE IN OIL?

Answer:

- Karl Fischer Titration (Coulometric/Volumetric)
- Capacitive (Relative Humidity) Probes
- Infrared (IR) Spectroscopy
- Equilibrium (Oil–Paper Equilibrium Method)
- Online Moisture Sensors

Q2 KARL FISCHER TITRATION (COULOMETRIC)

Answer:
The most accurate and widely accepted laboratory method.

Principle:
Moisture reacts with iodine in the reagent. The amount of iodine used is measured electrochemically and is equivalent to the water content.

Advantages:

- Very high accuracy (±1 ppm or better)
- Suitable for very low moisture levels
- Reference method (IEC 60814)

Limitations:

- Time consuming (5–15 minutes per test)
- Requires skilled operator and maintenance
- Laboratory based (not field portable)

Q3 KARL FISCHER TITRATION (VOLUMETRIC)

Answer:
A titration method using volumetric reagent.

Principle:
Moisture reacts with Karl Fischer reagent. The endpoint is detected visually or electronically.

Advantages:

- Good accuracy for higher moisture levels
- Simple setup

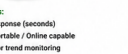
Limitations:

- Lower accuracy than coulometric
- Not suitable for very low moisture (<10 ppm)
- Endpoint detection may be subjective

Q4 CAPACITIVE (RELATIVE HUMIDITY) PROBES

Answer:
Measures moisture based on the relative humidity (aw) of oil.

Principle:
A sensing element changes capacitance with the water activity in oil. The value is converted to ppm using temperature compensation.



Advantages:

- Fast response (seconds)
- Field portable / Online capable
- Good for trend monitoring

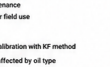
Limitations:

- Requires regular calibration
- Accuracy affected by oil condition
- Not a primary reference method

Q5 INFRARED (IR) SPECTROSCOPY

Answer:
Measures moisture by detecting infrared absorption of water molecules.

Principle:
Water absorbs IR radiation at specific wavelengths. The absorbance is proportional to the moisture content.



Advantages:

- Very fast (seconds)
- Low maintenance
- Suitable for field use

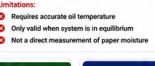
Limitations:

- Requires calibration with KF method
- Accuracy affected by oil type and contaminants
- Not suitable for very low moisture (<10 ppm)

Q6 EQUILIBRIUM (OIL–PAPER EQUILIBRIUM METHOD)

Answer:
Estimates paper moisture based on oil moisture and temperature.

Principle:
At equilibrium, moisture in oil and paper are in balance. Using temperature-corrected equilibrium charts or models, paper moisture is estimated.



Advantages:

- Essential for estimating paper moisture
- Industry standard (IEC 60814, IEEE C57.154)

Limitations:

- Requires accurate oil temperature
- Only valid when system is in equilibrium
- Not a direct measurement of paper moisture

Q7 ONLINE MOISTURE SENSORS

Answer:
Continuously monitors moisture in oil in real-time.

Principle:
Typically uses capacitive or polymer technology to measure water activity or ppm continuously.

Advantages:

- Continuous monitoring
- Early detection of moisture ingress
- Trend analysis and alarms

Limitations:

- Higher initial cost
- Requires periodic verification
- Sensor drift possible over time

Q8 COMPARISON OF METHODS

Method	Accuracy (typical)	Response Time	Field Use	Best Use
Karl Fischer (Coulometric)	±1 ppm or better	5 – 15 min	No	Reference laboratory measurement
Karl Fischer (Volumetric)	±5 – 20 ppm (>20 ppm)	15 – 30 min	No	Higher moisture levels
Capacitive (RH Probe)	±2 – 5 ppm	Seconds	Yes	Field/Online trend monitoring
Infrared Spectroscopy	±2 – 10 ppm	Seconds	Yes	Field quick measurement
Equilibrium Method	N/A (Estimation)	Minutes (Analysis)	No	Paper moisture estimation
Online Sensors	±2 – 5 ppm	Continuous	Yes	Continuous monitoring & alarm

HOW TO CHOOSE THE RIGHT METHOD?

Objective	Recommended Method
Highest accuracy (reference)	Karl Fischer Coulometric
Routine laboratory testing	Karl Fischer Coulometric / Volumetric
Field testing / Quick check	IR Spectroscopy or Capacitive Probe
Continuous online monitoring	Online Moisture Sensor
Estimating paper moisture	Oil–Paper Equilibrium Method
Very low moisture measurement	Karl Fischer Coulometric

BEST PRACTICES

- Use KF titration as the primary reference method.
- Calibrate field instruments regularly with KF results.
- Always measure and record oil temperature.
- Use equilibrium methods only when the system is in thermal equilibrium.
- Monitor trends, not just single values.
- Combine multiple methods for better confidence.

DRYTRANS INSIGHT

Accurate moisture measurement is the foundation of effective moisture management.

Right method
+
Correct interpretation
=
Longer transformer life and higher reliability

KEY TAKEAWAYS

- Different methods are available, each with strengths and limitations.
- KF Coulometric titration is the most accurate reference method.
- Field and online methods are essential for trend monitoring.
- Oil–paper equilibrium helps estimate the true insulation condition.
- Correct method selection leads to correct decisions and asset life extension.

REFERENCES

- IEC 60814 – Determination of Water by Karl Fischer Titration
- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- IEEE C57.154 – Guide for Moisture Equilibrium in Transformer Insulation
- CIGRE TB 741 – Moisture Measurement and Interpretation
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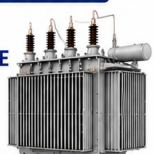
SECTION 6

OIL-PAPER EQUILIBRIUM: THE SCIENCE BEHIND MOISTURE BALANCE

Why Transformer Moisture Always Seeks Balance

Moisture in a transformer is not static. It continuously moves between the oil and the cellulose insulation until both reach an equilibrium condition at a given temperature. Understanding this principle is essential for accurate moisture assessment and effective moisture management.



KEY MESSAGE

Moisture does not stay where it is. It migrates until oil and paper reach equilibrium at the same temperature.

Equilibrium is the foundation of moisture assessment and life management.

Q1 WHAT IS OIL–PAPER EQUILIBRIUM?

Answer:

Oil–paper equilibrium is the condition where moisture in oil and cellulose paper insulation are in balance at a specific temperature.

At equilibrium, there is no net movement of moisture between oil and paper.

Equilibrium = No net moisture movement

Q2 WHY DOES EQUILIBRIUM OCCUR?

Answer:

Moisture naturally migrates:

- From higher concentration to lower concentration
- From higher water activity to lower water activity

This continues until both oil and paper have the same water activity (aw) at a given temperature.

At Equilibrium: No net migration

Q3 WHAT FACTORS AFFECT EQUILIBRIUM?

Answer:

Oil–paper equilibrium depends on:

- ✔ Temperature (most important)
- ✔ Paper type and quality
- ✔ Oil type and condition
- ✔ Total moisture content
- ✔ Pressboard and barriers (minor effect)

Temperature is the dominant factor.
Even small temperature changes significantly shift equilibrium.

Q4 HOW DOES TEMPERATURE AFFECT EQUILIBRIUM?

Answer:

As temperature increases:

- Oil holds more moisture ↑
- Paper holds less moisture ↓
- Equilibrium shifts from paper to oil

As temperature decreases:

- Oil holds less moisture ↓
- Paper holds more moisture ↑
- Equilibrium shifts from oil to paper

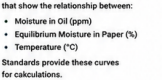
Q5 HOW IS EQUILIBRIUM REPRESENTED?

Answer:

Equilibrium is represented using curves that show the relationship between:

- Moisture in Oil (ppm)
- Equilibrium Moisture in Paper (%)
- Temperature (°C)

Standards provide these curves for calculations.



Q6 HOW CAN WE ESTIMATE PAPER MOISTURE FROM OIL MOISTURE?

Answer:

By using oil–paper equilibrium curves.

Steps:

1. Measure oil moisture (ppm)
2. Note operating temperature (°C)
3. Use equilibrium curve for the oil type
4. Read corresponding paper moisture (%)

EXAMPLE

Oil moisture = 25 ppm
Temperature = 40 °C

From equilibrium curve (mineral oil):
Estimated paper moisture ≈ 2.3%

Q7 IS THE TRANSFORMER ALWAYS AT EQUILIBRIUM?

Answer:

Not always. When conditions change, equilibrium takes time to re-establish.

Examples:

- After oil drying
- After filling with new oil
- After load or temperature change
- After moisture ingress

Equilibration time can range from several days to several weeks, depending on transformer design, temperature, and moisture difference.

Q8 WHY IS EQUILIBRIUM IMPORTANT IN MOISTURE MANAGEMENT?

Answer:

Because all moisture assessments depend on it.

- ✔ Estimating paper moisture
- ✔ Assessing insulation condition
- ✔ Predicting aging and life
- ✔ Planning drying and maintenance
- ✔ Understanding moisture behavior

KEY POINT

Without considering equilibrium, moisture interpretation can be misleading and risky.

TYPICAL EQUILIBRIUM PAPER MOISTURE (%) AT DIFFERENT TEMPERATURES (MINERAL OIL)

Oil Moisture (ppm)	Equilibrium Paper Moisture (%)			
	10 °C	30 °C	50 °C	70 °C
5	1.8	1.1	0.7	0.5
10	2.3	1.4	0.9	0.6
20	2.9	1.8	1.2	0.8
50	3.6	2.3	1.6	1.1
100	4.3	2.9	2.0	1.4
200	4.8	3.4	2.4	1.7
500	5.4	4.1	2.9	2.1
1,000	6.1	4.8	3.4	2.4

Note: Values are typical. Use standard curves for accurate calculation.

EQUILIBRIUM IS THE REASON WHY...

Oil moisture changes with temperature	Equilibrium shifts with temperature.
Paper moisture cannot be measured directly in service	We estimate it using oil–paper equilibrium.
Moisture returns to paper after filtration	Oil becomes dry, so moisture migrates from paper to oil.
Wet climates increase insulation moisture	Oil absorbs moisture until equilibrium with paper is re-established.
Different transformers show different moisture levels	Due to temperature, design, oil type, load and history.

BEST PRACTICES

- ✔ Always consider operating temperature when interpreting moisture.
- ✔ Use oil–paper equilibrium curves from reliable standards.
- ✔ Allow time for equilibration after any change before taking decisions.
- ✔ Track both oil moisture and temperature trends.
- ✔ Understand equilibrium to plan effective drying and maintenance.
- ✔ Interpret moisture data in combination with other tests and trends.

KEY TAKEAWAYS

- ✔ Moisture continuously moves between oil and paper.
- ✔ Equilibrium occurs when both have the same water activity.
- ✔ Temperature is the most critical factor.
- ✔ Oil–paper equilibrium curves help estimate true paper moisture.
- ✔ Equilibrium understanding is essential for correct decisions and longer transformer life.

DRYTRANS INSIGHT

Equilibrium is the hidden rule that controls moisture behavior. Mastering it transforms moisture data into reliable insights and actionable strategies for insulation life management.

REFERENCES

- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEC 60814 – Determination of Water by Karl Fischer Titration
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- IEEE C57.91 – Moisture Equilibrium Models for Transformer Insulation
- CIGRÉ TB 349 – Moisture Equilibrium and Moisture Assessment
- CIGRÉ TB 741 – Moisture Measurement and Interpretation
- T.V. Oommen – Moisture Equilibrium in Paper–Oil Insulation Systems
- Koch & Tenbohlen – Moisture Assessment Using Dielectric Response Methods

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ESTIMATING PAPER MOISTURE: FROM OIL MEASUREMENT TO INSULATION INSIGHT

The Key to Understanding True Insulation Condition

Direct measurement of paper moisture is not possible in service. However, by using oil test results and temperature, we can accurately estimate paper moisture using oil–paper equilibrium principles and proven models.

KEY MESSAGE

Oil test + Temperature + Equilibrium Model = Estimated Paper Moisture = Real Insulation Condition = Better Decisions & Longer Life

Q1 WHY CAN'T WE MEASURE PAPER MOISTURE DIRECTLY?

Answer:
Paper moisture is locked inside the transformer insulation and cannot be measured without disassembling the active part.

Therefore, we estimate it indirectly using science.

Q2 WHAT IS THE PRINCIPLE BEHIND PAPER MOISTURE ESTIMATION?

Answer:
Oil and paper are in equilibrium. At a given temperature, they reach a balance where:

Moisture in Oil ⟷ Moisture in Paper

If we know the moisture in oil (ppm) and temperature, we can calculate the corresponding paper moisture (%).

Q3 WHAT INPUTS ARE REQUIRED TO ESTIMATE PAPER MOISTURE?

Answer:
We need three inputs:

- Moisture in Oil (ppm)
- Temperature (°C)
- Oil–Paper Equilibrium Model (e.g., IEEE / IEC / CIGRÉ models)

Oil Moisture (ppm) + Temperature (°C) = Estimated Paper Moisture (%)

Q4 WHICH MODELS ARE USED FOR ESTIMATION?

Answer:
Commonly used and widely accepted models:

- IEEE C57.106
- IEC 60422
- CIGRÉ TB 349
- Duval Triangle / Moisture Equilibrium Curves

All models are based on extensive research and field data.

Q5 HOW IS PAPER MOISTURE CALCULATED?

Answer:
Moisture in oil and temperature are used in the equilibrium equation or curve to obtain the corresponding paper moisture.

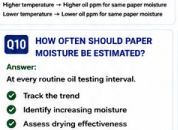
Example (conceptual):

Oil Moisture (ppm) + Temperature (°C)
↓
Equilibrium Model / Curve
↓
Estimated Paper Moisture (%)

Different models use equations, tables or curves.

Q6 WHAT IS A TYPICAL OIL–PAPER EQUILIBRIUM CURVE?

Answer:
The curve shows the relationship between oil moisture (ppm) and equilibrium paper moisture (%) at different temperatures.



Higher temperature → Higher oil ppm for same paper moisture
Lower temperature → Lower oil ppm for same paper moisture

Q7 WHAT IS A GOOD, ACCEPTABLE OR HIGH PAPER MOISTURE?

Answer:
General guideline for in-service transformers (cellulose insulation):

Estimated Paper Moisture (%)	Condition
< 1%	Very Dry
1 – 2%	Preferred (Good)
2 – 3%	Acceptable
3 – 4%	Elevated (Monitor Closely)
> 4%	High Risk

Higher paper moisture = Higher aging rate = Higher risk of insulation failure

Q8 HOW ACCURATE IS PAPER MOISTURE ESTIMATION?

Answer:
When good quality oil test data, correct temperature and proven models are used, the estimation accuracy is typically:

± 10% to 15%

of the actual paper moisture.

This is sufficiently accurate for asset management and life assessment decisions.

Q9 WHAT FACTORS AFFECT ESTIMATION ACCURACY?

Answer:

- Accuracy of oil moisture measurement
- Accuracy of temperature
- Correct model for oil type
- Transformer design and oil circulation
- Equilibrium status of the insulation system
- Recent drying or oil change

Correct data + Correct model = Reliable estimation

Q10 HOW OFTEN SHOULD PAPER MOISTURE BE ESTIMATED?

Answer:
At every routine oil testing interval.

- Track the trend
- Identify increasing moisture
- Assess drying effectiveness
- Plan maintenance and drying strategies

Trend analysis is more important than single value.

Q11 HOW DOES PAPER MOISTURE HELP IN LIFE ASSESSMENT?

Answer:
Paper moisture is the foundation for:

- Aging rate calculation
- Loss of Life estimation
- Remaining Life prediction
- Drying requirement decision
- Risk assessment

If paper moisture is high, life consumption accelerates.

Q12 WHAT IS THE GOAL OF PAPER MOISTURE ESTIMATION?

Answer:
To reveal the hidden insulation condition and take timely actions to:

- Control aging
- Maintain dielectric strength
- Prevent failures
- Optimize maintenance
- Extend transformer life

Know the paper moisture, know the true condition.

EXAMPLE: PAPER MOISTURE ESTIMATION

Using IEEE C57.106 Equation (Mineral Oil)

Oil Moisture (ppm)	Temperature (°C)	Estimated Paper Moisture (%)	
		Typical Range	Approx. Value
10	20	0.8 – 1.1	~ 0.9%
20	20	1.5 – 1.9	~ 1.7%
30	20	2.2 – 2.8	~ 2.5%
40	20	2.9 – 3.6	~ 3.2%
60	20	4.3 – 5.1	~ 4.7%

Note: Values are approximate. Use exact model/curves for precise calculation.

OIL–PAPER EQUILIBRIUM: KEY FACTS

- Moisture migrates until oil and paper reach equilibrium at the same temperature.
- Temperature changes shift equilibrium. Re-equilibration takes time.
- After any drying, oil change or moisture ingress, equilibrium must be re-established.
- Paper holds 95–99% of total moisture. Oil holds only 1–5%.
- Small change in oil moisture can mean large change in paper moisture.

BEST PRACTICES

- Always use accurate oil moisture and temperature.
- Use appropriate equilibrium model for the oil type.
- Record estimated paper moisture at every test.
- Monitor the trend, not just the single reading.
- Combine with other tests (DGA, Furan, DF, TAN) for better understanding.
- Plan drying strategy based on paper moisture and aging rate.

KEY TAKEAWAYS

- Paper moisture is the most important indicator of insulation health.
- It cannot be measured directly, but it can be accurately estimated.
- Oil–paper equilibrium is the scientific principle behind estimation.
- Accurate estimation enables better decisions and longer transformer life.

DRYTRANS INSIGHT

You cannot manage what you cannot measure.
Paper moisture estimation turns invisible moisture into actionable insight.
Insight drives action. Action extends life.

REFERENCES

- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- CIGRÉ TB 349 – Moisture Equilibrium and Moisture Assessment
- T.V. Oommen – Moisture Equilibrium in Paper-Oil Systems
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SECTION 8

INSULATION LIFE MODELS: PREDICTING TRANSFORMER LIFE

Turning Data into Remaining Life

Insulation life is consumed by moisture, temperature and chemical aging. Life models combine these factors to predict aging rate and estimate remaining useful life (RUL) of a transformer.

KEY MESSAGE

Life models help answer the most important question:

"How much life is left?"

Use the right model, with the right inputs, and interpret results wisely.

Q1 WHY DO WE NEED LIFE MODELS?

Answer:
Because insulation aging is a continuous process that cannot be measured directly.

Life models help us:

- ✔ Quantify aging rate
- ✔ Estimate remaining life (RUL)
- ✔ Compare transformers
- ✔ Plan maintenance and replacement
- ✔ Optimize asset life and cost

Models convert data into decisions and strategy.

Q2 WHAT ARE THE MAIN LIFE CONSUMPTION FACTORS?

Answer:
Insulation life is consumed by three primary factors:

- Moisture (Accelerates aging)
- Temperature (Most dominant)
- Chemical Degradation (Oil aging, acidity, etc.)

These factors work together. Ignoring one leads to wrong conclusions.

Q3 WHAT ARE THE COMMON LIFE MODELS USED?

Answer:
The most widely used insulation life models are:

- ✔ IEEE C57.91 (Mineral Oil & Paper Insulation)
- ✔ IEC 60422 (Mineral Oil Insulation)
- ✔ Duval Triangle / Moisture Equilibrium Curves (Support Models)
- ✔ Arrhenius Model (Temperature Effect)
- ✔ Moisture Diffusion / Equilibrium Models

IEEE C57.91 is the most accepted standard for life assessment.

Q4 WHAT IS IEEE C57.91 MODEL BASED ON?

Answer:
IEEE C57.91 is based on:

- ✔ Arrhenius equation (temperature effect)
- ✔ Inverse power law (moisture effect)
- ✔ Empirical aging data from field and laboratory

Basic Principle:
Aging rate increases exponentially with temperature and increases with paper moisture content.

Q5 HOW DOES TEMPERATURE AFFECT AGING?

Answer:
Aging rate doubles for every 6–7 °C increase in average winding temperature. (Arrhenius Rule)

Relative Aging Factor (F_T)
Compared to 98 °C reference:

Hot-Spot Temp (°C)	Aging Factor (Approx.)
80	0.25
90	0.50
98 (Reference)	1.00
110	2.00
120	4.00
130	8.00

Lower temperature = Exponential life gain

Q6 HOW DOES MOISTURE AFFECT AGING?

Answer:
Aging rate increases with paper moisture. IEEE C57.91 uses an inverse power law.

Moisture Aging Factor (F_M)
(Example at 98 °C)

Paper Moisture (%)	Moisture Factor (Approx.)
0.5	0.25
1.0	0.56
2.0	1.00 (Reference)
3.0	1.70
4.0	2.70
5.0	4.20

Higher moisture = Higher aging rate

Q7 HOW IS AGING RATE CALCULATED?

Answer:
IEEE C57.91 calculates Aging Acceleration Factor (AAF):

$$AAF = F_T \times F_M \times F_C$$

Where:

- F_T = Temperature aging factor
- F_M = Moisture aging factor
- F_C = Chemical aging factor (Oil condition)

$$\text{Aging Rate (\%)} = AAF \times 100$$

Example:
If AAF = 2.5 → Aging rate = 250%
(Aging 2.5 times faster than reference condition)

Q8 HOW IS REMAINING LIFE (RUL) ESTIMATED?

Answer:
Remaining Life is the ratio of Remaining Life Consumption to Aging Rate.

$$\text{RUL (Years)} = \frac{100 - \text{Life Consumed (\%)}}{\text{Aging Rate (\% per year)}}$$

Where:
Life Consumed (%) = Total aging already occurred
Aging Rate (%/year) = Current aging speed

RUL is dynamic, not static. It changes with condition.

Q9 WHAT INPUTS ARE REQUIRED FOR LIFE MODELS?

- ✔ Moisture in oil (ppm)
- ✔ Paper moisture (%)
- ✔ Hot-spot / Top-oil temperature (°C)
- ✔ Average load / loading history
- ✔ Oil condition (TAN / acidity)
- ✔ Transformer design data (paper type, insulation class)

Q10 EXAMPLE: LIFE ESTIMATION

Answer:
Given:

- Top-oil temp = 70 °C (Hot-spot ≈ 85 °C)
- Paper moisture = 2.5%
- Oil TAN = 0.05 mgKOH/g
- Life consumed = 30%

Calculated:

- F_T = 0.35
- F_M = 1.35
- F_C = 1.10

→ AAF = 0.35 × 1.35 × 1.10 = 0.52
→ Aging Rate = 52% per year

RUL = (100 − 30) / 52 = 1.35 years

Q11 WHAT ARE THE LIMITATIONS OF LIFE MODELS?

Answer:

- ✔ Models are based on assumptions and averages
- ✔ Extreme faults or events are not predicted
- ✔ Input accuracy directly affects output
- ✔ Different models may give different results
- ✔ Not a replacement for engineering judgment

Models are guides, not guarantees. Always use with engineering experience and trends.

Q12 WHAT IS THE GOAL OF LIFE ASSESSMENT?

Answer:

- ✔ Know the true insulation health
- ✔ Prioritize assets
- ✔ Plan maintenance intelligently
- ✔ Avoid unexpected failures
- ✔ Optimize replacement timing
- ✔ Extend life safely and economically

Right assessment today = Reliable transformer tomorrow.

AGING ACCELERATION FACTORS (TYPICAL VALUES)

Parameter	Reference	Lower Than Reference	Higher Than Reference
Temperature (Hot-Spot)	98 °C	↓ Aging rate	↑↑ Aging rate
Paper Moisture	2.0%	↓ Aging rate	↑ Aging rate
Oil Acidity (TAN)	0.03 mgKOH/g	Slight effect	↑ Aging rate
Load Factor	100%	↓ Aging rate	↑ Aging rate

IEEE C57.91 REFERENCE CONDITION

- 98 °C — Hot-Spot
- 2.0% — Paper Moisture
- 0.03 mgKOH/g — Oil TAN
- 100% — Load Factor

KEY TAKEAWAYS

- ✔ Life is consumed by moisture, temperature and chemistry.
- ✔ Temperature is the most dominant factor.
- ✔ Moisture is the second most important factor.
- ✔ Models help quantify aging and estimate RUL.
- ✔ Good inputs = Good outputs.
- ✔ Use models with trends, tests and judgment.

DRYTRANS INSIGHT

Data without interpretation is just numbers. Use life models to turn data into actionable insights and strategic decisions.

BEST PRACTICES

- ✔ Maintain accurate test data and trends.
- ✔ Measure moisture and temperature regularly.
- ✔ Use IEEE C57.91 as the primary life model.
- ✔ Update RUL after every test.
- ✔ Combine model results with DGA, Furan, DF, TAN.
- ✔ Focus on controlling moisture and temperature.
- ✔ Plan maintenance based on life assessment.

REFERENCES

- IEEE C57.91 – Guide for Loading Mineral-Oil-Immersed Transformers
- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEC 60141 – Guide for the Loading of Power Transformers
- CIGRE TB 349 – Moisture Equilibrium and Moisture Assessment
- Duval, M. – Interpretation of Dissolved Gas Analysis
- Koch & Tenbohlen – Moisture Assessment Using Dielectric Response Methods

REMEMBER

Insulation life is not about age, it is about condition. Manage the condition, extend the life.

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SECTION 9

POWER OF TRENDS : INTERPRETING MOISTURE DATA OVER TIME

From Single Data Points to Reliable Insights

A single test is only a snapshot.
Trends reveal the real story of transformer insulation health.
Consistent monitoring and correct interpretation of moisture trends enable early action, risk reduction and life extension.

KEY MESSAGE

Trends, not single readings, drive correct decisions.

Measure → Trend → Interpret → Act → Extend Life

Q1 WHY ARE TRENDS MORE IMPORTANT THAN SINGLE READINGS?

Answer:

- Moisture is dynamic, not static
- Single reading can be misleading
- Trends show direction and rate of change
- Trends enable prediction and prevention
- Trends support risk-based asset management

A trend is the real indicator of insulation behavior.

Q2 WHAT DOES AN INCREASING MOISTURE TREND INDICATE?

Answer:
An increasing trend suggests:

- Moisture ingress
- Breather issue
- Seal leakage
- High ambient humidity
- Oil degradation affecting equilibrium

Early action can prevent insulation acceleration and failures.

Q3 WHAT DOES A DECREASING MOISTURE TREND INDICATE?

Answer:
A decreasing trend suggests:

- Effective drying or filtration
- Good sealing and breather condition
- Lower ambient humidity
- Stable or improving insulation condition

Keep doing what is working and continue monitoring.

Q4 WHAT IS A STABLE MOISTURE TREND?

Answer:
A stable trend indicates:

- Equilibrium is maintained
- No significant moisture ingress
- Insulation system is under control
- Continue routine monitoring

Stable is good, but continuous monitoring is still essential.

Q5 HOW OFTEN SHOULD MOISTURE BE MONITORED TO BUILD TRENDS?

Answer:

- Every 6 months to 1 year
- Across different climatic conditions (summer, monsoon, winter)
- After major maintenance or events

Consistency in frequency creates reliability in trends.

Q6 WHAT FACTORS AFFECT MOISTURE TRENDS?

Answer:
Trends can be influenced by:

- Temperature variations
- Ambient humidity
- Load cycles
- Moisture ingress
- Oil quality and degradation

Always evaluate trends along with operating and environmental conditions.

Q7 HOW DO YOU INTERPRET MOISTURE TRENDS CORRECTLY?

Answer:
Use the 3R principle:

1. REVIEW – Look at long-term data (at least 2–3 years)
2. RELATE – Relate with temperature, load and events
3. RESPOND – Take action based on the trend direction and rate

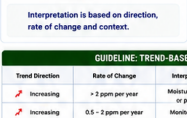
Right interpretation leads to right action.

Q8 WHAT ACTIONS SHOULD BE TAKEN BASED ON TRENDS?

Answer:

Trend	Recommended Action
Increasing	• Investigate ingress sources • Check breather & seals • Consider drying/filtration • Increase monitoring frequency
Stable	• Continue routine monitoring • Verify equilibrium condition • Maintain current practices
Decreasing	• Continue drying/filtration • Monitor to reach target • Prevent re-ingress

Q9 EXAMPLE: MOISTURE TREND INTERPRETATION



Interpretation is based on direction, rate of change and context.

Q10 HOW LONG OF A DATA HISTORY IS REQUIRED?

Answer:
For meaningful trend analysis:

- Minimum 2 years of data preferred
- More data = higher confidence
- Include different seasons and load conditions

Patience in data collection leads to confidence in decisions.

Q11 WHAT ARE THE BENEFITS OF TREND-BASED DECISIONS?

Answer:

- Early detection of problems
- Prevents insulation acceleration
- Optimizes maintenance and spending
- Extends transformer life
- Improves reliability and safety
- Supports asset management and planning

Trends turn data into action and value.

Q12 WHAT IS THE GOAL OF TREND ANALYSIS?

Answer:

- Understand insulation behavior
- Predict future condition
- Prevent failures
- Plan right actions at right time
- Extend life safely and economically

The goal is not just data, the goal is longer life and higher reliability.

GUIDELINE: TREND-BASED ASSESSMENT

Trend Direction	Rate of Change	Interpretation	Risk Level	Action Priority
Increasing	> 2 ppm per year	Moisture ingress or problem	High	Immediate
Increasing	0.5 – 2 ppm per year	Monitor closely	Medium	High
Stable	± 0.5 ppm per year	Under control	Low	Routine
Decreasing	Any	Improving	Low	Maintain & Monitor

Rate of change must be evaluated along with temperature and operating conditions.

GOOD DATA PRACTICES

- Use calibrated instruments
- Maintain consistent test methods
- Record temperature with each test
- Use the same sampling points
- Keep good data records
- Validate data quality

DRYTRANS INSIGHT

Moisture trends reveal hidden problems before they become failures. They enable proactive management instead of reactive actions.

Measure consistently.
Track trends. Interpret wisely.
Act early. Extend life.

KEY TAKEAWAYS

- Trends are more meaningful than single readings.
- Increasing trend = Risk, Decreasing trend = Improvement, Stable trend = Control.
- Interpret trends with context, not in isolation.
- Trend-based actions prevent failures and extend life.

REFERENCES

- IEC 60422 – Mineral Insulating Oils in Electrical Equipment
- IEC 60464 – Guide for the Interpretation of Dissolved and Free Gases Analysis
- IEEE C57.91 – Guide for Loading Mineral-Oil-Immersed Transformers
- CIGRE TB 349 – Moisture Equilibrium and Moisture Assessment

REMEMBER

Data is history.
Trends are understanding.
Action is protection.
Protection is reliability.

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SECTION 10

FURAN ANALYSIS: MEASURING PAPER AGING

Understanding Insulation Life Consumption

Furan compounds are formed when cellulose insulation (paper) degrades due to heat and moisture. Furan analysis is a proven method to quantify paper aging and estimate remaining life of a transformer.

KEY MESSAGE

Furan analysis tells you how much life the paper has already consumed – so you can act before it becomes risky.

Q1 WHAT IS FURAN ANALYSIS?

Answer:
Furan analysis measures furanic compounds dissolved in transformer oil. These compounds are by-products of cellulose (paper) degradation.

Main furans:

- 2-Furfural (2-FAL)
- 5-Hydroxymethylfurfural (5-HMF)
- 2-Acetylfuran (2-ACF)
- 5-Methylfurfural (5-MEF)
- 2-Furfuryl alcohol (2-FOL)

Furan = Direct indicator of paper aging.

Q2 HOW ARE FURANS FORMED?

Answer:
Furans are formed when cellulose breaks down due to:

- Heat (high temperature)
- Moisture (high paper moisture)
- Time (long-term aging)

Heat and moisture accelerate cellulose breakdown exponentially.

Q3 WHAT DOES FURAN LEVEL INDICATE?

Answer:
Furan level indicates the percentage of paper life already consumed.

Higher furan = More aging = Less remaining life

Benefits:

- ✔ Quantifies paper aging
- ✔ Helps estimate remaining life (RUL)
- ✔ Supports maintenance planning
- ✔ Helps in risk-based decisions

Q4 WHICH STANDARD IS USED?

Answer:
IEC 61198 is the most widely used standard for furan interpretation.

It provides:

- Life consumed (%) calculation
- Aging severity classification
- Guidance for decision making

IEC 61198 – Industry accepted worldwide.

Q5 HOW ARE FURANS MEASURED?

Answer:
Furans are measured using HPLC (High Performance Liquid Chromatography) with UV detection.

Key requirements:

- Proper sampling (oil)
- Clean and representative sample
- Calibrated instrument
- Correct method as per IEC 61198

Q6 HOW IS LIFE CONSUMED (%) CALCULATED?

Answer:
IEC 61198 uses empirical equations based on 2-FAL (and total furans) to calculate Life Consumed (%).

Example (simplified using 2-FAL):

$$\text{Life Consumed (\%)} = D \times \text{2-FAL (ppm)}^{0.81}$$

Where D = Ageing Acceleration Factor (based on temperature & paper moisture)

Always use tools/software or laboratory reports for accurate calculation.

Q7 HOW IS AGING SEVERITY INTERPRETED?

Answer:
IEC 61198 classification:

Life Consumed (%)	Aging Condition
< 10%	Very Low
10 – 20%	Low
20 – 40%	Moderate
40 – 60%	High
> 60%	Very High

Above 40% life consumed, risk of insulation failure increases significantly.

Q8 WHAT FACTORS AFFECT FURAN RESULTS?

Answer:
Furan formation depends on:

- ✔ Temperature (most critical)
- ✔ Paper moisture content
- ✔ Oil quality
- ✔ Oxygen exposure
- ✔ Transformer design & hot spots

Control temperature and moisture to slow down paper aging.

TYPICAL FURAN GUIDELINE (IEC 61198)

Life Consumed (%)	Aging Condition	Recommended Action
< 10%	Very Low	Continue routine monitoring
10 – 20%	Low	Continue monitoring
20 – 40%	Moderate	Plan maintenance, control moisture & temperature
40 – 60%	High	Investigate, reduce stress, consider refurbishment
> 60%	Very High	High risk – plan major intervention / replacement

Guidelines may vary based on utility experience and risk tolerance.

BEST PRACTICES

- ✔ Sample oil properly and avoid contamination.
- ✔ Use accredited laboratory and IEC 61198 method.
- ✔ Measure 2-FAL and total furans.
- ✔ Record paper moisture and hot-spot temperature.
- ✔ Calculate Life Consumed (%) using IEC 61198.
- ✔ Track trend over time, not just single value.
- ✔ Combine furan with DGA, moisture and DF for complete picture.
- ✔ Act early when furan trend is increasing.

FURAN – THE BOTTOM LINE

Furan analysis measures what has already happened.

It helps you understand how much life is left – so you can take the right action, at the right time.

Measure – Interpret – Act = Longer Life & Lower Risk

KEY TAKEAWAYS

- ✔ Furans are by-products of cellulose degradation.
- ✔ Furan level indicates life consumed (%).
- ✔ IEC 61198 is the standard for interpretation.
- ✔ Higher furan = More aging = Less remaining life.
- ✔ Trend analysis is more important than single value.

DRYTRANS INSIGHT

Furan analysis, when combined with moisture, temperature and DGA, provides the most reliable view of insulation aging and remaining life.

REFERENCES

- IEC 61198 – Mineral oil-impregnated electrical equipment in service – Guidance on the interpretation of dissolved and free furans
- IEC 60422 – Mineral insulating oils in electrical equipment
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- CIGRE TB 761 – Ageing of Paper and Moisture Equilibrium
- Duval M. – The Transformer Furan Handbook

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SECTION 11

DGA INTERPRETATION: DETECTING DEVELOPING FAULTS EARLY

Gases Speak First – Listen Early, Act Early

Dissolved Gas Analysis (DGA) detects gases generated by thermal and electrical faults in transformer insulation. Interpreting DGA correctly helps identify the type, severity and evolution of faults – before they become failures.

KEY MESSAGE

DGA is not just numbers.
It is an early warning system.

Correct interpretation =
Early action = Prevent failures,
Reduce downtime, Extend life.

01 WHAT IS DGA?

Answer:

DGA measures the concentration of dissolved gases in transformer oil that are produced due to thermal and electrical faults.

Key gases:

H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2

DGA detects faults before major damage occurs.

02 HOW ARE GASES GENERATED?

Answer:

Faults create heat and electrical energy that break down oil and paper, producing gases.

Main sources:

- Electrical discharges (PD, arcing)
- Overheating (low or high temperature)
- Severe overheating / burning
- Oil and paper degradation

03 WHAT DOES EACH GAS INDICATE?

Answer:

Gas	Indicates
H_2	Partial Discharge (PD)
CH_4	Low temperature overheating
C_2H_6	Higher temperature overheating
C_2H_4	High temperature overheating
C_2H_2	Very high temperature / arcing
CO	Paper insulation overheating
CO_2	Paper insulation overheating

No single gas gives the answer. Look at the complete picture.

04 WHAT ARE THE COMMON FAULT TYPES?

Answer:

DGA helps identify:

- Partial Discharge (PD)
- Low temperature overheating (T1)
- Medium temperature overheating (T2)
- High temperature overheating (T3)
- Arcing / Discharges
- Thermal faults in paper
- Tracking (surface discharges)

Identify the fault, not just the gas.

05 WHICH METHODS ARE USED FOR DGA INTERPRETATION?

Answer:

Common interpretation methods:

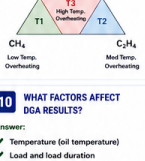
- Key Gas Method (IEC 60599)
- Duval Triangle Method (IEC 60599)
- Duval Pentagon Method (IEC 60599)
- Doernenburg Ratio Method
- IEC 62770 (Rogers Ratios)

Use methods together. Cross-check for accuracy.

06 DUVAL TRIANGLE: HOW DOES IT WORK?

Answer:

Plot % CH_4, % C_2H_4 and % C_2H_2 (based on total combustible gases) to locate the fault zone.



07 WHAT IS THE IMPORTANCE OF GAS TRENDS?

Answer:

- A single test is a snapshot.
- Trends reveal the story.
- Increasing gas levels = Active or escalating fault
- Stable gas levels = Condition under control
- Decreasing gas levels = Fault mitigating

Trend is more important than absolute value.

08 WHAT ACTIONS SHOULD BE TAKEN BASED ON DGA?

Answer:

Take action based on:

- Fault type
- Fault severity
- Rate of gas increase
- Transformer criticality
- Operating condition

High-risk trend requires immediate attention. Do not wait.

09 HOW OFTEN SHOULD DGA BE PERFORMED?

Answer:

- Every 6 months to 1 year
- For critical transformers: 3–6 months
- After fault, maintenance or filtering
- Across different load and temperature conditions

Consistent monitoring builds confidence.

10 WHAT FACTORS AFFECT DGA RESULTS?

Answer:

- Temperature (oil temperature)
- Load and load duration
- Oil condition and age
- Moisture and paper condition
- Recent maintenance activities

Always interpret DGA with operating context.

11 LIMITATIONS OF DGA INTERPRETATION?

Answer:

- Overlapping fault zones
- New oil may mask gas generation
- Inactive faults may not produce gas
- Requires experience and correlation
- Not a replacement for other tests

Use DGA with moisture, furan, DF, and other tests.

12 WHAT IS THE GOAL OF DGA PROGRAM?

Answer:

- Detect developing faults early
- Understand fault type and severity
- Track fault evolution over time
- Plan timely maintenance
- Prevent failures and downtime
- Extend transformer life

Early detection. Safe operation. Long life.

TYPICAL DGA GAS RANGES (ppm) – GUIDE ONLY*

Fault Condition	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
Normal	<100	<120	<65	<50	<1	<350	<2500
PD Activity	100–700	<120	<65	<50	<1	<350	<2500
Low Temp Overheating (T1)	<100	120–400	<65	<50	<1	<350	2500–4000
Med Temp Overheating (T2)	<100	400–1000	65–300	50–200	<1	350–570	4000–10,000
High Temp Overheating (T3)	100–700	>1000	>300	>200	<1	570–1400	>10,000
Arcing / Discharges	>700	>1000	>300	>200	>1	>1400	>10,000

*Values are indicative. Use standards and experience for final assessment.

BEST PRACTICES

- Sample correctly and avoid contamination.
- Use IEC 60599 and IEC 62770 methods.
- Interpret with trends and operating data.
- Combine with moisture, furan, DF, TAN.
- Maintain healthy oil and keep moisture low.
- Act early on abnormal trends.

DGA INTERPRETATION CHECKLIST

- Sample taken correctly?
- Oil temperature recorded?
- All key gases measured?
- Trends analyzed?
- Method cross-checked?
- Fault type identified?
- Severity assessed?
- Action plan defined?

KEY TAKEAWAYS

- Gases are the early indicators of faults.
- Interpretation needs method + experience + context.
- Trends drive correct actions.
- Act early, prevent failures, extend life.

DRYTRANS INSIGHT

DGA is your transformer's early warning system. Listen to the gases, understand the message, and act before it is too late.

REFERENCES

- IEC 60599 – Mineral oil-immersed electrical equipment – Guidance on the interpretation of dissolved and free gases
- IEC 62770 – Dissolved gas analysis (DGA) of mineral insulating oils
- IEEE C57.104 – Guide for the interpretation of gases in transformers
- Duval, M. – The Transformer Furan Handbook

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SECTION 12

MAKING IT ACTIONABLE: FROM DATA TO DECISIONS

Turning Insights into Reliability and Life

Data has value only when it leads to the right action.
A structured approach converts test results and trends into decisions that improve transformer reliability, reduce risk and extend asset life.

KEY MESSAGE

Data → Insight → Decision → Action

- ✔ Understand the true condition
- ✔ Take the right action
- ✔ Reduce risk and downtime
- ✔ Extend transformer life

01 WHY IS ACTION BASED ON INSIGHT IMPORTANT?

Answer:
Because transformer failures are preventable. Acting on insights:

- ✔ Prevents small issues from becoming big problems
- ✔ Optimizes maintenance spending
- ✔ Improves reliability and availability
- ✔ Extends useful life

Insight without action does not create value.

02 WHAT STEPS TURN DATA INTO ACTION?

Answer:

1. Collect accurate test data
2. Analyze trends and relationships
3. Interpret using engineering knowledge
4. Identify risk and priority
5. Decide the right action
6. Implement and verify

Follow a structured decision process.

03 HOW DO YOU PRIORITIZE TRANSFORMERS?

Answer:
Use risk-based prioritization based on:

- ✔ Moisture level and trend
- ✔ Aging (furan, acidity, methanol)
- ✔ DGA and fault risk
- ✔ Load and criticality
- ✔ Consequence of failure

Focus on high-risk assets first.

04 WHAT ACTIONS CAN BE TAKEN IMMEDIATELY?

Answer:
If moisture is high or trending up:

- ✔ Improve sealing and breather condition
- ✔ Start online or offline drying
- ✔ Reduce ingress sources
- ✔ Increase monitoring frequency

Early action prevents acceleration of aging.

05 WHEN SHOULD DRYING BE CONSIDERED?

Answer:
Consider drying when:

- ✔ Moisture is above target
- ✔ Moisture trend is rising
- ✔ Paper moisture is high
- ✔ After major maintenance or oil ingress event

Moisture control is the most effective life extension strategy.

06 HOW DO YOU SET TARGETS?

Answer:
Typical targets (guideline):

- Oil Moisture ≤ 15 ppm
- Paper Moisture ≤ 2.0%
- Relative Saturation (RS) ≤ 60%
- Water Activity (aw) ≤ 0.30

Targets may vary based on transformer and environment.

07 HOW DO YOU CONFIRM ACTION EFFECTIVENESS?

Answer:
Verify with trend improvement in:

- ✔ Moisture (oil & paper)
- ✔ RS% and aw
- ✔ DGA gases
- ✔ Dielectric performance
- ✔ Aging indicators

Measure → Monitor → Confirm → Continue.

08 HOW OFTEN SHOULD YOU REVIEW AND UPDATE?

Answer:
Review insights and decisions:

- ✔ After every test cycle
- ✔ After major events
- ✔ When trends change
- ✔ At least annually for strategy

Continuous review keeps the strategy relevant and effective.

09 WHAT TO DOCUMENT?

Answer:
Maintain a complete record of:

- ✔ Test results and trends
- ✔ Interpretation and insights
- ✔ Decisions taken
- ✔ Actions implemented
- ✔ Results after action

Good documentation builds knowledge and supports decisions.

10 HOW DOES THIS IMPACT MAINTENANCE?

Answer:
It enables:

- ✔ Condition-based maintenance
- ✔ Right activity at the right time
- ✔ Avoids unnecessary work
- ✔ Reduces downtime
- ✔ Improves life-cycle cost

From reactive to proactive maintenance.

11 WHAT IS THE END GOAL?

Answer:
To achieve:

- ✔ Healthy insulation system
- ✔ Lower risk of failure
- ✔ Higher reliability and availability
- ✔ Longer asset life
- ✔ Better ROI

Reliable transformers. Stronger grid. Lower cost.

12 WHAT IS THE DRYTRANS APPROACH?

Answer:
We help utilities:

- ✔ Understand the real condition
- ✔ Interpret with engineering insight
- ✔ Recommend the right actions
- ✔ Support implementation
- ✔ Ensure measurable results

Your partner in moisture management and reliability.

CONDITION ASSESSMENT – ACTION MATRIX

Condition	Moisture (Oil ppm)	Trend	Risk Level	Recommended Action
Good	≤ 15	Stable or Decreasing	Low	Continue routine monitoring. Maintain sealing & breather.
Caution	15 – 30	Stable	Medium	Increase monitoring. Improve ingress control. Consider drying.
Warning	30 – 60	Increasing	High	Start drying immediately. Investigate ingress. Increase test frequency.
Critical	> 60	Increasing Rapidly	Very High	Immediate drying. Detailed investigation. Monitor closely.

Risk level depends on overall insulation condition, load, age and criticality.

DECISION FRAMEWORK

1. **Collect Data** – Oil, Paper, DGA, Electrical, Temperature, Load, etc.
2. **Analyze & Interpret** – Identify trends, relationships and root causes.
3. **Assess Risk & Priority** – Evaluate impact and consequence.
4. **Decide Action** – Select the most effective action.
5. **Implement & Verify** – Take action, monitor results and confirm improvement.
6. **Document & Review** – Record, learn and improve continuously.

BEST PRACTICES FOR ACTIONABLE INSIGHTS

- ✔ **Understand the Whole Picture** – Look at all parameters together, not in isolation.
- ✔ **Trust Trends, Not Single Tests** – Trends reveal the real story.
- ✔ **Act Early** – Early action is faster, easier and cheaper.
- ✔ **Control Moisture Continuously** – Moisture is the primary driver of insulation life.
- ✔ **Use the Right Tools** – Accurate testing and reliable data are essential.
- ✔ **Build Knowledge** – Every transformer has a history – use it.
- ✔ **Review and Improve** – Keep improving your process and decisions.

KEY TAKEAWAYS

- ✔ Data becomes valuable only when acted upon.
- ✔ Use a structured approach to make better decisions.
- ✔ Moisture control delivers the highest impact.
- ✔ Trends, not single readings, drive reliability.
- ✔ Right action at the right time extends life.

DRYTRANS INSIGHT

We turn data into actionable insights and actionable insights into results. Better decisions today for a more reliable tomorrow.

REFERENCES

- IEC 60599 – Mineral oil-impregnated electrical equipment
- IEC 60247 – Guide to the loading of power transformers
- IEEE C57.106 – Guide for acceptance and maintenance of insulating oil
- IEEE C57.91 – Guide for loading mineral-oil-immersed transformers
- CIGRE TB 349 – Moisture equilibrium and moisture assessment
- Duval M. – The Transformer DGA Book
- Koch & Tenbohlen – Transformer Assessment Using Dielectric Response

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SECTION 13

MOISTURE MANAGEMENT STRATEGIES: PROTECT, CONTROL, EXTEND LIFE

Proactive Moisture Control is Proactive Asset Management

Moisture is the #1 driver of insulation failure. A strong moisture management strategy prevents aging, improves reliability, and significantly extends transformer life.

KEY MESSAGE

You cannot eliminate moisture completely, but you can control it continuously.

Control moisture = Control aging
Control aging = Extend life

01 WHY IS MOISTURE MANAGEMENT CRITICAL?

Answer:

- ✓ Moisture accelerates insulation aging
- ✓ Reduces dielectric strength
- ✓ Increases risk of fault and breakdown
- ✓ Leads to higher maintenance cost
- ✓ Shortens transformer life

Moisture control is the most effective way to extend transformer life.

02 WHAT IS THE GOAL OF MOISTURE MANAGEMENT?

Answer:

Maintain moisture at safe levels in both oil and paper to:

- ✓ Minimize aging
- ✓ Maintain dielectric performance
- ✓ Prevent faults
- ✓ Ensure long-term reliability

Goal: Keep oil & paper moisture as low and stable as possible.

03 WHAT ARE THE KEY ELEMENTS OF A MOISTURE MANAGEMENT PLAN?

Answer:

1. Monitor – Measure regularly
2. Analyze – Understand trends
3. Control Ingress – Stop new moisture
4. Remove Moisture – Dry the system
5. Maintain Sealing – Prevent leaks
6. Verify & Improve – Continuously

A plan is effective only when all elements work together.

04 HOW DOES MOISTURE ENTER A TRANSFORMER?

Answer:

- ✓ Breather dessicant failure or bypass
- ✓ Leakage through seals and gaskets
- ✓ Oil sampling and maintenance
- ✓ High humidity environment
- ✓ Through conservator expansion / contraction

Stopping ingress is as important as removing moisture.

05 WHAT ARE THE BEST WAYS TO REDUCE MOISTURE?

Answer:

- ✓ Vacuum dehydration (highly effective)
- ✓ Online drying systems
- ✓ Hot oil circulation with vacuum drying
- ✓ Oil purification with moisture removal
- ✓ Molecular sieve / silica gel systems

Remove moisture continuously, not just during outages.

06 HOW DOES VACUUM DEHYDRATION WORK?

Answer:

Reduces pressure to lower water boiling point and removes moisture from oil and paper.

Moisture evaporates at low pressure and is removed.

Most effective method to achieve low and stable moisture.

07 WHAT IS THE TARGET MOISTURE LEVEL?

Answer:

Recommended targets (typical):

Parameter	Target Value
Moisture in Oil	≤ 15 ppm
Paper Moisture	≤ 2.0%
Relative Saturation (RS)	≤ 60%
Water Activity (aw)	≤ 0.30

Lower moisture = Slower aging = Longer life.

08 HOW OFTEN SHOULD MOISTURE BE MONITORED?

Answer:

- ✓ Every 6 months to 1 year (or more frequently if critical)
- ✓ After major maintenance or drying
- ✓ After breather replacement
- ✓ During seasonal climate changes

Frequent monitoring detects changes early.

09 HOW DO BREATHERS HELP?

Answer:

- ✓ Prevent moisture from entering
- ✓ Maintain oil conservator dryness
- ✓ Extend transformer life

Breather Best Practices

- Use high-quality dessicant
- Check color regularly
- Replace when saturated
- Ensure proper sealing

A good breather is a low-cost life insurance.

10 HOW DOES SEALING IMPACT MOISTURE?

Answer:

- ✓ Poor seals allow continuous ingress
- ✓ Leads to rising moisture
- ✓ Increases aging and risk

Sealing Best Practices

- Inspect gaskets and seals
- Tighten flanges properly
- Avoid oil leaks
- Use quality sealing materials

Small leaks = Big moisture problems.

11 WHAT ROLE DOES OIL QUALITY PLAY?

Answer:

- ✓ Clean oil holds less moisture
- ✓ Good oil improves heat transfer
- ✓ Reduces aging and sludge formation
- ✓ Supports better dielectric strength

Oil Quality Best Practices

- Filter and purify oil
- Remove sludge and contaminants
- Maintain proper oil level
- Test oil regularly

Good oil + Low moisture = Reliable insulation.

12 HOW DO YOU KNOW IF YOUR STRATEGY IS WORKING?

Answer:

- ✓ Moisture levels are stable or decreasing
- ✓ PI, DF, and aw are within target
- ✓ Furan and aging rate are low
- ✓ Fewer faults and alarms
- ✓ Longer maintenance intervals

Results confirm that your strategy is effective.

MOISTURE MANAGEMENT ACTION MATRIX

Action	Purpose	Frequency	Effectiveness
Monitor	Know the moisture status	6–12 months	★★★☆☆
Control Ingress	Stop new moisture entry	Continuous	★★★★☆
Remove Moisture	Dry oil and paper	As needed	★★★★★
Maintain Sealing	Prevent leakage	Continuous	★★★☆☆
Maintain Breather	Keep air clean and dry	3–6 months	★★★☆☆
Verify & Improve	Ensure effectiveness	Continuous	★★★★☆

The best results come when all actions are implemented together.

BEST PRACTICES FOR MOISTURE MANAGEMENT

- ✓ Make moisture control a top priority.
- ✓ Monitor regularly and analyze trends.
- ✓ Act before moisture crosses limits.
- ✓ Use vacuum dehydration for best results.
- ✓ Maintain breathers and sealing systems.
- ✓ Use quality oil and maintain cleanliness.
- ✓ Combine online and offline drying.
- ✓ Track performance and keep improving.
- ✓ Train and align the maintenance team.

DRYTRANS INSIGHT

Moisture management is not a one-time activity. It is a continuous commitment to reliability and asset life.

THE BENEFITS OF EFFECTIVE MOISTURE MANAGEMENT

- **Slower Aging** – Lower aging rate and furan formation
- **Higher Reliability** – Fewer faults and unexpected outages
- **Lower Maintenance Cost** – Less breakdown maintenance and repairs
- **Longer Transformer Life** – Better insulation health for years to come
- **Better ROI** – Higher return on asset investment

Protect today. Control moisture. Extend life.

KEY TAKEAWAYS

- ✓ Moisture is the biggest threat – control it first.
- ✓ A proactive strategy prevents problems.
- ✓ Monitoring + Action = Reliability.
- ✓ Small actions today prevent big failures tomorrow.
- ✓ Moisture management extends life and value.

REMEMBER

You cannot see moisture.
But you can measure it.
You cannot stop aging.
But you can slow it down.
Control moisture. Control aging.

REFERENCES

- IEC 60422 – Mineral insulating oils in electrical equipment
- IEC 60599 – Guide for loading mineral-oil-immersed transformers
- IEEE C57.104 – Guide for acceptance and maintenance of insulating oil
- CIGRE TB 349 – Moisture equilibrium and moisture assessment
- Drytrans Technical Library and Field Experience

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SECTION 14

INSULATION LIFE EXTENSION: THE MOISTURE ADVANTAGE

Manage Moisture. Control Aging. Extend Life.

Moisture is the primary driver of insulation aging.
By controlling moisture proactively, you slow down aging, improve reliability, and significantly extend transformer life.

KEY MESSAGE

Insulation life is not fixed.
It is a result of how well you control moisture.

Lower Moisture = Slower Aging
Slower Aging = Longer Life

01 WHAT DRIVES INSULATION AGING?

Answer:

- ✔ Moisture (primary driver)
- ✔ Temperature
- ✔ Oxygen
- ✔ Electrical stress
- ✔ Contaminants
- ✔ Load cycling

Of these, moisture has the highest impact and is the most controllable.

02 HOW DOES MOISTURE REDUCE INSULATION LIFE?

Answer:
High moisture:

- ✔ Accelerates paper aging
- ✔ Reduces dielectric strength
- ✔ Increases risk of faults
- ✔ Promotes chemical degradation
- ✔ Leads to sludge and deposit formation

More moisture = Faster aging
Less moisture = Slower aging

03 WHAT IS THE IMPACT OF MOISTURE CONTROL?

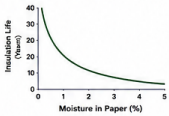
Answer:

- ✔ Slows down aging
- ✔ Maintains dielectric performance
- ✔ Reduces fault probability
- ✔ Improves reliability
- ✔ Extends transformer life
- ✔ Lowers life-cycle cost

Invest in moisture control, gain years of life.

04 WHAT IS THE RELATIONSHIP BETWEEN MOISTURE AND LIFE?

Answer:
The relationship is exponential.
Small reduction in moisture creates a big increase in life.



05 WHAT IS THE OPTIMAL MOISTURE LEVEL?

Answer:
Recommended targets (typical):

Parameter	Target Value
Moisture in Oil	≤ 15 ppm
Paper Moisture	≤ 2.0%
Relative Saturation (RS)	≤ 60%
Water Activity (a_w)	≤ 0.30

Lower moisture levels deliver maximum life extension.

06 HOW MUCH LIFE CAN YOU GAIN BY CONTROLLING MOISTURE?

Answer:
Life extension potential (guideline):

Paper Moisture (%)	Expected Life (Relative)
≤ 1.0%	1.5 – 2.5 ×
1.0 – 2.0%	1.2 – 1.5 ×
2.0 – 3.0%	1.0 × (Base)
> 3.0%	< 1.0 × (Reduced Life)

Every 1% reduction in paper moisture can add 20–50% more life.

07 WHAT ROLE DOES TEMPERATURE PLAY?

Answer:
Temperature and moisture work together.

High temperature + high moisture = Fast aging

Keep both under control for maximum benefit.

Control moisture.
Control temperature.
Control aging.

08 WHAT STRATEGIES EXTEND INSULATION LIFE?

Answer:

- ✔ Maintain low and stable moisture
- ✔ Control temperature
- ✔ Use online monitoring
- ✔ Prevent moisture ingress
- ✔ Regular maintenance
- ✔ Use high-quality oil and materials

A proactive strategy always outperforms a reactive one.

09 HOW DOES THIS IMPACT RELIABILITY?

Answer:

- ✔ Lower moisture = Fewer faults
- ✔ More stable operation
- ✔ Better performance during overloads
- ✔ Improved grid reliability
- ✔ Higher asset availability

Reliable transformers start with dry insulation.

10 HOW DOES LIFE EXTENSION REDUCE COST?

Answer:

- ✔ Delays replacement
- ✔ Reduces unplanned outages
- ✔ Lowers maintenance cost
- ✔ Improves energy efficiency
- ✔ Better return on investment

Moisture control is one of the highest ROI actions.

11 WHAT IS THE KEY TO SUSTAINED LIFE EXTENSION?

Answer:

- ✔ Continuous monitoring
- ✔ Early detection of moisture rise
- ✔ Consistent drying and filtering
- ✔ Sealing and breathing management
- ✔ Data-driven decisions

Sustained results come from consistent actions.

12 WHAT IS THE ULTIMATE BENEFIT?

Answer:

- ✔ Longer asset life
- ✔ Lower risk
- ✔ Higher reliability
- ✔ Better performance
- ✔ Stronger grid
- ✔ Peace of mind

Control moisture today.
Enjoy benefits for years.

MOISTURE LEVEL vs INSULATION LIFE IMPACT

Paper Moisture (%)	Aging Rate (Relative)	Insulation Life (Relative)	Impact
≤ 1.0%	0.25 – 0.40 ×	1.5 – 2.5 ×	Excellent – Maximum life extension
1.0 – 2.0%	0.50 – 0.70 ×	1.2 – 1.5 ×	Good – Significant life extension
2.0 – 3.0%	1.00 ×	1.0 × (Base)	Moderate – Normal aging
3.0 – 4.0%	1.5 – 2.0 ×	0.6 – 0.8 ×	High – Life reduction starts
> 4.0%	> 2.0 ×	< 0.5 ×	Very High – Severe life reduction

Lower moisture dramatically reduces aging rate and extends insulation life.

BEST PRACTICES FOR LIFE EXTENSION

- ✔ Keep moisture as low as possible
- ✔ Monitor regularly and trend data
- ✔ Dry oil and paper when required
- ✔ Prevent moisture ingress
- ✔ Maintain temperature within limits
- ✔ Maintain breathing and sealing systems
- ✔ Act early on any deviation
- ✔ Review and improve continuously

DRYTRANS INSIGHT

Life extension is not a one-time event.
It is a continuous commitment to moisture control and asset care.

LIFE EXTENSION – THE BOTTOM LINE

- Moisture is the #1 factor you can control.
- Lower moisture slows aging.
- Slower aging means longer life.
- Longer life means lower cost.
- Better reliability supports a stronger grid.

**Manage moisture.
Extend life. Deliver value.**

KEY TAKEAWAYS

- ✔ Moisture drives aging.
- ✔ Moisture control extends life.
- ✔ Small actions today = Big benefits tomorrow.
- ✔ Proactive management is the key.

REMEMBER

You cannot change the design life, but you can influence the actual life with the right moisture strategy.

REFERENCES

- IEC 60076 – Power Transformers
- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- CIGRE TB 349 – Moisture Equilibrium and Moisture Assessment
- Drytrans Technical Library and Field Experience

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SECTION 15

VACUUM DRYING OF TRANSFORMERS: THE MOST EFFECTIVE MOISTURE SOLUTION

Remove Moisture. Restore Insulation. Extend Life.

Vacuum drying is the only process that removes moisture from both oil and paper insulation to the lowest possible level. It restores dielectric strength, improves reliability, and significantly extends transformer life.

KEY MESSAGE

Moisture is the root cause.
Vacuum drying is the cure.

Remove Moisture = Restore Insulation
Restore Insulation = Extend Life
Extend Life = Maximize Value

01 WHY IS VACUUM DRYING SO EFFECTIVE?

Answer:

- ✓ Reduces pressure to lower water boiling point
- ✓ Water evaporates at low temperature
- ✓ Removes moisture from oil and paper
- ✓ Achieves extremely low moisture levels
- ✓ Restores original insulation condition

It is the only method that truly removes moisture – not just moves it around.

02 WHAT DOES VACUUM DRYING REMOVE?

Answer:

- ✓ Free and dissolved moisture in oil
- ✓ Moisture from paper insulation
- ✓ Sludge and soluble deposits (with filtration)
- ✓ Gases and volatile contaminants

Cleaner oil + Drier paper = Stronger insulation.

03 WHAT ARE THE KEY BENEFITS?

Answer:

- ✓ Restores dielectric strength
- ✓ Improves insulation resistance
- ✓ Reduces risk of faults and breakdowns
- ✓ Extends transformer life
- ✓ Improves reliability and availability
- ✓ Reduces maintenance cost
- ✓ Better return on investment

Vacuum drying delivers the highest life extension potential.

04 WHEN SHOULD VACUUM DRYING BE DONE?

Answer:

- ✓ When moisture level is high
- ✓ After major fault or overheating
- ✓ After water ingress or flooding
- ✓ During routine life extension program
- ✓ Before putting new or rewound transformers into service

The earlier you dry, the more life you save.

05 WHAT ARE THE TYPICAL TARGETS AFTER VACUUM DRYING?

Answer:

Typical achievable targets:

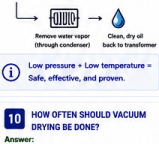
Parameter	Target Value
Moisture in Oil (ppm)	≤ 10 ppm
Paper Moisture (%)	≤ 1.0%
Relative Saturation (RS)	≤ 20%
Water Activity (a_w)	≤ 0.20

Lower moisture targets lead to exponential life improvement.

06 HOW DOES VACUUM DRYING WORK?

Answer:

The process is simple and powerful:



Low pressure + Low temperature = Safe, effective, and proven.

07 HOW LONG DOES VACUUM DRYING TAKE?

Answer:

Duration depends on:

- ✓ Initial moisture level
- ✓ Transformer size
- ✓ Oil volume
- ✓ Paper condition
- ✓ Temperature

Typical duration:

- 2 to 7 days
- Longer for very wet units

We do not rush drying.
We remove moisture completely.

08 IS VACUUM DRYING SAFE?

Answer:

- ✓ Yes. When done by trained experts using the right equipment.
- ✓ Low temperature process
- ✓ No damage to insulation
- ✓ No heating stress
- ✓ Maintains transformer integrity

Safe for the transformer.
Safe for the asset.

09 HOW DOES IT COMPARE WITH OTHER METHODS?

Answer:

Method	Removes Moisture from Paper	Achievable Moisture Level	Life Extension Potential
Oil Filtration	✗	Medium	Low
Online Drying	✗	Medium	Medium
Nitrogen Drying	✗	Medium	Medium
Vacuum Drying	✓	Very Low	Very High

If paper is not dry, the transformer is not dry.

10 HOW OFTEN SHOULD VACUUM DRYING BE DONE?

Answer:

- ✓ Not every year.
- ✓ Only when required based on:
  - Moisture level
  - Condition assessment
  - Operating environment
  - Maintenance strategy

Typically once in 5–10 years or as per condition.

Do it right. Do it on time.
Do not do it too often.

11 WHAT EQUIPMENT IS USED?

Answer:

- ✓ High vacuum drying unit
- ✓ Vacuum pump system
- ✓ Condenser (water cooled)
- ✓ Heaters (low temperature)
- ✓ Fine filtration system
- ✓ Oil handling system
- ✓ Moisture measurement instruments

Right equipment + Right process = Right people = Right results.

12 WHAT IS THE RESULT?

Answer:

- ✓ Dry insulation
- ✓ High dielectric strength
- ✓ Low loss
- ✓ Stable operation
- ✓ Longer asset life
- ✓ Peace of mind

Dry today. Reliable tomorrow.
Value for years.

TYPICAL MOISTURE LEVEL vs LIFE EXPECTANCY (GUIDELINE)

Paper Moisture (%)	Relative Saturation (RS)	Condition	Expected Life (Typical)
≤ 1.0	≤ 20%	Excellent	30+ years
1.0 – 2.0	20 – 40%	Good	20 – 30 years
2.0 – 3.0	40 – 60%	Fair	10 – 20 years
3.0 – 4.0	60 – 80%	Poor	5 – 10 years
> 4.0	> 80%	Very Poor	< 5 years

Lower moisture = Longer life. It's that simple.

BEST PRACTICES FOR VACUUM DRYING

- ✓ Assess transformer condition before drying
- ✓ Use calibrated instruments for moisture measurement
- ✓ Ensure good sealing and no leakage
- ✓ Maintain vacuum and temperature within limits
- ✓ Use fine filtration during and after drying
- ✓ Monitor progress with online moisture measurement
- ✓ Dry until target is achieved – not by time only
- ✓ Record before, during and after results
- ✓ Follow up with proper maintenance practices

Good drying is a process.
Complete drying is a commitment.

THE VALUE OF VACUUM DRYING

Restores Insulation
Removes moisture from oil and paper.

Reduces Risk
Lower risk of breakdowns and outages.

Extends Life
Significant life extension potential.

Cost Effective
Prevents major failures and costly repairs.

Improves Reliability
Better performance and availability.

It is not an expense. It is an investment.

KEY TAKEAWAYS

- ✓ Moisture is the #1 threat to transformer insulation.
- ✓ Vacuum drying removes moisture from oil and paper.
- ✓ It restores insulation and extends transformer life.
- ✓ Do it only when required – but do it completely.
- ✓ Choose quality experts. Follow best practices.

DRYTRANS INSIGHT

Vacuum drying is not just a service.
It is a life extension solution.
When done right, it delivers results that last for decades.

REFERENCES

- IEC 60422 – Mineral insulating oils in electrical equipment
- IEC 60076-2 – Power transformers
- IEC 60599 – Guide for loading of oil-immersed transformers
- CIGRE TB 349 – Moisture equilibrium and Moisture Assessment
- Drytrans Technical Library and Field Experience

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SECTION 16

CONTINUOUS MOISTURE MANAGEMENT: THE ONLY WAY TO CONTROL INSULATION LIFE

Measure. Monitor. Manage. Maintain.

Transformer insulation is a dynamic system. Moisture continuously changes with temperature, load, and environment. Only continuous moisture management can keep it under control.

KEY MESSAGE

Testing shows the condition.
Monitoring shows the trend.
Management changes the future.

Continuous Moisture Control = Controlled Aging
Controlled Aging = Longer Life

01 WHY CONTINUOUS MOISTURE MANAGEMENT?

Answer:

- ✓ Moisture is always moving
- ✓ Environment is always changing
- ✓ Temperature and load are always changing
- ✓ Ingress cannot be stopped
- ✓ Aging never stops

You cannot eliminate moisture, but you can control it continuously.

02 WHAT DOES CONTINUOUS MANAGEMENT ACHIEVE?

Answer:

- ✓ Keeps moisture at safe levels
- ✓ Maintains dielectric strength
- ✓ Slows down aging
- ✓ Prevents faults and breakdowns
- ✓ Improves reliability
- ✓ Extends transformer life

The goal is not zero moisture. The goal is safe and stable moisture.

03 WHAT ARE THE KEY COMPONENTS?

Answer:

1. Online moisture monitoring
2. Vacuum dehydration system
3. Moisture control logic
4. Sealing and breathing management
5. Trend analysis and alerts

Right system + Right process + Right monitoring = Success.

04 HOW DOES IT WORK?

Answer:

- ✓ Moisture is measured online
- ✓ Trends are analyzed
- ✓ Dehydration removes moisture
- ✓ Ingress is minimized
- ✓ System keeps moisture in control

Continuous cycle of measure → remove → control → maintain.

05 WHAT IS THE IDEAL MOISTURE RANGE?

Recommended targets:

• Moisture in Oil	≤ 15 ppm
• Paper Moisture	≤ 2.0%
• Relative Saturation (RS)	≤ 60%
• Water Activity (a_w)	≤ 0.30

Lower moisture = slower aging. Stable moisture = longer life.

06 WHAT HAPPENS WITHOUT CONTINUOUS CONTROL?

Answer:

- ✓ Moisture keeps entering
- ✓ Moisture level keeps rising
- ✓ Aging rate accelerates
- ✓ Risk of faults increases
- ✓ Dielectric strength reduces
- ✓ Life shortens

No control = Faster aging. Faster aging = Higher risk.

07 HOW OFTEN SHOULD SYSTEMS BE MONITORED?

Answer:

- ✓ Online systems: 24 x 7
- ✓ Data review: Weekly
- ✓ Detailed analysis: Monthly
- ✓ Comprehensive review: Quarterly

Real-time monitoring enables real-time action.

08 HOW DOES TEMPERATURE AFFECT MOISTURE?

Answer:

- ✓ Higher temperature → more evaporation
- ✓ Lower temperature → more condensation
- ✓ Seasonal changes impact equilibrium

Moisture control must adapt to temperature and load.

09 WHAT ROLE DOES LOAD PLAY?

Answer:

- ✓ High load → high temperature → more evaporation
- ✓ Low load → low temperature → more condensation
- ✓ Load cycles cause moisture fluctuations

Lower management and moisture management go hand in hand.

10 HOW IS INGRESS CONTROLLED?

Answer:

- ✓ High-quality breathers
- ✓ Proper sealing of tank and components
- ✓ Regular inspection and maintenance
- ✓ Minimize oil conservator breathing
- ✓ Monitoring helps detect ingress early

Stop new moisture. Then remove existing moisture.

11 WHAT TECHNOLOGIES ARE USED?

Answer:

- ✓ Online moisture sensors
- ✓ Vacuum dehydration units
- ✓ PLC/SCADA based control
- ✓ Data logging and analytics
- ✓ Remote monitoring and alerts

Technology + Process + People = Reliable Results.

12 WHAT ACTIONS ARE TAKEN BASED ON DATA?

Answer:

- ✓ Adjust dehydration cycle
- ✓ Optimize drying time
- ✓ Investigate high moisture events
- ✓ Improve sealing or breather
- ✓ Review load and temperature impact

Data without action has no value.

13 HOW DOES IT IMPACT RELIABILITY?

Answer:

- ✓ Fewer faults and trips
- ✓ More stable operation
- ✓ Higher asset availability
- ✓ Better performance under stress
- ✓ Improved customer satisfaction

Reliable transformers start with controlled moisture.

14 HOW DOES IT IMPACT COST?

- ✓ Reduces unplanned outages
- ✓ Extends maintenance intervals
- ✓ Lowers repair and replacement cost
- ✓ Improves energy efficiency
- ✓ Better return on investment

Moisture control pays for itself many times over.

15 WHAT IS THE ULTIMATE GOAL?

- ✓ Keep moisture low and stable
- ✓ Keep aging slow and controlled
- ✓ Keep insulation strong
- ✓ Keep transformer reliable
- ✓ Keep life long and cost low

Sustained moisture control = Sustained asset value.

16 WHAT IS THE MINDSET SHIFT?

From:

✗ Periodic testing & occasional drying

To:

✓ Continuous monitoring & continuous management

From reactive maintenance to proactive asset care.

MOISTURE BEHAVIOR – A CONTINUOUS CYCLE

CONTINUOUS MANAGEMENT VS PERIODIC APPROACH

Aspect	Periodic Approach	Continuous Management
Data	Snapshot	Real-time trend
Moisture Control	Reactive	Proactive
Aging Rate	Uncontrolled	Controlled
Risk of Faults	High	Low
Asset Life	Shorter	Longer
Maintenance Cost	Higher	Lower
Reliability	Lower	Higher
Peace of Mind	Low	High

BEST PRACTICES FOR CONTINUOUS MOISTURE MANAGEMENT

- ✓ Make moisture control a top priority
- ✓ Invest in online monitoring and drying systems
- ✓ Use calibrated instruments and reliable sensors
- ✓ Maintain sealing and breather systems
- ✓ Dry oil and paper continuously
- ✓ Monitor trends. Act before limits are reached
- ✓ Record, analyze and improve continuously
- ✓ Work with experienced partners

Consistent Action. Continuous Control. Maximum Life. Maximum Value.

KEY TAKEAWAYS

- ✓ Moisture is a threat. Control is the solution.
- ✓ Continuous management is the only effective strategy.
- ✓ Small actions today deliver big benefits tomorrow.
- ✓ Control moisture. Control aging. Extend life.

DRYTRANS INSIGHT

We do not just provide equipment.
We provide complete moisture management solutions – technology, process, and partnership.

REFERENCES

- IEC 60076 – Power Transformers
- IEC 60422 – Mineral insulating oils in electrical equipment
- IEEE C57.106 – Guide for loading mineral-oil-immersed transformers
- CIGRE TB 349 – Moisture equilibrium and Moisture Assessment
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SECTION 17

BREATHERS: FIRST LINE OF DEFENSE AGAINST MOISTURE INGRESS

A Small Component. A Big Impact.

Breathers protect transformers by keeping moisture out.
A neglected breather can undo all other efforts.

Good breathers = Dry insulation. Bad breathers = Moisture problems.

KEY MESSAGE

Clean and effective breathers prevent moisture ingress.

A good breather is essential for insulation life.

Good Breather = Low Ingress
Bad Breather = High Moisture

01 WHAT IS THE FUNCTION OF A BREATHER?

Answer:

- Allows air to enter/exit during cooling and heating
- Absorbs moisture from incoming air
- Protects oil and insulation from humidity

Breather is the gatekeeper of dry air.

02 HOW DOES A BREATHER WORK?

Answer:

- Air enters through silica gel
- Silica gel absorbs moisture
- Dry air goes into the transformer
- Moisture stays trapped in silica gel

Good silica gel = Dry air. Moisture out.

03 WHAT ARE THE TYPES OF BREATHERS?

Answer:

- Silica gel breathers
- Self-indicating breathers
- Non-indicating breathers
- Conservator breathers

Self-indicating breathers are strongly recommended.

04 WHY ARE SELF-INDICATING BREATHERS BETTER?

Answer:

- Show silica gel condition
- Color change indicates saturation
- Helps in timely maintenance
- Reduces risk of moisture ingress

Visibility leads to action. Action prevents moisture.

05 WHAT IS THE IDEAL BREATHER INSTALLATION?

Answer:

- At the highest point
- Away from rain splash
- Vertical and secure
- Properly sealed connections

Correct installation ensures maximum protection.

06 HOW OFTEN SHOULD BREATHERS BE INSPECTED?

Answer:

- Every 3 to 6 months
- More frequently in humid seasons
- Check color and gel condition
- Record and trend condition

Regular checks prevent unexpected saturation.

07 WHAT INDICATES A SATURATED BREATHER?

Answer:

- Silica gel turns from blue to pink
- Indicator shows "Saturated"
- High moisture in oil
- Rising paper moisture

Pink gel = Warning. Take action immediately.

08 WHAT HAPPENS IF A BREATHER IS SATURATED?

Answer:

- Moisture enters the transformer
- Increases oil and paper moisture
- Reduces dielectric strength
- Accelerates insulation aging

A saturated breather can cause prevous damage.

09 HOW IS SILICA GEL REGENERATED OR REPLACED?

Answer:

- Remove and replace the gel
- Or bake in oven at 120–150°C for 4–6 hours (if reusable)
- Ensure proper drying
- Reassemble and test

Fresh silica gel = Effective moisture absorption.

10 CAN BREATHERS BE RECONDITIONED?

Answer:

- Yes, if designed for reconditioning
- Follow manufacturer instructions
- Check for mechanical damage
- Replace if damaged or corroded

Recondition only if safe and recommended.

11 WHAT OTHER FACTORS AFFECT BREATHER PERFORMANCE?

Answer:

- Ambient humidity
- Rain and flooding
- Dust and contamination
- Poor sealing or leaks

Environment matters. So does maintenance.

12 HOW DO BREATHERS IMPACT TRANSFORMER LIFE?

Answer:

- Prevent moisture ingress
- Maintain insulation dryness
- Improve reliability
- Extend transformer life

Good breathers (small cost) bring big benefits.

13 WHAT ARE THE BEST PRACTICES FOR BREATHERS?

Answer:

- Use high-quality breathers
- Inspect regularly
- Replace or regenerate on time
- Keep area clean and dry

Best practice today ensures reliability tomorrow.

14 HOW DO YOU CHOOSE THE RIGHT BREATHER?

Answer:

- Right capacity
- Self-indicating type
- Quality of silica gel
- Trusted manufacturer

Right breather for right protection.

15 WHAT IS THE COST OF NEGLECTING BREATHERS?

Answer:

- Moisture ingress
- Insulation aging
- Breakdowns and outages
- High repair and replacement cost

Neglect today = High cost tomorrow.

16 WHAT IS THE SIMPLE RULE TO REMEMBER?

Answer:

> "A good breather breathes dry air in.
> A bad breather lets moisture in."

Protect the breather. Protect the transformer.

SILICA GEL COLOR INDICATION GUIDE

Silica Gel Color	Condition	Action Required
Blue	Dry / Active	No action required
Purple / Lilac	Partially Saturated	Monitor closely
Pink	Saturated	Regenerate or replace immediately
White / Light Pink	Exhausted	Replace immediately

Color indication may vary based on silica gel type and manufacturer.

BREATHER MAINTENANCE CHECKLIST

- Inspect every 3–6 months
- Check silica gel color
- Check seals, gaskets and O-rings
- Ensure proper installation and sealing
- Keep the breather housing clean and dry
- Record condition and maintenance
- Replace or regenerate as per condition
- Always use high-quality silica gel

A small checklist today can prevent major failures tomorrow.

THE VALUE OF GOOD BREATHER MAINTENANCE

- Prevents moisture ingress
- Maintains dielectric strength
- Reduces insulation aging
- Improves reliability
- Lowers maintenance and repair cost
- Extends transformer life

Good Breather Maintenance = Reliable Transformers

KEY TAKEAWAYS

- Breathers are essential for keeping moisture out.
- Self-indicating breathers are highly recommended.
- Inspect, monitor and maintain regularly.
- Fresh silica gel = Dry air = Long transformer life.
- A little attention to breathers prevents big problems.

DRYTRANS INSIGHT

Most moisture problems start with a saturated or poor breather.
Focus on breathers – it is the simplest and most effective protection.

REFERENCES

- IEC 60599 – Guide for loading mineral-oil-immersed transformers
- IEC 60076-2 – Power transformers
- CIGRE TB 349 – Moisture equilibrium and Moisture Assessment
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SECTION 18

LEAKS & SEALING: SMALL GAPS, BIG CONSEQUENCES

Seal it Right. Keep Moisture Out. Protect Your Transformer.

Even the smallest leak can allow moisture to enter, degrade insulation, and reduce transformer life. Sealing and integrity are critical for long-term reliability.

KEY MESSAGE

Leaks are silent.
Moisture is persistent.
The damage is expensive.

Find the leaks.
Seal the leaks.
Stop the moisture.
Extend transformer life.

01 WHY ARE LEAKS SO DANGEROUS?

Answer:

- ✓ Allow moisture ingress
- ✓ Accelerate insulation aging
- ✓ Reduce dielectric strength
- ✓ Increase risk of fault and failure
- ✓ Shorten transformer life

A small leak today can cause a big failure tomorrow.

02 WHERE DO LEAKS TYPICALLY OCCUR?

Answer:

- ✓ Tank gaskets and flanges
- ✓ Bushings and bushing flanges
- ✓ Drain valves and fittings
- ✓ Radiator connections
- ✓ Breather and conservator joints
- ✓ Weld cracks and tank seams

Any joint or connection can be a leakage point.

03 WHAT CAUSES LEAKS?

Answer:

- ✓ Gasket aging and hardening
- ✓ Poor installation
- ✓ Loose bolts and connections
- ✓ Vibration and mechanical stress
- ✓ Corrosion and wear
- ✓ Thermal expansion and fatigue

Leaks develop over time. Inspection must be regular.

04 HOW DO LEAKS ALLOW MOISTURE IN?

Answer:

- ✓ Negative pressure during cooling
- ✓ Breathing cycles
- ✓ Conservator oil level changes
- ✓ Humidity enters through the leak
- ✓ Moisture dissolves in oil
- ✓ Migrates to paper insulation

Leak + Breathing = Moisture Ingress.

05 WHAT ARE THE SIGNS OF A LEAK?

Answer:

- ✓ Oil seepage or stains
- ✓ Drop in oil level
- ✓ Moisture rise in tests
- ✓ Rust around joints
- ✓ Wet or oily conservator walls
- ✓ Visible oil on gaskets or bolts

Visible signs are warnings. Don't ignore them.

06 HOW OFTEN SHOULD LEAKS BE CHECKED?

Answer:

- ✓ Routine visual inspection: Monthly
- ✓ Detailed inspection: Every 6 months
- ✓ After overload or fault
- ✓ After short-circuit or vibration
- ✓ During major maintenance

Regular checks prevent small leaks from growing.

07 WHAT IS THE IMPACT OF POOR SEALING?

Answer:

- ✓ Continuous moisture ingress
- ✓ Faster insulation degradation
- ✓ Higher maintenance cost
- ✓ More frequent outages
- ✓ Reduced reliability
- ✓ Shorter transformer life

Poor sealing = Higher risk + Higher cost + Lower life.

08 WHAT IS THE CORRECT SEALING PRACTICE?

Answer:

- ✓ Use quality gaskets
- ✓ Ensure clean sealing surfaces
- ✓ Apply correct torque
- ✓ Use proper gasket material
- ✓ Check alignment
- ✓ Verify after tightening

Right material + Right method = Leak-free performance.

09 CAN OLD GASKETS BE REUSED?

Answer:

- ✓ No, gaskets age and harden
- ✓ Lose elasticity and seal
- ✓ Risk of future leakage
- ✓ Always use new gaskets

Old gasket = Future leak. Always replace.

10 HOW DOES TEMPERATURE AFFECT SEALING?

Answer:

- ✓ High temperature hardens gaskets
- ✓ Causes loss of elasticity
- ✓ Leads to cracks and leaks
- ✓ Cold weather causes contraction
- ✓ Both increase leak risk

Temperature cycles stress gaskets and seals.

11 WHAT TESTS CAN DETECT LEAKS?

Answer:

- ✓ Visual inspection
- ✓ Soap bubble test
- ✓ Oil dye penetrant test
- ✓ Vacuum box test
- ✓ Pressure holding test
- ✓ Helium leak test (advanced)

Test it. Don't guess it. Detect leaks early.

12 HOW SHOULD LEAKS BE REPAIRED?

Answer:

- ✓ Clean the area
- ✓ Replace gasket or seal
- ✓ Tighten to correct torque
- ✓ Repair damaged parts
- ✓ Retest after repair
- ✓ Monitor after re-energization

Repair right. Test right. Stay leak-free.

13 WHAT ROLE DOES TRAINING PLAY?

Answer:

- ✓ Trained teams find small leaks
- ✓ Use correct tools and methods
- ✓ Avoid mistakes and over-tightening
- ✓ Ensure long-term sealing integrity

Skilled people = Reliable sealing.

14 WHAT IS THE COST OF IGNORING LEAKS?

Answer:

- ✓ Moisture damage
- ✓ Premature aging
- ✓ Frequent outages
- ✓ Expensive repairs
- ✓ Early replacement

Ignoring leaks is always more expensive.

15 WHAT IS THE BENEFIT OF GOOD SEALING?

Answer:

- ✓ Prevents moisture ingress
- ✓ Maintains insulation dryness
- ✓ Improves reliability
- ✓ Extends transformer life
- ✓ Reduces maintenance cost

Good sealing = Longer life + Lower cost.

16 WHAT IS THE GOLDEN RULE?

Answer:

> "A tight seal today keeps moisture away. A dry transformer today ensures reliable power tomorrow."

Seal Today. Protect Tomorrow. Ensure Reliability.

COMMON LEAK POINTS & SOLUTIONS

Leak Point	Cause	Solution
Tank Flanges	Aged gasket, loose bolts	Replace gasket, tighten to torque
Bushings	Flange gasket failure	Replace gasket, check alignment
Drain Valves	Worn packing	Replace packing, tighten
Breather & Conservator	Loose connection, worn seal	Tighten, replace seal, check alignment
Radiator Connections	Loose or damaged gasket	Replace gasket, secure bolts
Weld Seams	Cracks, vibration	Repair weld, inspect regularly

LEAK INSPECTION CHECKLIST

- ✓ Check oil level and look for unusual drop
- ✓ Inspect all flanges, gaskets and joints
- ✓ Check bushings and their flanges
- ✓ Inspect drain valves and fittings
- ✓ Check radiator connections
- ✓ Check breather and conservator joints
- ✓ Look for oil stains or seepage
- ✓ Perform leak test if required
- ✓ Record findings and corrective actions
- ✓ Verify after repair and recheck

A checklist today prevents a breakdown tomorrow.

THE BENEFITS OF EFFECTIVE LEAK MANAGEMENT

- Prevents moisture ingress
- Maintains insulation integrity
- Reduces risk of faults and failures
- Lowers maintenance and repair cost
- Extends transformer life
- Improves reliability and availability

KEY TAKEAWAYS

- ✓ Leaks are the main entry for moisture.
- ✓ Inspect regularly and act early.
- ✓ Use quality materials and correct methods.
- ✓ Seal it right to protect your investment.

DRYTRANS INSIGHT

Leak management is not a one-time job. It is a continuous commitment to reliability and asset life.

REFERENCES

- IEC 60076-2 – Power Transformers
- IEC 60599 – Guide for loading mineral-oil-immersed transformers
- CIGRE TB 349 – Moisture equilibrium and Moisture Assessment
- DryTrans Technical Library and Field Experience

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SECTION 19

OIL QUALITY MATTERS: KEEP IT CLEAN, DRY & RELIABLE

Good Oil = Good Insulation = Long Life

Transformer oil is more than just a coolant.
It is the lifeline of insulation.
Clean, dry, and good quality oil protects your transformer.

KEY MESSAGE

Oil quality directly impacts insulation performance.
Monitor. Maintain. Manage.
Good oil today,
Reliable transformer tomorrow.

Clean Oil = Strong Insulation
Strong Insulation = Long Life

01 WHY IS OIL QUALITY SO IMPORTANT?

Answer:

- ✓ Provides dielectric strength
- ✓ Cools the transformer
- ✓ Insulates and prevents arcing
- ✓ Carries heat away
- ✓ Protects paper insulation

Good oil = Strong protection.
Poor oil = Higher risk.

02 WHAT AFFECTS OIL QUALITY?

Answer:

- ✓ Moisture ingress
- ✓ High temperature
- ✓ Oxidation and aging
- ✓ Sludge and contaminants
- ✓ Overloading and thermal stress

Many factors. One result.
Oil quality goes down.

03 WHAT ARE THE KEY OIL QUALITY PARAMETERS?

Answer:

- ✓ Moisture (ppm)
- ✓ Breakdown Voltage (BDV)
- ✓ Acidity (TAN)
- ✓ Interfacial Tension (IFT)
- ✓ Dissipation Factor (tan δ)
- ✓ Color
- ✓ Sludge and sediment

Test. Track. Trend.
Take Action.

04 HOW DOES MOISTURE AFFECT OIL QUALITY?

Answer:

- ✓ Reduces dielectric strength
- ✓ Slows down heat transfer
- ✓ Causes paper insulation aging
- ✓ Forms sludge and deposits
- ✓ Increases risk of faults

Moisture is the #1 enemy.
Keep it out.

05 WHAT IS THE IDEAL MOISTURE LEVEL IN OIL?

Answer:
Recommended targets:

Parameter	Target Value
Moisture in Oil	≤ 15 ppm
Relative Saturation (RS)	≤ 20%
Water Activity (a_w)	≤ 0.20

Lower moisture.
Better performance.

06 HOW DOES OIL AGING OCCUR?

Answer:

- ✓ High temperature breakdown
- ✓ Oxidation with oxygen
- ✓ Contamination by particles
- ✓ Reaction with metals
- ✓ Electrical stress and arcing

Aging is natural.
Control is critical.

07 WHAT ARE SIGNS OF DEGRADED OIL?

Answer:

- ✓ High acidity (TAN)
- ✓ Low BDV
- ✓ High dissipation factor
- ✓ Dark color
- ✓ Sludge and sediments

Detect early.
Prevent failure.

08 HOW OFTEN SHOULD OIL BE TESTED?

Answer:

- ✓ Routine: Every 6 to 12 months
- ✓ After overload or fault
- ✓ After maintenance or oil top-up
- ✓ Before and after filtration
- ✓ During high humidity season

Regular testing.
Better decisions.

09 CAN OIL QUALITY BE IMPROVED?

Answer:

- ✓ Yes, with proper maintenance
- ✓ Remove moisture
- ✓ Filter and clean oil
- ✓ Remove sludge and deposits
- ✓ Use high-quality oil

Good maintenance.
Better oil.

10 WHAT IS OIL FILTRATION?

Answer:

- ✓ Removes particles and sludge
- ✓ Removes moisture
- ✓ Improves dielectric strength
- ✓ Restores oil clarity
- ✓ Extends oil and transformer life

Clean oil flows.
Protection grows.

11 WHEN SHOULD OIL BE REPLACED?

Answer:

- ✓ When oil is severely degraded
- ✓ High acidity and low BDV
- ✓ Sludge cannot be removed
- ✓ After major internal fault
- ✓ As per manufacturer advice

Replace when needed.
Don't take risk.

12 WHAT IS THE ROLE OF GOOD OIL IN RELIABILITY?

Answer:

- ✓ Ensures high dielectric strength
- ✓ Improves cooling efficiency
- ✓ Reduces insulation aging
- ✓ Prevents faults and outages
- ✓ Extends transformer life

Good oil = Reliable transformer.
Reliable grid.

13 WHAT HAPPENS IF OIL QUALITY IS IGNORED?

Answer:

- ✓ Insulation breaks down faster
- ✓ More faults and trips
- ✓ Higher maintenance cost
- ✓ Shorter transformer life
- ✓ Risk of catastrophic failure

Ignoring oil quality
leads to big losses.

14 HOW DOES TEMPERATURE AFFECT OIL QUALITY?

Answer:

- ✓ Higher temperature speeds aging
- ✓ Oxidation rate increases
- ✓ Moisture solubility changes
- ✓ Sludge and acidity increase
- ✓ Reduces overall oil life

Lower temperature.
Better oil life.

15 WHAT IS THE BEST PRACTICE FOR OIL QUALITY?

Answer:

- ✓ Keep moisture low
- ✓ Filter oil regularly
- ✓ Monitor key parameters
- ✓ Seal and protect from ingress
- ✓ Use quality oil and components

Best practice today.
Reliability tomorrow.

16 WHAT IS THE GOLDEN RULE TO REMEMBER?

Answer:

> "Clean oil,
> dry oil,
> good oil –
> that's the key
> to long transformer life."

Oil quality is not a cost.
It is an investment.

TYPICAL OIL QUALITY LIMITS (GUIDELINE)

Parameter	Good Condition	Caution	Poor Condition
Moisture in Oil (ppm)	≤ 15	15 – 30	> 30
Relative Saturation (RS %)	≤ 20	20 – 35	> 35
Water Activity (a_w)	≤ 0.20	0.20 – 0.30	> 0.30
Breakdown Voltage (kV)	≥ 60	40 – 60	< 40
Acidity (TAN mg KOH/g)	≤ 0.10	0.10 – 0.20	> 0.20
Interfacial Tension (mN/m)	≥ 40	30 – 40	< 30
Dissipation Factor (tan δ)	≤ 0.005	0.005 – 0.01	> 0.01
Color (ASTM)	≤ 2.5	2.5 – 4.0	> 4.0
Sludge	None	Trace	Present

Limits may vary based on standards and transformer type.

OIL QUALITY MAINTENANCE CHECKLIST

- ✓ Keep moisture within target limits
- ✓ Test oil at regular intervals
- ✓ Trend results, not just snapshots
- ✓ Filter oil to remove moisture and particles
- ✓ Check breather and sealing condition
- ✓ Monitor temperature and load
- ✓ Top-up with same grade oil only
- ✓ Avoid unnecessary opening of transformer
- ✓ Use proper handling and storage practices
- ✓ Act early on any oil quality alarm

A small checklist today can prevent a major failure tomorrow.

THE BENEFITS OF GOOD OIL QUALITY

- High dielectric strength
- Better cooling and heat transfer
- Reduced aging of insulation
- Lower risk of faults and breakdowns
- Lower maintenance and repair cost
- Longer transformer life

Good Oil Quality = High Performance
High Performance = Long, Reliable Life

KEY TAKEAWAYS

- ✓ Oil quality affects every part of insulation.
- ✓ Moisture and aging are the main threats.
- ✓ Test, trend, and take timely action.
- ✓ Clean, dry, good oil ensures reliability.
- ✓ Prevention is always better than repair.

DRYTRANS INSIGHT

Oil quality is not just a test result.
It is a reflection of how well
you care for your transformer.
Care today. Reliability always.

REFERENCES

- IEC 60296 – Mineral insulating oils in electrical equipment
- IEC 60076-2 – Power transformers
- CIGRE TB 349 – Moisture equilibrium and moisture assessment
- IEEE C57.106 – Guide for loading mineral-oil-immersed transformers
- DryTrans Technical Library and Field Experience

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SECTION 20

WATER ACTIVITY (a_w): THE MOST MISUNDERSTOOD PARAMETER

Small Number. Big Meaning. Critical to Insulation Life.

Water activity (a_w) is not the amount of moisture.
It is the availability of moisture to affect the insulation.
It is the single best indicator of insulation risk, aging rate, and remaining life.

KEY MESSAGE

PPM tells you how much moisture is present.
Water activity tells you how harmful that moisture is.

Low a_w = Safe Insulation
High a_w = Rapid Aging

01 WHAT IS WATER ACTIVITY (a_w)?

Answer:

- ✓ Water activity is the ratio of the vapor pressure of water in oil to the vapor pressure of pure water at the same temperature.
- ✓ It ranges from 0 (completely dry) to 1.0 (saturated).

a_w shows how "active" the moisture is.

02 HOW IS WATER ACTIVITY DIFFERENT FROM PPM?

Answer:

- ✓ PPM = Total moisture content (how much is present)
- ✓ a_w = Free / available moisture (how much can cause damage)
- ✓ Two oils can have same PPM but different a_w and risk.

a_w is the real risk indicator.

03 WHY IS WATER ACTIVITY SO IMPORTANT?

Answer:

- ✓ It determines the aging rate of paper insulation
- ✓ It controls chemical reactions in the insulation
- ✓ It drives moisture migration
- ✓ It defines the actual risk, not just moisture quantity

a_w directly controls insulation life.

04 WHAT IS THE SAFE RANGE OF a_w?

Answer:

- ✓ Best practice target: $a_w \leq 0.20$
- ✓ Good condition: $a_w \leq 0.30$
- ✓ Caution: $0.30 < a_w \leq 0.50$
- ✓ High risk: $a_w > 0.50$

Keep a_w as low as practically possible.

05 HOW DOES a_w AFFECT PAPER AGING?

Answer:

- ✓ As a_w increases, the rate of cellulose aging increases exponentially.
- ✓ Higher a_w = Faster aging
- ✓ Lower a_w = Slower aging

Small increase in a_w can greatly reduce life.

06 WHAT IS THE RELATIONSHIP BETWEEN a_w AND RS%?

Answer:

- ✓ a_w is the driving force.
- ✓ RS% is the equilibrium result.
- ✓ Even at same RS%, different temperatures can give different a_w.

a_w changes with temperature.

07 HOW DOES TEMPERATURE AFFECT a_w?

Answer:

- ✓ At higher temperature, same PPM gives higher a_w.
- ✓ When oil cools, a_w drops.
- ✓ This is why seasonal changes matter.

Hot oil = Higher a_w
Cool oil = Lower a_w

08 WHAT IS A GOOD a_w FOR LONG LIFE?

Answer:

- ✓ For maximum insulation life, target $a_w \leq 0.20$ consistently.
- ✓ This minimizes aging, slows reactions, and keeps insulation stable.

Lower a_w = Longer life
Higher a_w = Shorter life.

09 HOW IS WATER ACTIVITY MEASURED?

Answer:

- ✓ Using calibrated Water Activity metors (capacitive sensor)
- ✓ Measures moisture in oil phase directly
- ✓ Fast, accurate, and reliable

Measure it.
Manage it.

10 CAN PPM BE LOW BUT a_w HIGH?

Answer:

- ✓ Yes. If temperature is high,
- ✓ or if oil is contaminated, same PPM can give higher a_w.
- ✓ Always look at both PPM and a_w.

PPM alone can be misleading.

11 HOW DOES a_w IMPACT CHEMICAL REACTIONS?

Answer:

- ✓ Most aging reactions need available water.
- ✓ Higher a_w accelerates hydrolysis of cellulose.
- ✓ Lower a_w slows chemical aging.

a_w fuels aging reactions.
Control a_w, control aging.

12 WHAT IS THE BEST PRACTICE FOR MANAGING a_w?

Answer:

- ✓ Keep $a_w \leq 0.20$
- ✓ Use good breathers
- ✓ Prevent ingress
- ✓ Seal leaks
- ✓ Use continuous moisture management

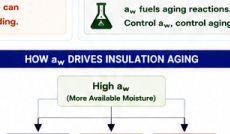
Monitor a_w continuously.
Keep it low. Keep it safe.

a_w VS INSULATION CONDITION

Water Activity (a_w)	Condition	Impact on Insulation
≤ 0.20	Excellent	Very slow aging, long life
0.20 – 0.30	Good	Controlled aging, normal life
0.30 – 0.50	Caution	Accelerated aging begins
0.50 – 0.70	Poor	High aging rate, risk rising
> 0.70	Very Poor	Severe aging, failure risk

Water activity is the single most important parameter for insulation health and life prediction.

HOW a_w DRIVES INSULATION AGING



LOW a_w = SLOW AGING = LONGER LIFE

TARGET. TREND. CONTROL.

Target
Keep $a_w \leq 0.20$ at all times

Trend
Watch a_w trend, not just single value

Control
Remove moisture, prevent ingress, manage continuously

FACTS TO REMEMBER

- ✓ a_w is not moisture content.
- ✓ a_w is moisture availability.
- ✓ a_w is the real aging driver.
- ✓ Monitor a_w, not just PPM.
- ✓ Low a_w is the key to long life.

BEST PRACTICES

- ✓ Measure a_w regularly
- ✓ Maintain < 0.20
- ✓ Use quality breathers
- ✓ Seal leaks
- ✓ Use continuous moisture management
- ✓ Review trends and act early

DRYTRANS INSIGHT

If you control water activity, you control aging.
If you control aging, you control life.
Simple. Science. Effective.

DEFERENCES

- IEC 60076-22: Transformer Oil Guide
- IEC 60422: Mineral Insulating Oils
- CIGRE TB 349: Moisture Equilibrium
- DryTrans Technical Library
- Field Experience & Research

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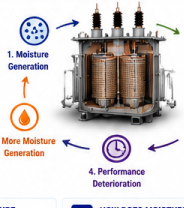
SECTION 21

THE MOISTURE CYCLE INSIDE TRANSFORMERS: A CONTINUOUS CHALLENGE

Moisture Never Stands Still. It Moves, Reacts, Ages, and Multiplies the Damage.

Moisture follows a continuous cycle inside a transformer. If not controlled, each step accelerates insulation aging and increases the risk of failure.



KEY MESSAGE

The moisture cycle is self-reinforcing.
Break the cycle anywhere, and you protect the transformer completely.

Control moisture. Control aging. Control reliability.

01 WHAT IS THE MOISTURE CYCLE?

Answer:

- ✔ A continuous sequence of events that increases moisture and accelerates insulation aging.
- ✔ It repeats unless the source of moisture is controlled.

It is a cycle, not an event. It keeps repeating.

02 WHERE DOES MOISTURE GENERATE?

Answer:

- ✔ From external ingress (breathers, leaks, seals, handling).
- ✔ From oil oxidation and paper oxidation.
- ✔ From chemical reactions during aging.

Moisture is generated inside and outside.

03 HOW DOES MOISTURE MIGRATE?

Answer:

- ✔ High temperature drives moisture from oil to paper.
- ✔ Low temperature or low load brings it back to oil.
- ✔ It moves until equilibrium is reached.

Temperature drives the movement.

04 WHAT HAPPENS IN THE DEGRADATION STAGE?

Answer:

- ✔ Moisture weakens cellulose bonds.
- ✔ It accelerates chemical reactions
- ✔ and produces by-products (acidity, methanol, furans).
- ✔ Paper insulation loses strength.

Moisture + Heat = Faster chemical aging.

05 HOW DOES PERFORMANCE DETERIORATE?

Answer:

- ✔ Dielectric strength reduces.
- ✔ Insulation becomes weaker.
- ✔ Risk of PD, breakdown, and failure increases.

The transformer becomes more vulnerable.

06 HOW DOES THIS CREATE MORE MOISTURE?

Answer:

- ✔ Aged paper holds more moisture.
- ✔ More by-products attract moisture.
- ✔ Poor oil quality holds more dissolved water.

Aging creates conditions that attract more moisture.

07 WHAT MAKES THE CYCLE DANGEROUS?

Answer:

- ✔ Each loop makes the insulation weaker.
- ✔ Damage is cumulative and irreversible.
- ✔ Failure is not sudden, it is the result of many cycles.

Slow damage. Sudden failure.

08 WHAT ARE THE MAIN DRIVERS OF THE CYCLE?

Answer:

- ✔ Temperature variations
- ✔ Moisture ingress
- ✔ Oxygen and oil oxidation
- ✔ Load cycles and hot spots

Multiple factors work together.

09 HOW CAN THE CYCLE BE IDENTIFIED?

Answer:

- ✔ Rising moisture trend (ppm, a_w, RS%)
- ✔ Rising acidity (TAN)
- ✔ Rising methanol and furan
- ✔ Low BDV and high tan δ

Trends reveal the cycle. Not single tests.

10 WHAT IS THE IMPACT OF IGNORING THE CYCLE?

Answer:

- ✔ Insulation ages rapidly.
- ✔ Unexpected failures.
- ✔ High repair or replacement cost.
- ✔ Reduced asset life.

Ignoring today, costs tomorrow.

11 HOW CAN THE CYCLE BE BROKEN?

Answer:

- ✔ Prevent moisture ingress.
- ✔ Maintain oil quality.
- ✔ Control temperature.
- ✔ Remove existing moisture.
- ✔ Monitor continuously.

Break the cycle. Protect the life.

12 WHERE SHOULD WE BREAK THE CYCLE?

Answer:

- ✔ At the source (ingress)
- ✔ During migration (temperature and load control)
- ✔ Before degradation (dry insulation)

Break anywhere, stop everywhere.

13 WHAT IS THE ROLE OF TEMPERATURE?

Answer:

- ✔ High temperature drives moisture into paper.
- ✔ Hot spots accelerate aging.
- ✔ Temperature control is critical.

Temperature is the engine of the cycle.

14 HOW DOES LOAD AFFECT THE CYCLE?

Answer:

- ✔ High load = High temperature
- ✔ More moisture in paper
- ✔ Faster aging
- ✔ Low load = Moisture returns to oil

Load management controls the cycle.

15 WHAT IS THE GOAL?

Answer:

- ✔ Keep insulation dry.
- ✔ Minimize aging rate.
- ✔ Extend life.
- ✔ Ensure reliability.

Control the cycle. Extend the life.

16 WHAT IS THE GOLDEN RULE?

Answer:

> "A dry transformer does not age fast. A controlled transformer lives long."

Moisture control is life control.

THE MOISTURE CYCLE EXPLAINED

Step	Stage	What Happens	Impact
1	Moisture Generation	Moisture enters from outside or is generated inside	Initial moisture increase
2	Moisture Migration	Moisture moves between oil and paper	Moisture in paper rises
3	Insulation Degradation	Moisture + heat cause chemical aging	Paper weakens, by-products form
4	Performance Deterioration	Dielectric strength reduces, risk increases	Higher risk of failure
5	More Moisture Generation	Aged insulation attracts and holds more moisture	Cycle restarts stronger

CYCLE BREAK STRATEGY

- **Prevent Ingress** — Use good breathing, seal leaks, maintain gaskets
- **Control Temperature** — Manage load, improve cooling, avoid hot spots
- **Remove Moisture** — Vacuum drying / continuous dehydration
- **Maintain Oil Quality** — Filter, degas, inhibit oxidation
- **Monitor Continuously** — Moisture, temperature, DGA, acidity, trends

Consistent action breaks the cycle. Consistent monitoring keeps it broken.

DISTURB THE CYCLE – SAVE THE TRANSFORMER

One weak point allows the cycle. Strong control at every point stops it.

KEY TAKEAWAYS

- Moisture follows a continuous cycle.
- Each cycle causes more damage.
- Trends are more important than snapshots.
- Break the cycle early.
- Dry insulation = Long life + Reliability.

DRYTRANS INSIGHT

The moisture cycle is the root cause of insulation aging.
Our mission is to break this cycle continuously through science, technology, and monitoring.
We don't just remove moisture.
We break the cycle.

REFERENCES

- IEC 60076-22: Power Transformers – Load Guide
- IEC 60422: Mineral Insulating Oils
- CIGRE TB 349: Moisture Equilibrium and Moisture Assessment
- DryTrans Technical Library and Field Experience

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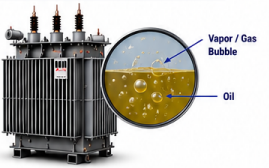
SECTION 22

BUBBLING RISK IN POWER TRANSFORMERS

Small Bubbles. Big Consequences.

Moisture + Heat = Bubbles. Bubbles reduce dielectric strength, cause partial discharges, and can lead to catastrophic failure. Understanding bubbling risk is critical for transformer reliability.



KEY MESSAGE

Bubbling is not just a sign of high temperature. It is a sign of moisture and reduced dielectric strength.

Prevent bubbling.
Protect the insulation.
Protect the transformer.

01 WHAT IS BUBBLING?

Answer:

- ✓ Formation of vapor / gas bubbles in the oil.
- ✓ Occurs when local temperature exceeds the oil's boiling point at that pressure.
- ✓ Bubbles collapse or grow, disturbing the electric field.

Bubbles = Weakness in the insulation system.

02 WHAT CAUSES BUBBLING?

Answer:

- ✓ High temperature (hot spots)
- ✓ Excess moisture in oil / paper
- ✓ Low oil quality (acidity, sludge)
- ✓ Overloading
- ✓ Poor cooling
- ✓ Sudden load changes

Moisture lowers oil's boiling point and increases risk.

03 HOW DOES MOISTURE INCREASE BUBBLING RISK?

Answer:

- ✓ Water has a lower boiling point than oil.
- ✓ Moisture in oil reduces overall boiling point.
- ✓ Moisture in paper releases vapor under heat.
- ✓ Both lead to bubble formation.

More moisture = Higher bubbling risk.

04 WHAT HAPPENS WHEN BUBBLING OCCURS?

Answer:

- ✓ Dielectric strength reduces.
- ✓ Partial discharges can start.
- ✓ Insulation ages faster.
- ✓ Gas is generated.
- ✓ May lead to breakdown.

Bubbling today can become a breakdown tomorrow.

05 WHAT ARE THE TYPES OF BUBBLING?

Answer:

- ✓ General bubbling (bulk oil)
- ✓ Localized bubbling (hot spots)
- ✓ Surface bubbling (near windings / conductors)
- ✓ Interface bubbling (oil—paper interface)

Localized bubbling is the most dangerous.

06 WHAT TEMPERATURES CAUSE BUBBLING?

Answer:

- ✓ Depends on pressure, oil type and moisture content.
- ✓ More moisture = lower boiling point.
- ✓ Rule of thumb: 10 ppm moisture can reduce boiling point by ~10°C.

Hotter oil + more moisture = Bubbling at lower temperature.

07 WHERE DOES BUBBLING OCCUR MOST?

Answer:

- ✓ In hottest parts of the winding.
- ✓ Near conductor joints.
- ✓ At loose connections.
- ✓ In oil pockets with poor circulation.

Find the hot spot. Control the bubbles.

08 HOW DOES BUBBLING LEAD TO FAILURE?

Answer:

- ✓ Partial discharge erodes insulation.
- ✓ Carbonization of paper begins.
- ✓ Mechanical stress on windings.
- ✓ Loss of dielectric strength.
- ✓ Eventual breakdown.

Bubbling is the early warning of a bigger failure.

09 HOW CAN WE DETECT BUBBLING RISK?

Answer:

- ✓ Monitor moisture (ppm, a_w, RS%).
- ✓ Monitor top oil temperature.
- ✓ Monitor load and hot spot temperature.
- ✓ Use DGA – look for H_2 and CO.
- ✓ Watch for tan δ increase.

Test. Trend. Analyze. Act before it bubbles.

10 HOW DO LOAD CONDITIONS AFFECT BUBBLING?

Answer:

- ✓ Higher load = higher temperature.
- ✓ Higher temperature = higher bubbling risk.
- ✓ Sudden load changes create thermal stress.
- ✓ Overloading is a major risk factor.

Manage load. Manage risk.

11 HOW DOES COOLING IMPACT BUBBLING?

Answer:

- ✓ Good cooling removes heat.
- ✓ Maintains safe oil temperature.
- ✓ Prevents hot spots.
- ✓ Poor cooling increases bubbling risk significantly.

Good cooling = Lower bubbling risk.

12 HOW DO WE PREVENT BUBBLING?

Answer:

- ✓ Keep moisture level low.
- ✓ Maintain oil quality.
- ✓ Control temperature.
- ✓ Ensure proper cooling.
- ✓ Avoid overloading.

Prevention is always cheaper than failure.

MOISTURE LEVEL VS BUBBLING RISK

Moisture in Oil (ppm)	Relative Saturation (RS%)	Bubbling Risk	Impact on Insulation
≤ 10	≤ 15%	Very Low	Excellent insulation Reliability high
10 – 20	15 – 30%	Low	Safe under normal conditions
20 – 30	30 – 50%	Moderate	Bubbling possible under high heat
30 – 50	50 – 70%	High	High bubbling risk Insulation stress high
> 50	> 70%	Very High	Very high bubbling risk Failure risk high

Lower moisture. Lower risk. Longer life.

THE BUBBLING CHAIN REACTION

Moisture in Oil / Paper
Lowers boiling point
↓
Heat from Load / Hot Spots
Temperature increases
↓
Bubbles Form
Vapor pockets appear
↓
Dielectric Strength Reduces
Partial discharges start
↓
Insulation Degrades
Aging accelerates
↓
Failure / Breakdown
Transformer trips or fails

BREAK THE CHAIN. CONTROL MOISTURE AND HEAT.

BEST PRACTICES TO REDUCE BUBBLING RISK

- ✓ Maintain moisture at safe levels (RS% < 30%).
- ✓ Use online moisture monitoring if possible.
- ✓ Monitor top oil, hotspot and load regularly.
- ✓ Ensure proper cooling – radiators, fans, pumps.
- ✓ Avoid overload and sudden load changes.
- ✓ Maintain oil quality – filtration, degassing.
- ✓ Check and tighten all connections.
- ✓ Use high quality breathers and seals.
- ✓ Review trends and act early.

Consistent action = Consistent reliability.

KEY TAKEAWAYS

- ✓ Moisture lowers boiling point.
- ✓ Heat + Moisture = Bubbles.
- ✓ Bubbles reduce dielectric strength.
- ✓ Bubbling leads to partial discharges.
- ✓ Control moisture. Control temperature.
- ✓ Prevent bubbling. Extend transformer life.

DRYTRANS INSIGHT

Most bubbling-related failures are preventable. Moisture management is the most effective way to stop bubbling and extend life.

REMEMBER

You cannot see bubbles.
You can see the signs.
You can control the causes.
You can prevent the failure.

REFERENCES

- IEC 60076-2: Power Transformers
- IEC 60422: Mineral Insulating Oils
- CIGRE TB 349: Moisture Equilibrium
- IEEE C57.104: Guide for Moisture in Transformers
- DryTrans Technical Library & Field Experience

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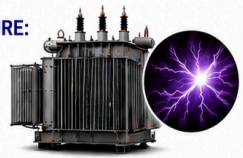
SECTION 23

PARTIAL DISCHARGE (PD) & MOISTURE: THE INVISIBLE CONNECTION

Moisture is one of the strongest enablers of Partial Discharge. It reduces dielectric strength, lowers inception voltage, and accelerates insulation deterioration.

LESS MOISTURE = FEWER PDs = LONGER LIFE



KEY MESSAGE

PD is a symptom.
Moisture is a root cause.

Control moisture.
Suppress PD.
Protect insulation.

1 WHAT IS PARTIAL DISCHARGE (PD)?

- ✓ Localized electrical discharges that occur in a small part of the insulation.
- ✓ Does not bridge the full insulation gap.
- ✓ A warning sign of insulation weakness.

Small today.
Big failure tomorrow.

2 HOW DOES MOISTURE CAUSE PD?

- ✓ Moisture reduces dielectric strength of oil and paper.
- ✓ Creates weak spots and voids in cellulose.
- ✓ Lowers PD inception voltage (PDIV).
- ✓ Increases conductivity and charge mobility.

Moisture creates the conditions.
PD reveals the damage.

3 EFFECT OF MOISTURE ON PD LEVELS

- ✓ Higher moisture = Lower PDIV
- ✓ Higher PD magnitude
- ✓ More frequent PD pulses
- ✓ Faster insulation aging

More moisture.
More PD activity.

4 PD LOCATION IN TRANSFORMERS

- ✓ Windings (turn-to-turn, layer-to-layer)
- ✓ Core to ground
- ✓ Floating metal parts
- ✓ Oil voids and gas bubbles
- ✓ Bushings (inside insulation)

PD can be anywhere.
Detection is critical.

5 PD ACTIVITY OVER TIME

- ✓ PD starts small.
- ✓ Increases with moisture, temperature & aging.
- ✓ Eventually causes insulation breakdown.

PD grows.
So does the risk.

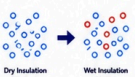
6 THE MOISTURE–PD–AGING FEEDBACK LOOP

- ✓ Moisture causes PD
- ✓ PD generates heat
- ✓ Heat drives off more moisture
- ✓ More moisture returns
- ✓ Cycle repeats
- ✓ Insulation ages quickly

Break the loop.
Extend life.

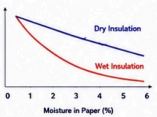
THE SCIENCE BEHIND IT

Moisture Lowers Dielectric Strength



Water molecules create conductive paths and reduce breakdown strength.

Moisture Lowers PD Inception Voltage (PDIV)



More moisture = PD starts at lower voltage.

PD Accelerates Insulation Aging

PD does not just indicate aging.
It accelerates aging.

7 HOW TO REDUCE PD BY MANAGING MOISTURE

- ✓ Keep moisture in oil low (ppm).
- ✓ Maintain paper moisture at safe level.
- ✓ Control relative saturation (RS%).
- ✓ Prevent moisture ingress.
- ✓ Use continuous dehydration (DryTrans system).

Low moisture.
Low PD.
High reliability.

8 INDICATORS THAT MOISTURE MAY BE CAUSING PD

- ✓ High PD at normal voltage
- ✓ PD increases at high humidity
- ✓ PD reduces after dehydration
- ✓ High RS% or high ppm
- ✓ High tan δ with PD

If PD improves after dehydration, moisture was the driver.

9 TESTS THAT HELP CORRELATE PD & MOISTURE

- ✓ Moisture in Oil (ppm)
- ✓ Moisture in Paper (%)
- ✓ Relative Saturation (RS%)
- ✓ Dissipation Factor (tan δ)
- ✓ PD Measurement (IEC 60270)
- ✓ Temperature Monitoring

Combine data.
Understand the root cause.

10 TYPICAL PD LEVELS (IEC 60270)

PD Level	Typical Interpretation
< 10 pC	Normal / Very Low
10 – 100 pC	Acceptable
100 – 500 pC	Caution
500 – 1000 pC	High
> 1000 pC	Very High / Urgent Action

Lower PD levels mean stronger, healthier insulation.

11 BEST PRACTICES

- ✓ Keep moisture low at all times.
- ✓ Monitor PD periodically.
- ✓ Investigate any increasing trend.
- ✓ Combine PD data with moisture, gas, and electrical tests.
- ✓ Act early. Do not wait for failure.

Early action on moisture keeps PD under control.

12 THE BOTTOM LINE

"Moisture is silent.
PD is the alarm.

Ignoring either can be costly.

Control moisture.
Control PD.
Control the future."

MOISTURE LEVEL vs PD BEHAVIOR (TYPICAL GUIDE)

Relative Saturation (RS%)	Paper Moisture (%)	Expected PD Behavior
< 20%	< 1.0%	Very Low PD Risk
20% – 40%	1.0 – 2.0%	Low PD Risk
40% – 60%	2.0 – 3.0%	Moderate PD Risk
60% – 80%	3.0 – 4.0%	High PD Risk
> 80%	> 4.0%	Very High PD Risk

PD DETECTION METHODS

- Online PD Monitoring (IEC 60270)
- Off-line PD Measurement (IEC 60270)
- HFCT / UHF Sensors
- Acoustic Emission Sensors

DRYTRANS INSIGHT

In thousands of transformers, we have seen the same truth:

When moisture is controlled, PD levels drop.
When PD levels drop, insulation life extends significantly.

Moisture management is the most effective way to keep PD low and transformers reliable.

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ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protect your investment. Our solutions are proven in utilities, industries and critical infrastructure around the world.

DRY TODAY. RELIABLE TOMORROW.
POWER FOR YEARS.

"Control moisture.
Protect your transformer.
Protect your future."

SCAN TO EXPLORE THE SERIES

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SECTION 24

INTERFACIAL TENSION (IFT) & MOISTURE: A CRITICAL, OFTEN IGNORED LINK

Interfacial tension (IFT) is the "health" of the oil. Moisture, aging, and contaminants reduce IFT, leading to poor oil impregnation, weak insulation, and higher failure risk.

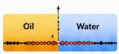
GOOD IFT = STRONG INSULATION = RELIABILITY

KEY MESSAGE

- ✓ IFT indicates oil's ability to wet cellulose.
- ✓ Moisture lowers IFT.
- ✓ Low IFT increases the risk of partial discharge and aging.
- ✓ Monitor IFT. Maintain it. Protect life.

1 WHAT IS INTERFACIAL TENSION (IFT)?

- ✓ IFT is the force at the interface between oil and water.
- ✓ It represents the ability of oil to repel water and wet the cellulose.
- ✓ Measured in mN/m (milliNewton per meter).



2 WHY IS IFT IMPORTANT IN TRANSFORMERS?

- ✓ High IFT ensures good oil impregnation of paper.
- ✓ It minimizes moisture pockets and voids.
- ✓ It maintains dielectric strength.
- ✓ It reduces risk of partial discharge (PD).

High IFT = Good Wetting = Strong Insulation

3 HOW DOES MOISTURE AFFECT IFT?

- ✓ Moisture competes with cellulose for oil.
- ✓ It forms a water layer at the interface.
- ✓ This lowers IFT.
- ✓ Low IFT means oil cannot properly wet the paper.

More Moisture = Lower IFT = Higher Risk

4 OTHER FACTORS THAT REDUCE IFT

- ✓ Aging (acidic compounds increase polarity).
- ✓ Oxidation by-products (sludges, gums).
- ✓ Contaminants and dirt particles.
- ✓ Use of low-quality or degraded oil.

Aging + Contaminants + Moisture = Low IFT

5 WHAT HAPPENS WHEN IFT IS LOW?

- ✓ Poor oil impregnation.
- ✓ Moisture pockets remain in paper.
- ✓ Increased partial discharge activity.
- ✓ Faster aging of cellulose.
- ✓ Reduced dielectric strength.
- ✓ Higher risk of failure.

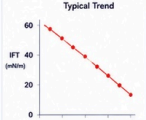
Low IFT = High Risk

6 WHAT IS THE IDEAL IFT RANGE?

- ✓ New, high quality oil: IFT > 40 mN/m
- ✓ Good condition: IFT 30 – 40 mN/m
- ✓ Caution: IFT 20 – 30 mN/m
- ✓ Poor / High Risk: IFT < 20 mN/m

Keep IFT High. Keep Risk Low.

THE RELATIONSHIP: MOISTURE vs IFT



- ✓ As moisture increases, IFT decreases.
- ✓ Even small moisture increase can significantly reduce IFT.

Control moisture. Maintain IFT.

LOW IFT = HIGH PD RISK (WHY?)

Low IFT | Poor Wetting of Cellulose | Voids & Moisture Pockets | Partial Discharges Start | Insulation Degrades

Low IFT creates the path. PD accelerates the damage.

BEST PRACTICES TO MAINTAIN IFT

- ✓ Keep moisture in oil low (ppm).
- ✓ Prevent moisture ingress.
- ✓ Use high-quality, inhibitor-treated oil.
- ✓ Avoid overheating and oxidation.
- ✓ Filter and remove contaminants.
- ✓ Monitor IFT regularly.
- ✓ Act early if IFT starts dropping.

Monitor IFT. Manage Moisture. Ensure Reliable Insulation.

7 HOW OFTEN SHOULD IFT BE TESTED?

- ✓ For critical transformers: Every 6 – 12 months.
- ✓ After any major oil handling or filtration.
- ✓ When moisture or aging indicators are high.

Regular Test. Early Detection.

8 IFT AS AN EARLY WARNING INDICATOR

- ✓ IFT starts dropping before insulation fails.
- ✓ It gives early indication of oil and moisture problems.
- ✓ Use it with moisture, DGA, and acidity for better decisions.

IFT Trend = Early Insight = Smart Action

9 COMBINE IFT WITH OTHER TESTS

- ✓ Moisture (ppm, RS%, a_w)
- ✓ Acidity (TAN)
- ✓ DGA (gases)
- ✓ Dielectric Strength (BDV)

Complete Picture. Better Decisions. Longer Life.

10 THE BOTTOM LINE

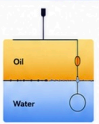
"IFT is small in numbers, but huge in impact.

High IFT protects. Low IFT warns.

Manage moisture. Maintain IFT.

Protect your transformer.

HOW IFT IS TESTED



- ✓ A platinum ring is pulled at the interface.
- ✓ The force required to break the interface is measured.
- ✓ Reported in mN/m.

Test Method: ASTM D971 / IEC 62961

KEY TAKEAWAYS

- ✓ IFT shows the oil's ability to keep water away and wet the paper.
- ✓ Moisture, aging, and contaminants reduce IFT.
- ✓ Low IFT leads to poor impregnation, PD, and faster aging.
- ✓ Monitor IFT regularly and manage moisture continuously.

DRYTRANS INSIGHT

In thousands of transformers, we have seen the same truth: When moisture is controlled and IFT is maintained high, insulation stays strong, PD stays low, and transformers deliver reliable performance for decades.

REFERENCE STANDARDS

- IEC 62961: Interfacial tension – Measurement of interfacial tension
- ASTM D971: Interfacial tension of oil against water by the ring method
- IEC 60296: Specification for unused mineral insulating oils
- CIGRE TB 349: Moisture Equilibrium in Transformer Insulation
- DryTrans Technical Library

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SECTION 25

METHANOL AS AN EARLY AGING INDICATOR: THE FIRST CHEMICAL WHISPER

Methanol is the earliest by-product of cellulose degradation.
It appears long before furans rise.
Ignoring methanol means ignoring the first warning.

EARLY DETECTION. TIMELY ACTION. LONGER LIFE.

KEY MESSAGE

- ✓ Methanol = Early aging indicator.
- ✓ It forms first. It warns first.
- ✓ Track it. Understand it.
- ✓ Act early. Save insulation life.
- ✓ Moisture accelerates methanol formation.
- ✓ Control moisture. Control aging.

1 WHAT IS METHANOL?

- ✓ Methanol (CH_3OH) is a simple alcohol.
- ✓ It is a by-product of cellulose (paper) degradation.
- ✓ It dissolves in transformer oil.
- ✓ It is not produced by faults.
- ✓ It is produced by aging.

Methanol = Aging Signature

2 HOW DOES METHANOL FORM?

- ✓ Cellulose breaks down due to:
  - Heat
  - Moisture
  - Oxygen
- ✓ In early stages, methanol is released.
- ✓ More aging = more methanol.

First by-product of cellulose degradation

3 WHY IS METHANOL IMPORTANT?

- ✓ It is the earliest measurable aging indicator.
- ✓ It appears before furans.
- ✓ It helps in early trend detection.
- ✓ It indicates the rate of insulation aging.

Early Warning. Early Action. Life Extension.

4 METHANOL vs FURAN (2-FAL)

Parameter	Methanol	Furan (2-FAL)
Stage	Early	Later
Source	Cellulose degradation	Advanced degradation
Appearance	First	After methanol
Sensitivity	High (early detection)	Lower (late detection)
Use	Trend & rate of aging	Insulation life estimation

Methanol shows the beginning. Furan shows the extent.

5 WHAT INCREASES METHANOL LEVELS?

- ✓ High moisture in paper and oil
- ✓ High temperature
- ✓ Oxygen (air ingress)
- ✓ Longer exposure to thermal stress
- ✓ Overloading

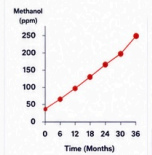
Moisture + Heat + Oxygen = More Methanol

6 WHAT DO HIGH LEVELS MEAN?

- ✓ Active cellulose degradation
- ✓ Faster aging rate
- ✓ Reduced insulation life
- ✓ Higher risk of failure
- ✓ Need for immediate moisture & aging management

High Methanol = High Aging = High Risk

METHANOL TREND = AGING TREND



- ✓ A rising methanol trend confirms active aging.
- ✓ The slope indicates the rate of aging.
- ✓ Early control can change the trend.

Don't wait for furans. Watch methanol trend.

TYPICAL METHANOL LEVELS (GUIDELINE*)

Methanol in Oil (ppm)	Interpretation	Action
< 10	Normal / Very Low Aging	Continue Monitoring
10 – 50	Low Aging	Monitor & Manage Moisture
50 – 100	Moderate Aging	Investigate & Reduce Moisture
100 – 200	High Aging	Take Corrective Action
> 200	Severe Aging	Immediate Action Required

*Guidelines may vary based on transformer design, oil type and operating conditions.

HOW TO USE METHANOL DATA?

- ✓ Sample oil regularly (6–12 months).
- ✓ Track methanol trend over time.
- ✓ Compare with moisture, temperature and load.
- ✓ Use with Furan, TAN, DGA and other parameters.
- ✓ Integrate in a holistic aging assessment.

Methanol data + Other data = Accurate aging picture

7 METHANOL & MOISTURE CONNECTION

- ✓ Moisture accelerates cellulose hydrolysis.
- ✓ Higher moisture = More methanol.
- ✓ Keep moisture low, Keep methanol low.

Control Moisture. Control Methanol. Control Aging.

8 BEST PRACTICES

- ✓ Maintain low moisture in oil and paper.
- ✓ Use continuous dehydration (DryTrans system).
- ✓ Maintain oil quality (low acidity, low sludge).
- ✓ Monitor methanol trend regularly.
- ✓ Act early. Do not wait.

Proactive care. Saves insulation. Saves assets.

9 CASE EXAMPLE

A 40 MVA transformer showed:

- Methanol increased from 25 ppm to 120 ppm in 18 months.
- Furan was still low (150 ppb).
- After continuous dehydration and load optimization:
  - Methanol trend reversed.
  - Furan rise was prevented.
  - Insulation life extended significantly.

Methanol warned. Action protected. Life extended.

10 THE BOTTOM LINE

"Methanol is the first sign of cellulose aging.
It whispers before furans shout.
Listen early. Act early.
Protect always."

METHANOL TESTING

Test Method
GC (Gas Chromatography)

Standard
IEC 60567

Sample
Oil sample

Typical Detection Limit
1 – 2 ppm

KEY TAKEAWAYS

- ✓ Methanol is the earliest aging by-product.
- ✓ It appears before furans.
- ✓ It indicates the rate of insulation aging.
- ✓ Rising methanol = active aging.
- ✓ Control moisture to control methanol.

DRYTRANS INSIGHT

In thousands of transformers, we have seen the same truth:
Methanol never lies.
It tells the real story of aging.
Use it. Understand it.
Act on it. Extend life.

REFERENCE STANDARDS

- IEC 60567: Insulating liquids – Determination of methanol content
- IEEE C57.104: Guide for the Interpretation of Gases in Transformers and Electrical Equipment
- CIGRE TB 349: Moisture Equilibrium in Transformer Insulation
- DryTrans Technical Library

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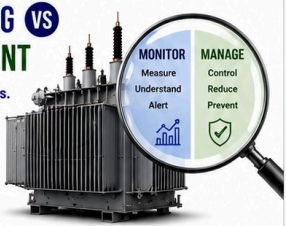
SECTION 26

MOISTURE MONITORING VS MOISTURE MANAGEMENT

Know the Difference. Protect What Matters.

Monitoring tells you what is happening.
Management ensures it stays under control.
One informs. The other protects.

Data without action has no value.
Action without data has no direction.



KEY MESSAGE

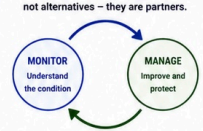
- ✓ Monitoring shows the problem.
- ✓ Management solves the problem.
- ✓ Monitoring is periodic.
- ✓ Management is continuous.
- ✓ Monitoring reports moisture.
- ✓ Management removes moisture.
- ✓ Monitoring reacts.
- ✓ Management prevents.
- ✓ Monitoring is a cost.
- ✓ Management is an investment.
- ✓ Monitor to know.
- ✓ Manage to protect.

MONITORING vs MANAGEMENT – AT A GLANCE

FEATURE	MOISTURE MONITORING	MOISTURE MANAGEMENT
Purpose	Measure and report moisture levels	Control and reduce moisture levels
Nature	Periodic (snapshot in time)	Continuous (24/7 protection)
Output	Data, trends, alarms	Dry, stable, healthy insulation
Action	Reacts after moisture increase	Prevents moisture from rising
Focus	Information	Results
Impact	Helps in decision making	Extends life, improves reliability
Limitations	Late warning, cannot remove moisture	Requires proper system & discipline
Outcome	You know the risk	You eliminate the risk

WHY BOTH ARE IMPORTANT

Monitoring and Management are not alternatives – they are partners.



Monitor without manage = Risk continues
Manage without monitor = No direction

THE REAL GOAL

Not just to measure low moisture, but to keep it low – all the time.

This is Moisture Management.
This is Transformer Reliability.

THE CONSEQUENCES OF DOING ONLY ONE

ONLY MONITORING (NO MANAGEMENT)

- ✗ Moisture keeps fluctuating
- ✗ Paper keeps aging
- ✗ Dielectric strength reduces
- ✗ Risk of PD, corrosion, and failure increases
- ✗ Unexpected outages and repairs

You see the problem, but cannot stop it.

MOISTURE DOES NOT WAIT

ONLY MANAGEMENT (NO MONITORING)

- ✗ No visibility of actual condition
- ✗ No way to validate effectiveness
- ✗ Hidden issues may be missed
- ✗ Poor optimization and higher cost
- ✗ Uncertainty remains

You act, but may not be addressing the real need.

BEST PRACTICE APPROACH

- ✓ Monitor continuously for early detection.
- ✓ Analyze trends, not just numbers.
- ✓ Manage proactively to keep moisture low.
- ✓ Verify effectiveness through monitoring.
- ✓ Document, review and improve.

Data-driven + Action-oriented = Reliable Transformers

HOW TO MAKE THE SHIFT: FROM MONITORING TO MANAGEMENT

1. MEASURE
Establish baseline moisture levels.

2. ANALYZE
Identify trends, sources & risks.

3. ACT
Implement continuous moisture removal.

4. MAINTAIN
Keep moisture low and stable.

5. VERIFY
Monitor results and optimize continuously.

A systematic approach. A continuous cycle. A reliable future.

KEY TAKEAWAY

> "Monitoring tells you where you are today. Management decides where your transformer will be tomorrow."

Monitor to know.
Manage to protect.
Protect to perform.
Perform to deliver.

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DRYTRANS INSIGHT

In thousands of transformers worldwide, the ones that perform best are not the ones monitored most, but the ones where moisture is managed best.
Make the shift. See the difference.

REFERENCE STANDARDS

- IEC 60076-22: Transformer Oil Guide
- IEC 60296: Mineral Insulating Oils
- IEC 60422: Mineral Oil Impregnated Paper
- CIGRE TB 349: Moisture Equilibrium in Transformers
- DryTrans Technical Library

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SECTION 27

PERIODIC DEHYDRATION VS CONTINUOUS MOISTURE MANAGEMENT

A CHOICE THAT DEFINES TRANSFORMER LIFE

Both approaches remove moisture.
But the results, the impact on insulation life,
and the long-term reliability are drastically different.

The goal is not just to remove moisture.
The goal is to keep it low – all the time.

KEY MESSAGE

- ✓ Moisture is always trying to come in.
- ✓ Periodicity cannot stop ingress.
- ✓ Only continuous management can keep moisture low.
- ✓ Low moisture = long insulation life.
- ✓ Choose management, not just removal.
- ✓ Think long term. Act continuously.

PERIODIC DEHYDRATION vs CONTINUOUS MOISTURE MANAGEMENT

PERIODIC DEHYDRATION (Fix It Now)	PARAMETER	CONTINUOUS MOISTURE MANAGEMENT (Keep It Low)
Done once in 2–5 years	Approach	24/7, all year, every day
Removes bulk moisture	Purpose	Prevents moisture from rising
High initially, rises again	Moisture Trend	Low and stable
Moisture re-enters from ingress	Moisture Ingress	Continuously blocked and removed
Temporary improvement	Effect Duration	Permanent improvement
Cyclic aging continues	Insulation Aging	Aging rate significantly reduced
Higher risk	Risk of Failure	Much lower risk
Higher over life cycle	Life Cycle Cost	Lower over life cycle
Repairs and unplanned outages	Operational Impact	Fewer outages, higher reliability
Reactive	Strategy	Proactive

WHY PERIODIC DEHYDRATION IS NOT ENOUGH

- ✗ Moisture ingress never stops.
- ✗ Oil breathes with temperature and humidity.
- ✗ Paper is hygroscopic and re-wets.
- ✗ Moisture migrates inside the insulation.
- ✗ Moisture pockets cannot be eliminated fully.
- ✗ After every dehydration, moisture starts rising again.
- ✗ Insulation spends most of its life in a "wet" condition.

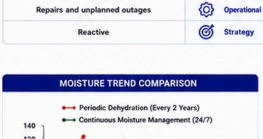
Result: Short-term benefit, Long-term damage.

WHY CONTINUOUS MANAGEMENT IS SUPERIOR

- ✓ Continuously removes incoming moisture.
- ✓ Maintains low moisture in oil and paper.
- ✓ Prevents moisture pockets.
- ✓ Reduces temperature–moisture interaction.
- ✓ Greatly slows down insulation aging.
- ✓ Extends transformer life significantly.
- ✓ Improves reliability and reduces risk.

Result: Long-term protection, Maximum life.

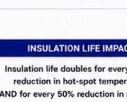
MOISTURE TREND COMPARISON



Periodic dehydration gives a temporary drop.
Continuous management keeps moisture low and stable.

INSULATION LIFE IMPACT

Insulation life doubles for every 6–7°C reduction in hot-spot temperature
AND for every 50% reduction in moisture.



Low and stable moisture
= Slower aging = Longer life

TOTAL COST OF OWNERSHIP (TCO)
(Typical 25-Year Comparison)

Periodic Dehydration	Continuous Moisture Management
Dehydration every 2–5 years	One-time installation
Higher moisture related aging	Low and stable moisture
More breakdowns	Less aging
More repairs	Fewer breakdowns
More outages	Minimal outages
Higher risk	Lower risk
Higher total cost	Lower total cost

Continuous moisture management reduces life cycle cost by 30–50%*

*Typical industry observation

BEST PRACTICE APPROACH

RECOMMENDED IMPLEMENTATION

- Install a continuous dehydration system designed for on-spot operation.
- Ensure breathers are active and protected throughout the year.
- Use data-driven monitoring to validate performance.
- Review trends and optimize as per load and climate.
- Make moisture management a standard operational practice.

PROTECT CONTINUOUSLY PERFORM RELIABLY

THE BOTTOM LINE

"Periodic dehydration is like visiting a doctor after you get sick.
Continuous moisture management is like staying healthy every day.

Don't just remove moisture.
Manage it continuously.
That's how you extend life.
That's how you ensure reliability."

DRYTRANS INSIGHT

In thousands of transformers worldwide, the ones that last the longest have one thing in common:
They are continuously protected from moisture. Not just periodically dried.

REFERENCE STANDARDS

- IEC 60076-22: Transformer Oil Guide
- IEC 60422: Mineral Oil Impregnated Paper
- CIGRE TB 349: Moisture Equilibrium in Transformers
- IEEE C57.143: Guide for Acceptance and Maintenance of Moisture Control Systems

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SECTION 28

TRANSFORMER END-OF-LIFE: CAN MOISTURE MANAGEMENT STILL HELP?

When a transformer is old and heavily aged, many believe it is beyond recovery. While true aging cannot be reversed, effective moisture management can still deliver significant benefits and extend useful life.

Moisture is the accelerant. Control it, and you slow down the clock.

It's Not Over Until It's Over!

KEY MESSAGE

- Ageing is permanent. Moisture damage is not.
- Even at end-of-life, moisture control helps.
- Lower moisture = slower ageing rate.
- Improved reliability, fewer failures.
- Better dielectric strength and safety.
- Defer costly replacement.
- Get more years of service.
- Make the right decision based on data.

WHAT DOES "END-OF-LIFE" REALLY MEAN?

- Very old transformer (25–40+ years)
- High insulation aging
- High moisture
- Frequent issues / failures
- Low dielectric strength
- High maintenance cost

End-of-life is NOT a fixed number. It is a condition, not just an age.

Determined by:

- Insulation condition
- Moisture level
- Load and stress history
- Maintenance history
- Operational environment

THE IMPACT OF HIGH MOISTURE ON AGED INSULATION

High Moisture Causes	Impact on Aged Insulation
Hydrolysis	Paper chain scission (DP reduction)
Oxidation	More sludge, more acids, faster ageing
Low Dielectric Strength	Higher risk of PD, breakdown & failure
Poor Oil Quality	Reduced cooling, poor performance
Thermal Stress	Moisture + heat = accelerated ageing

Moisture turns ageing into rapid deterioration. Remove moisture, and you slow it down.

WHAT MOISTURE MANAGEMENT CAN STILL ACHIEVE

- Reduces ageing rate significantly
- Prevents further insulation degradation
- Improves dielectric strength
- Reduces PD risk
- Improves oil quality and cooling
- Increases reliability and availability
- Reduces risk of catastrophic failure
- Defers replacement / re-powering cost
- Provides more years of safe service
- Improves return on existing asset

Moisture management adds LIFE to what is LEFT.

DECISION FRAMEWORK: REPAIR, MANAGE OR REPLACE?

Condition	Moisture Level	Insulation Condition	Recommended Action
Good	Low (< 20–25 ppm)	DP Good BDV Good	Continue Monitoring Keep moisture low
Moderate	Moderate (25–50 ppm)	DP Moderate BDV Moderate	Moisture Management Extend Life
Poor	High (> 50 ppm)	DP Low BDV Low	Intensive Moisture Management Evaluate Risk vs. Reward
Very Poor	Very High (> 100 ppm)	DP Very Low Frequent Failures	Plan Replacement but manage moisture till then

Many transformers in "Poor" category have been successfully extended by 5–15 years through continuous moisture management.

REAL WORLD EXAMPLE

40 MVA transformer, 38 years old

Initial Condition:

- Oil Moisture: 78 ppm
- Paper Moisture (Est.): 4.2%
- DP: 210
- BDV: 18 kV
- History of OTF and high TAN

Action:

Installed DryTrans Continuous Moisture Management System

After 24 Months:

- Oil Moisture: 12 ppm
- Paper Moisture (Est.): 1.6%
- DP: 320 (52% improvement)
- BDV: 32 kV (78% improvement)
- No OTF, TAN stable

Result: Transformer life extended. Replacement deferred by ~10 years.

LIFE EXTENSION POTENTIAL (WITH MOISTURE CONTROL)

Life extension depends on:

- Initial condition
- Load profile
- Maintenance
- Environment
- System design

Continuous moisture management delivers the highest life extension.

KEY TAKEAWAYS

- End-of-life is a condition, not just an age.
- Moisture accelerates ageing — control it.
- Even heavily aged transformers can benefit.
- Moisture management can add 5–15+ years.
- Better reliability, safety and performance.
- Make data-driven decisions.
- Don't replace too early, don't take unnecessary risk.
- Manage moisture and maximize asset value.

RECOMMENDED APPROACH

1. **ASSESS** — Full diagnostic (Moisture, DGA, Furan, DP, BDV)
2. **DEHYDRATE** — Remove bulk moisture effectively
3. **MONITOR** — Track trends continuously
4. **MANAGE** — Keep moisture low 24/7 with DryTrans system
5. **MAINTAIN** — Prevent ingress & follow best practices

Assessment → Dehydration → Monitoring → Continuous Management → Life Extension

THE BOTTOM LINE

"Ageing is inevitable. Further deterioration is optional. Moisture management will not make an old transformer new, but it can make a tired transformer RELIABLE again.

More years. More value. More peace of mind."

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DRYTRANS INSIGHT

We cannot stop ageing, but we can control the biggest accelerant — moisture. Control moisture. Extend life.

REFERENCE STANDARDS

- IEC 60076-22: Transformer Oil Guide
- IEC 60422: Mineral Oil Impregnated Paper
- CIGRE TB 349: Moisture Equilibrium in Transformers
- IEEE C57.143: Guide for Acceptance and Maintenance of Moisture Control Systems

Scan to learn more about Continuous Moisture Management with DryTrans

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SECTION 29

BREATHERS: THE MOST COMMON MOISTURE INGRESS POINT AND HOW TO MANAGE THEM

A transformer breather is designed to protect the oil from contaminants. But if not maintained, it becomes the biggest source of moisture ingress. A small oversight in breather care can undo years of good transformer maintenance.

KEY MESSAGE

- ✓ Breathers protect oil only when they are dry and active.
- ✓ Saturated breathers allow moisture to enter the transformer.
- ✓ Regular inspection and maintenance prevent silent damage.
- ✓ A good breather habit = Long transformer life.

WHAT IS A BREATHER?

A breather allows the transformer to breathe as oil expands and contracts with temperature.

It prevents dust and moisture from entering the oil.

It contains desiccant that absorbs moisture from incoming air.

A healthy breather keeps moisture OUT.
A neglected breather lets moisture IN.

HOW DOES MOISTURE ENTER THROUGH A BREATHER?

- ✗ Desiccant gets saturated.
- ✗ Breather is not changed on time.
- ✗ Oil level rises and covers the breather.
- ✗ Breather seals leak.
- ✗ Cracked or damaged breather housing.
- ✗ Incorrect or poor quality desiccant.

Once saturated, the breather becomes a moisture source.

THE IMPACT OF A SATURATED BREATHER

- Moisture ingress increases
- Insulation ages faster
- Risk of PD and breakdown increases
- Oil quality deteriorates
- Higher chance of failures
- Reduced asset life and higher cost

A small maintenance lapse today can cause a major failure tomorrow.

HEALTHY BREATHER vs SATURATED BREATHER

✓ Dry desiccant (Orange)	✗ Wet desiccant (Purple)
✓ Low moisture	✗ High moisture
✓ Protects oil	✗ Allows moisture in
✓ Extends life	✗ Reduces life

BREATHER MAINTENANCE GUIDE

PARAMETER	BEST PRACTICE	FREQUENCY
Visual Inspection	Check color of desiccant	Monthly
Desiccant Condition	Orange = Good, Green/Purple = Replace	Monthly
Oil Level Check	Ensure oil level is below breather connection	Monthly
Breather Seal	Check for any leakage	Every 6 Months
Desiccant Replacement	Replace if saturated or as per schedule	Every 6 – 12 Months*
Breather Cleaning	Clean housing and seals	Every 6 – 12 Months
Record Keeping	Maintain log of checks and replacements	Every Time

* Depends on climate, load, and humidity conditions.

BEST PRACTICES FOR BREATHER MANAGEMENT

- ✓ Use high quality silica gel (Color indicator type).
- ✓ Replace desiccant before it gets saturated.
- ✓ Do not wait for failure – follow a time-based replacement.
- ✓ Always keep oil level 2–3 inches below breather connection.
- ✓ Ensure breather is vertically mounted and level.
- ✓ Check gaskets and seals during every inspection.
- ✓ Use weather shields in direct rain or dust conditions.
- ✓ Train maintenance team to recognize breather condition.
- ✓ Make breather maintenance a standard PM activity.

DESICCANT COLOR GUIDE

- Orange (Dry) Good
- Green (Slightly Wet) Monitor
- Purple (Wet) Replace
- Brown / Black (Very Wet) Replace Immediately

THE REALITY

- ✗ Most breathers are never checked.
- ✗ Desiccant is replaced only when it is fully saturated.
- ✗ Breathers are often ignored in maintenance plans.
- ✗ Moisture enters silently and causes hidden damage.
- ✗ Failures often start from something so simple.

Neglected breathers are one of the top reasons for high moisture in transformers.

THE SOLUTION

Inspect Regularly → Replace Timely → Protect Continuously → Extend Life & Improve Reliability

Simple breather care can save lakhs in repair and prevent long outages.

REMEMBER

> **A transformer can have the best oil, the best paper, and the best design. But if the breather is neglected, moisture will find its way in.**
>
> **Good breather maintenance is smart transformer management.**

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DRYTRANS INSIGHT

In thousands of transformers worldwide, we have seen one common pattern in failures: Moisture ingress through breathers that were not maintained on time.

Don't ignore the small gatekeeper. Protect the big asset.

REFERENCE STANDARDS

- IEC 60076-22: Transformer Oil Guide
- IEC 60422: Mineral Oil Impregnated Paper
- IEC 60599: Mineral Insulating Oils in Service
- CIGRE TB 349: Moisture Equilibrium in Transformers
- IEEE C57.143: Guide for Acceptance and Maintenance of Moisture Control Systems

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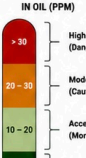
SECTION 30

UNDERSTANDING MOISTURE LEVELS: WHAT IS SAFE, RISKY AND DANGEROUS

Not all moisture levels are the same.
The difference between 10 ppm and 30 ppm can mean the difference between long life and early failure.

Moisture is the #1 driver of insulation aging in power transformers.
The key is not just to measure it,
but to understand what the number means.
This section helps you interpret moisture levels and take the right action.



KEY MESSAGE

- ✓ Moisture levels define the health of insulation.
- ✓ Lower moisture = Longer life.
- ✓ Higher moisture = Faster aging.
- ✓ Know your level. Understand the risk. Take action.
- ✓ Moisture management is not one-time. It is continuous.
- ✓ The best transformers are not dry by chance. They are kept dry by design and discipline.

MOISTURE LEVELS: RISK, IMPACT & ACTION

MOISTURE IN OIL (PPM)	RISK LEVEL	IMPACT ON TRANSFORMER	INSULATION CONDITION	ACTION REQUIRED
> 30 ppm	HIGH RISK (DANGEROUS)	• Very high aging rate • Paper gets saturated • PD risk increases • Dielectric strength decreases • Failure probability increases significantly	Paper moisture > 3.0% Insulation is wet and under stress	Immediate Action • Investigate source of moisture • Dehydrate immediately • Monitor closely • Review breather, sealing & leaks
20 – 30 ppm	MODERATE RISK (CAUTION)	• Aging rate is high • Insulation life reducing • Oil quality deteriorates • Higher carbonation of paper	Paper moisture 2.0% – 3.0% Insulation is moist, aging accelerated	Take Action Soon • Dehydrate • Improve sealing • Check breather • Increase monitoring frequency
10 – 20 ppm	ACCEPTABLE (MONITOR)	• Aging rate is moderate • Insulation life slightly affected • Dielectric strength is acceptable	Paper moisture 1.0% – 2.0% Insulation is acceptable	Monitor & Maintain • Continue monitoring • Maintain breather • Control ingress • Plan dehydration if rising trend
< 10 ppm	EXCELLENT (SAFE)	• Very low aging rate • Long insulation life • High dielectric strength • Very low failure risk	Paper moisture < 1.0% Insulation is dry and healthy	Maintain Excellence • Keep it dry • Monitor trends • Maintain systems • Protect your investment

HOW MOISTURE IMPACTS INSULATION LIFE

Insulation life reduces exponentially with increase in paper moisture.

PAPER MOISTURE (%)	RELATIVE LIFE (APPROX.)	COMMENT
< 1.0%	100%	Excellent Life
1.0 – 2.0%	50 – 70%	Normal Aging
2.0 – 3.0%	20 – 30%	High Aging
> 3.0%	< 10%	Very High Risk

WHY EVEN 10–20 PPM MATTERS?

- Moisture is dynamic. It keeps coming in.
- 10 ppm today can be 30 ppm in a few months.
- Transformer ages every day. Don't give moisture a chance.
- Good moisture management keeps you in the safe zone.

FACTORS THAT INCREASE MOISTURE LEVELS

- Saturated or faulty breather
- Poor sealing and leaks
- Opening tank during humid conditions
- High ambient humidity
- No dehydration / drying system
- Oil not maintained properly

RECOMMENDED MOISTURE TARGETS

NEW TRANSFORMER	NORMAL OPERATION	MAXIMUM ACCEPTABLE	TAKE ACTION	CRITICAL LEVEL
< 10 ppm	< 15 ppm	< 20 ppm	> 20 ppm	> 30 ppm
Aim for factory dry regulitory	Ideal range for long life	Monitor closely, take action	Plan dehydration immediately	Immediate action required

Target: Keep moisture in oil below 15 ppm and paper moisture below 2.0%

BEST PRACTICE APPROACH

1. **MONITOR** — Monitor moisture regularly
2. **CONTROL** — Control moisture ingress
3. **DEHYDRATE** — Remove moisture continuously
4. **PROTECT** — Protect insulation continuously
5. **EXTEND LIFE** — Extend life and improve reliability

Monitoring tells you. Management protects you. Action extends life.

THE BOTTOM LINE

> Moisture is invisible,
> but its impact is not.
> Understand your level.
> Control it continuously.
> That is how you ensure reliability and long life.

A dry transformer is a reliable transformer.
A wet transformer is a future failure.

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DRYTRANS INSIGHT

Controlling moisture is the most cost-effective way to extend transformer life. It reduces failures, outages, repairs, and replacement costs.

REFERENCE STANDARDS

- IEC 60076-22: Transformer Oil Guide
- IEC 60422: Mineral Oil Impregnated Paper
- IEC 60599: Mineral Insulating Oils in Service
- CIGRE TB 349: Moisture Equilibrium in Transformers
- IEEE C57.143: Guide for Acceptance and Maintenance of Moisture Control Systems

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SECTION 31

PAPER INSULATION & MOISTURE: THE TRUE CONNECTION

Paper is the heart of a transformer.
Moisture is its biggest enemy.

Transformer paper is hygroscopic – it naturally absorbs and releases moisture based on the environment and oil condition.

Control moisture, protect paper.
Protect paper, extend life.

KEY MESSAGE

- ✓ Transformer paper holds most of the insulation.
- ✓ Moisture in paper is more dangerous than in oil.
- ✓ Higher paper moisture = faster aging.
- ✓ Keep paper moisture low and stable.
- ✓ Continuous moisture management protects paper and extends transformer life.
- ✓ Dry transformer = Reliable transformer.

HOW PAPER ABSORBS MOISTURE

- Moisture enters from oil, air, and through insulation gaps.
- High humidity and poor breather condition accelerate ingress.
- Temperature rise causes moisture migration within paper.
- Paper holds moisture and releases it if oil becomes dry.

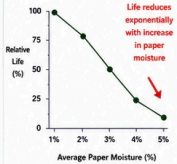
Moisture is always in motion. Balance is the key.

IMPACT OF HIGH PAPER MOISTURE

- Speeds up cellulose aging
- Reduces dielectric strength
- Increases risk of PD and breakdown
- Reduces mechanical strength
- Shortens transformer life

High paper moisture = Short life
Low paper moisture = Long life

PAPER MOISTURE vs LIFE EXPECTANCY



Keep paper moisture below 2% for maximum life and reliability.

SAFE PAPER MOISTURE GUIDELINE

Average Paper Moisture (%)	Condition	Risk Level
< 1.5%	Excellent	Low
1.5% – 2.0%	Good	Low
2.0% – 2.5%	Caution	Moderate
2.5% – 3.0%	High	High
> 3.0%	Very High	Very High

Target: Paper Moisture < 2.0%

FACTORS THAT INCREASE PAPER MOISTURE

High Ambient Humidity + Saturated or Faulty Breather + Oil Leaks & Poor Sealing + High Operating Temperature + Moisture in Oil (High ppm) + Weather Changes

Eliminate the source. Manage continuously.

BEST PRACTICES TO PROTECT PAPER

Monitor Moisture Regularly (Oil + Paper) → Remove Moisture Continuously → Maintain Sealing & Breather → Control Temperature → Track Trends & Take Action Early

Proactive care today. Reliable asset tomorrow.

PAPER MOISTURE MEASUREMENT METHODS

KARL FISCHER (OIL)
- ✓ Accurate
- ✓ Quick
- ✓ Essential

Measures moisture in oil (ppm)

EQUILIBRIUM METHOD (Paper)
- ✓ Reliable
- ✓ Field Proven
- ✓ Reference Method

Estimates average paper moisture (%)

ONLINE MOISTURE MONITORING
- ✓ Real-time
- ✓ Continuous
- ✓ Early Warning

Provides live moisture trend and alarm

THE GOLDEN RULE

Both extremes are harmful.
Maintain balance for maximum life.

THE BOTTOM LINE

"You cannot see moisture.
You can only measure it.
You cannot stop it once it enters.
You can only manage it continuously."

Manage moisture.
Protect paper. Extend life."

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DRYTRANS INSIGHT

More than 80% of insulation failures are moisture related. Paper moisture today defines your transformer's tomorrow.

REFERENCE STANDARDS

- IEC 60076-22: Transformer Oil Guide
- IEC 60422: Mineral Oil Impregnated Paper
- CIGRE TB 349: Moisture Equilibrium in Transformers
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SECTION 32

HOW TO ESTIMATE PAPER MOISTURE FROM OIL MEASUREMENTS

Oil moisture is easy to measure.
Paper moisture is what really matters.

More than 95–99% of the total moisture in a transformer resides in the cellulose insulation (paper). Since paper is difficult to access, we estimate its moisture using oil measurements, temperature and equilibrium models.

KEY MESSAGE

- ✓ Paper holds almost all the moisture.
- ✓ Oil moisture represents only a small portion of the total moisture.
- ✓ Estimate paper moisture using oil moisture, temperature and equilibrium models.
- ✓ Use trends, not single readings.
- ✓ Close to equilibrium = better estimation.
- ✓ Controlling oil moisture helps reduce paper moisture.
- ✓ Moisture management = Life extension.

WHY DIRECT MEASUREMENT IS DIFFICULT

- Paper is buried inside windings.
- Requires transformer shutdown.
- Paper sampling is destructive.
- Time consuming and costly.

Therefore, we estimate paper moisture using indirect methods.

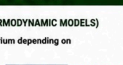
COMMON ESTIMATION METHODS

1 EQUILIBRIUM CURVES (THERMODYNAMIC MODELS)

Oil and paper reach an equilibrium depending on temperature and humidity.

Widely used models:

- Oommen Model
- Fabre–Pichon Model
- CIGRE Equilibrium Charts



2 ONLINE MONITORING SYSTEMS

Continuous measurement of oil moisture, temperature and %RS allows estimation of paper moisture.

Moisture (ppm) + Temperature (°C) + %RS (Relative Saturation) = Estimated Paper Moisture (%)

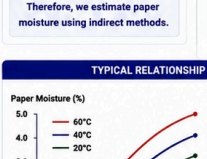
IMPORTANT LIMITATION

Paper moisture estimation is only valid when the transformer is near equilibrium.

Not at Equilibrium (Transient Condition)	Near Equilibrium (Stable Condition)
✗ After rapid loading	✓ Stable temperature
✗ During cooling	✓ Stable load
✗ During heating	✓ Stable ambient conditions
✗ After oil processing	✓ After sufficient time for equilibrium
✗ During major ambient changes	

In transient conditions, oil moisture may NOT represent actual paper moisture.

TYPICAL RELATIONSHIP

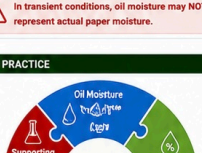


Higher temperature or higher %RS results in higher paper moisture for the same oil moisture (ppm).

Always use the actual operating temperature.

BEST PRACTICE

- Use TRENDS not single readings.
- Use actual oil temperature.
- Use %RS together with ppm.
- Correlate with electrical and chemical indicators.
- Confirm using multiple parameters.



RULE OF THUMB

If you reduce oil moisture (ppm) and %RS, paper moisture will slowly reduce.

Lower Paper Moisture
= Lower Aging Rate
= Longer Transformer Life

INDUSTRY REFERENCES

- IEEE C57.106 – Guide for Acceptance and Maintenance of Insulating Oil
- IEC 60422 – Mineral Oil Impregnated Paper
- CIGRE TB 349 – Moisture Equilibrium in Transformers
- IEEE C57.143 – Guide for Acceptance and Maintenance of Moisture Control Systems

THE BOTTOM LINE

> You cannot see paper moisture.
> You can only estimate it.
> But when you estimate it correctly, you can manage it effectively.
>
> **Good estimation leads to better decisions and longer life.**

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DRYTRANS INSIGHT

Oil is the window.
Paper is the heart.
Read the window correctly to protect the heart.

SCAN TO LEARN MORE

Learn more about Continuous Moisture Management with DryTrans

DRYTRANS SOLUTION

Continuous Moisture Management Systems for Reliable Transformers and Extended Life.

DryTrans – *Continuous Moisture Management Solutions for Reliable Transformers*

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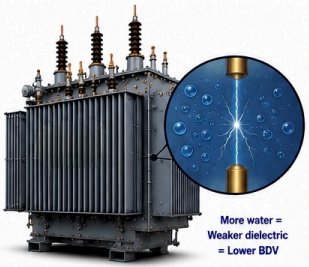
SECTION 33

MOISTURE AND DIELECTRIC BREAKDOWN VOLTAGE (BDV)

High moisture lowers dielectric strength. BDV is often the first property affected by excessive moisture.

Dielectric Breakdown Voltage (BDV) is the maximum voltage that insulation oil can withstand before it breaks down and conducts. As moisture increases, the oil's ability to withstand electric stress decreases.



More water = Weaker dielectric = Lower BDV

KEY MESSAGE

- ✓ Moisture reduces dielectric strength of oil.
- ✓ Higher moisture = lower BDV.
- ✓ BDV is a sensitive indicator of oil quality.
- ✓ Good BDV does not always mean dry paper.
- ✓ Correlate BDV with moisture, %RS, temperature and paper health.
- ✓ Control moisture to maintain high dielectric strength and reliability.

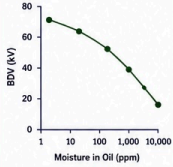
HOW MOISTURE REDUCES BDV

- Water molecules increase the conductivity of oil.
- Moisture forms microscopic bubbles under electric stress.
- Bubbles and water create weak paths for discharge.
- Breakdown occurs at a lower voltage.

More moisture → More weak paths → Lower BDV

TYPICAL TREND

BDV vs Moisture in Oil (at 25 °C)



BDV decreases significantly as moisture increases.

TYPICAL BDV RANGE

BDV (kV)	OIL CONDITION
> 60 kV	Excellent
40 – 60 kV	Good
30 – 40 kV	Caution
20 – 30 kV	Poor
< 20 kV	Very Poor

Values may vary with test method, electrode gap and temperature.

IMPORTANT LIMITATIONS

- BDV reflects oil condition, not paper moisture directly.
- Oil can be dry and paper can still be wet.
- Good BDV does not guarantee long insulation life.
- BDV is affected by temperature, gas, particles and test method.
- Always interpret BDV with other test results.

BDV is an indicator, not the complete answer.

CORRELATION: BDV WITH MOISTURE AND %RS

Moisture in Oil (ppm)	%RS (at 25 °C)	Typical BDV (kV)	Interpretation
< 10	< 20%	> 60	Excellent
10 – 50	20 – 40%	40 – 60	Good
50 – 200	40 – 60%	30 – 40	Caution
200 – 1,000	60 – 80%	20 – 30	Poor
> 1,000	> 80%	< 20	Very Poor

As %RS increases, BDV decreases. Keep %RS below 60% for safety.

BEST PRACTICES

- Keep oil moisture as low as practical.
- Maintain %RS below 60%.
- Monitor BDV regularly (6–12 monthly).
- Test at standard temperature (25 °C) and use same test method.
- Correlate BDV with moisture, %RS, Tan δ, resistivity and DGA.
- Investigate low BDV immediately.

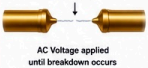
High BDV = Strong dielectric = Greater reliability

WHAT TO DO IF BDV IS LOW?

- ⚠ Check moisture level and %RS.
- ⚠ Verify temperature and test method.
- ⚠ Check for gas, particles and sludge.
- ⚠ Dry and filter the oil.
- ⚠ Identify and eliminate moisture ingress.
- ⚠ Monitor trend until improvement.

Low BDV is a warning. Act early to avoid failure.

BDV TEST METHOD (IEC 60156)



Key Points

- Standard gap: 2.5 mm
- Voltage ramp: 2 kV/s
- Minimum 3 breakdowns
- BDV = Average breakdown voltage
- Ensure oil is free from large bubbles and moisture during test

REMEMBER

> BDV is often the first electrical property to show the impact of moisture.

Control moisture.
Protect dielectric strength.
Ensure transformer reliability.

THE BOTTOM LINE

Moisture lowers BDV.
Monitoring improves visibility.
Management ensures reliability.
Dry insulation lasts longer.

CONTACT DRYTRANS

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DRYTRANS INSIGHT

BDV tells you how much voltage the oil can withstand. Moisture management ensures your transformer can withstand the stress throughout its life.

REFERENCE STANDARDS

- IEC 60156 – Insulating liquids – Determination of the breakdown voltage at power frequency
- IEC 60296 – Mineral oil-impregnated electrical equipment in service – Guide to the interpretation of dissolved and free gases analysis

SCAN TO LEARN MORE

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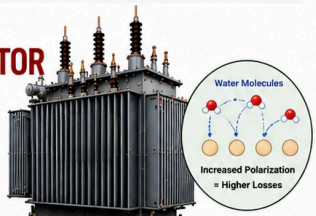
SECTION 34

MOISTURE AND DISSIPATION FACTOR (TAN δ)

Higher moisture increases dielectric losses.

Dissipation Factor (Tan δ) measures the energy lost as heat within the insulation system when subjected to AC voltage. Moisture increases these losses and accelerates insulation aging.



KEY MESSAGE

- ✓ Moisture increases dielectric losses.
- ✓ Higher Tan δ indicates deterioration.
- ✓ Tan δ is influenced by moisture, acids, sludge and aging.
- ✓ Always evaluate Tan δ at the same temperature.
- ✓ Compare trends, not single readings.
- ✓ Lower moisture = Lower Tan δ = Longer life.

WHAT IS TAN δ?

$$\text{Tan } \delta = \frac{\varepsilon''}{\varepsilon'}$$

Where:

- ε'' = Loss component (energy dissipated as heat)
- ε' = Storage component (energy stored in insulation)

Lower Tan δ = Better insulation

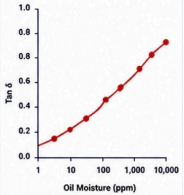
Higher Tan δ = Poor insulation

HOW MOISTURE AFFECTS TAN δ

- Water molecules increase dielectric losses.
- Increases dipole polarization and lag.
- Creates conductive paths and leakage current.
- Generates more heat inside insulation.
- Accelerates chemical aging of paper.

More moisture → Higher losses → Higher Tan δ → Faster aging

TYPICAL TREND: TAN δ vs MOISTURE



Tan δ increases significantly as moisture increases.

TYPICAL REFERENCE VALUES

Insulation Condition	Tan δ (at 25 °C / 50 Hz)
Excellent	< 0.3%
Good	0.3% – 0.5%
Caution	0.5% – 1.0%
Poor	1.0% – 1.5%
Very Poor	> 1.5%

Note: Values vary with transformer design, oil type and test method.

FACTORS THAT INFLUENCE TAN δ (BESIDES MOISTURE)

Acidity (TAN) · Sludge & Particles · Aging Products · Temperature · Electric Field Stress

Always correlate Tan δ with moisture, temperature, acidity and aging indicators.

CORRELATION: TAN δ WITH MOISTURE AND %RS

Oil Moisture (ppm)	%RS (at 25 °C)	Typical Tan δ (%)	Interpretation
< 10	< 20%	< 0.3	Excellent
10 – 50	20 – 40%	0.3 – 0.5	Good
50 – 200	40 – 60%	0.5 – 1.0	Caution
200 – 1,000	60 – 80%	1.0 – 1.5	Poor
> 1,000	> 80%	> 1.5	Very Poor

TEST METHOD

IEC 60247 (Oil)
ASTM D924

AC Voltage Applied
Measure Current & Phase Angle
Calculate Tan δ

BEST PRACTICES

- ✓ Measure Tan δ at standard temperature (20 °C or 25 °C).
- ✓ Keep oil moisture as low as practical.
- ✓ Use Tan δ trend for decision making.
- ✓ Correlate with BDV, moisture, %RS, resistivity, acidity and DGA.
- ✓ Repeat tests periodically (6–12 months).

WHAT TO DO IF TAN δ IS HIGH?

- ⚠ Check and reduce oil moisture.
- ⚠ Verify temperature and test conditions.
- ⚠ Check for acidity and sludge.
- ⚠ Perform oil filtration and dehydration.
- ⚠ Monitor trend after corrective action.

THE BOTTOM LINE

"High Tan δ means higher losses.
Higher losses mean more heat.
More heat means faster aging."

**Control moisture.
Lower Tan δ.
Extend transformer life.**

CONTACT DRYTRANS

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DRYTRANS INSIGHT

Tan δ is a window into insulation health.
Moisture management keeps losses low and insulation strong.

REFERENCE STANDARDS

- IEC 60247 – Measurement of relative permittivity, dielectric dissipation factor and DC resistivity of insulating liquids
- ASTM D924 – Standard Test Method for Dissipation Factor (or Relative Permittivity) of Electrical Insulating Liquids

SCAN TO LEARN MORE

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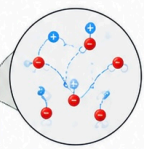
SECTION 35

MOISTURE AND RESISTIVITY

High moisture lowers resistivity.
Lower resistivity = higher risk.

Resistivity indicates how strongly the oil opposes the flow of electric current.

Moisture introduces ions and increases conductivity, reducing resistivity and weakening the insulation system.



KEY MESSAGE

- ✓ Moisture increases ionic conductivity.
- ✓ As moisture increases, resistivity decreases.
- ✓ Low resistivity reduces insulation strength.
- ✓ Resistivity is a sensitive indicator of oil quality.
- ✓ Always correlate resistivity with moisture, temperature and other diagnostic tests.
- ✓ Higher resistivity = Better insulation = Lower risk.

WHAT IS RESISTIVITY?

Resistivity (ρ) is a measure of a fluid's ability to resist the flow of electric current.

Formula:

$$\rho = R \times \left(\frac{A}{L}\right)$$

Where:
ρ = Resistivity (Ω·m)
R = Resistance (Ω)
A = Electrode area (m^2)
L = Electrode gap distance (m)

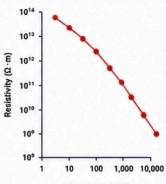
High ρ = Strong resistance = Good insulation

HOW MOISTURE AFFECTS RESISTIVITY

- Water dissociates into ions (H^+ and OH^-).
- Increases ionic concentration in the oil.
- Ions carry charge under electric field.
- More charge movement = Higher conductivity.
- Higher conductivity = Lower resistivity.

More moisture → More ions → Lower resistivity → Higher risk

TYPICAL TREND: RESISTIVITY VS MOISTURE



Resistivity decreases exponentially as moisture increases.

TYPICAL RESISTIVITY RANGE (at 25 °C)

Resistivity (Ω·m)	OIL CONDITION	RISK LEVEL
> 1 × 10^{13}	Excellent	Very Low
1 × 10^{12} – 1 × 10^{13}	Good	Low
1 × 10^{11} – 1 × 10^{12}	Caution	Moderate
1 × 10^{10} – 1 × 10^{11}	Poor	High
< 1 × 10^{10}	Very Poor	Very High

Note: Values vary with temperature, oil type and measurement method.

FACTORS THAT REDUCE RESISTIVITY (BESIDES MOISTURE)

Moisture | Acids (TAN) | Conductive Particles | Sludge | High Temperature | Aging Products

Always interpret resistivity along with moisture, Tan δ, BDV, acidity and DGA.

CORRELATION: RESISTIVITY WITH MOISTURE & %RS

Oil Moisture (ppm)	%RS (at 25 °C)	Typical Resistivity (Ω·m)	Interpretation
< 10	< 20%	> 1 × 10^{13}	Excellent
10 – 50	20 – 40%	1 × 10^{12} – 1 × 10^{13}	Good
50 – 200	40 – 60%	1 × 10^{11} – 1 × 10^{12}	Caution
200 – 1,000	60 – 80%	1 × 10^{10} – 1 × 10^{11}	Poor
> 1,000	> 80%	< 1 × 10^{10}	Very Poor

TEST METHOD

IEC 60247 (Oil)
ASTM D1169

AC Voltage Applied
Measure Resistance (R)
Calculate Resistivity (ρ)

BEST PRACTICES

- ✓ Maintain oil moisture as low as practical.
- ✓ Keep %RS below 60%.
- ✓ Monitor resistivity regularly (6–12 monthly).
- ✓ Correlate with moisture, Tan δ, BDV, acidity and DGA.
- ✓ Investigate sudden drops immediately.
- ✓ Filter and dehydrate the oil continuously.

WHAT TO DO IF RESISTIVITY IS LOW?

- ⚠ Check oil moisture and %RS.
- ⚠ Verify temperature and test method.
- ⚠ Check for acidity, sludge and particles.
- ⚠ Check transformer breathing system and seals.
- ⚠ Perform oil filtration and dehydration.
- ⚠ Monitor trend until improvement.

Low resistivity is a warning.
Act early to protect insulation life.

THE BOTTOM LINE

"Resistivity is the oil's ability to resist current flow.
Moisture destroys this ability.

Higher Resistivity = Stronger Insulation
Lower Risk = Longer Life."

Control moisture.
Maintain high resistivity.
Ensure transformer reliability.

CONTACT DRYTRANS

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DRYTRANS INSIGHT

Resistivity reacts quickly to moisture and contamination. It is one of the fastest indicators of oil deterioration.

REFERENCE STANDARDS

- IEC 60247 – Measurement of relative permittivity, dielectric dissipation factor and DC resistivity of insulating liquids
- ASTM D1169 – Standard Test Method for Specific Resistance (Resistivity) of Electrical Insulating Liquids

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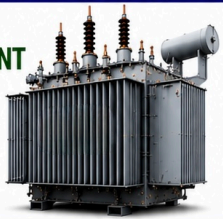
SECTION 36

TRANSFORMER MOISTURE ASSESSMENT FRAMEWORK

Key Message

No single test can define transformer moisture condition.
A comprehensive assessment requires combining multiple indicators across four levels to understand moisture impact, insulation health and failure risk.



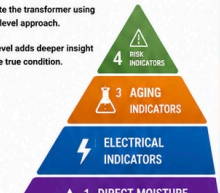
KEY MESSAGE

- ✓ Transformer condition is multi-dimensional.
- ✓ Moisture is the primary driver of insulation degradation.
- ✓ Use integrated data from all levels.
- ✓ Trend analysis is more important than single readings.
- ✓ Good assessment leads to the right action.
- ✓ Control of moisture = Control of life.

THE ASSESSMENT PYRAMID

Evaluate the transformer using a four-level approach.

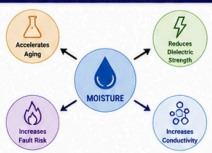
Each level adds deeper insight into the true condition.



LEVEL	WHAT IT TELLS US	TYPICAL PARAMETERS	WHY IT MATTERS
4 Risk Indicators	Indicates the risk of failure or active faults.	• DGA (H_2, CH_4, C_2H_2, etc.) • CO / CO_2 • Partial Discharge (PD) • Bubbling / Gassing	Confirms if a failure process is already developing. Helps in early intervention and risk mitigation.
3 Aging Indicators	Shows how fast the insulation is chemically aging.	• Furan (2-FAL) • Methanol • Acidity (TAN) • Interfacial Tension (IFT) • DP (Degree of Polymerization)*	Quantifies life consumed by thermal, moisture and chemical aging.
2 Electrical Indicators	Reflects the current dielectric performance.	• Breakdown Voltage (BDV) • Dissipation Factor (Tan δ) • Resistivity • Capacitance / Power Factor	Indicates how much dielectric strength and insulation margin is left.
1 Direct Moisture Indicators	Shows how much moisture is present in the insulation system.	• Moisture in Oil (ppm) • Relative Saturation (%RS) • Water Activity (aw) • Estimated Paper Moisture (%)	Moisture is the root cause that influences all other conditions.

* DP testing requires paper sampling (offline).

HOW MOISTURE AFFECTS ALL LEVELS

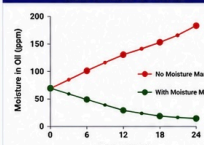


Moisture is the common factor that drives all forms of insulation deterioration and failure.

ASSESSMENT APPROACH

1. **Collect Data**
   Perform tests and record values across all four levels.
2. **Understand Moisture State (Level 1)**
   Evaluate ppm, %RS, aw and estimate paper moisture.
3. **Evaluate Electrical Margin (Level 2)**
   Check BDV, Tan δ and resistivity.
4. **Evaluate Aging (Level 3)**
   Assess furan, methanol, acidity and IFT.
5. **Evaluate Risk (Level 4)**
   Review DGA, CO/CO_2 and PD activity.
6. **Correlate & Trend**
   Compare with historical data and trends.
7. **Decide & Act**
   Define the right moisture management strategy.

TREND ANALYSIS IS CRITICAL



A single reading is a snapshot.
A trend is the real story.

TYPICAL ACCEPTANCE GUIDELINES (AS PER IEC & INDUSTRY PRACTICE)

Parameter	Good Condition
Moisture in Oil – %RS (at 25 °C)	< 60%
Moisture in Oil – ppm (at 25 °C)	< 50 ppm
Water Activity (aw)	< 0.5
Breakdown Voltage (BDV)	> 60 kV (typ.)
Dissipation Factor (Tan δ)	< 0.5%
Resistivity	> 1 × 10^{12} Ω-m
Furan (2-FAL)	Low (Trending Stable)

Note: Limits vary with transformer design, age and service conditions.

WHAT TO DO IF ASSESSMENT SHOWS HIGH MOISTURE

- ⚠ Reduce moisture continuously.
- ⚠ Improve sealing and breathers.
- ⚠ Perform oil filtration & dehydration.
- ⚠ Use online monitoring for trend.
- ⚠ Investigate source of ingress.
- ⚠ Review loading and temperature.

Act early – Prevent aging, failure and unplanned outages.

KEY INPUTS FOR ASSESSMENT

- ✓ Accurate sampling & testing
- ✓ Correct temperature correction
- ✓ Oil type and transformer design
- ✓ Loading history
- ✓ Ambient conditions
- ✓ History of maintenance
- ✓ Online monitoring data (if available)
- ✓ Historical test trend
- ✓ Operational events

LIMITATIONS TO REMEMBER

- ⓘ Oil tests reflect current condition.
- ⓘ Paper aging is cumulative.
- ⓘ Equilibrium may not be achieved during rapid load/temperature changes.
- ⓘ Sampling and test accuracy are critical.
- ⓘ Always rely on trends, not single values.

Good assessment = Right action = Extended life.

CONTACT DRYTRANS

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DRYTRANS INSIGHT

A structured assessment helps identify moisture as the root cause and enables effective life extension strategies.

REFERENCE STANDARDS

- IEC 60422 – Mineral insulating oils in electrical equipment – Supervision and maintenance guidance
- IEC 60599 – Mineral oil-impregnated electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis

RELATED DRYTRANS SOLUTIONS

- TRS / TRS0 – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

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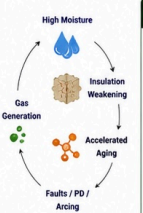
SECTION 37

MOISTURE AND DGA

Moisture does not create fault gases. Moisture accelerates the processes that generate gases.

Dissolved Gas Analysis (DGA) identifies symptoms of faults or abnormal conditions. High moisture lowers insulation strength, accelerates aging and partial discharge, which increases the probability and severity of gas generation.



KEY MESSAGE

- ✓ Moisture accelerates insulation aging.
- ✓ Moisture increases partial discharge (PD) activity.
- ✓ Moisture promotes thermal stress and overheating.
- ✓ These conditions lead to higher levels of dissolved gases.
- ✓ DGA shows the effect.
- ✓ Moisture is often the root cause.
- ✓ Control moisture to reduce gases and failure risk.

HOW MOISTURE INFLUENCES DGA

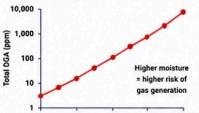
Mechanism	Effect of High Moisture	Result	Typical Gases
Cellulose Degradation (Hydrolysis)	Water + Heat breaks down cellulose chains.	Lower DP, weaker paper, increased gas generation.	CO, CO_2
Partial Discharge (PD)	Moisture lowers dielectric strength.	More PD activity in oil and paper.	H_2, C_2H_2, C_2H_4
Thermal Stress	High moisture increases hot-spot temperature.	Accelerated aging and overheating.	CH_4, C_2H_4, C_2H_6
Oil Oxidation	Moisture + Oxygen accelerates oxidation.	Acid formation, sludge, insulation aging.	CO, CO_2
Arcing / Faults	Weaker insulation more prone to arcing.	Severe faults generate high gas levels.	All key gases high (H_2, CH_4, C_2H_2, etc.)

KEY DGA GASES AND MOISTURE RELATIONSHIP

Gas	Source / Cause	Influence of Moisture
Hydrogen (H_2)	PD, partial arcing	Increases PD activity
Methane (CH_4)	Low energy thermal faults	Increases with overheating
Ethylene (C_2H_4)	Thermal faults	Increases with temperature
Acetylene (C_2H_2)	High energy arcing	Higher risk when insulation is weak & wet
Carbon Monoxide (CO)	Cellulose degradation	Accelerated by hydrolysis and oxidation
Carbon Dioxide (CO_2)	Advanced cellulose degradation	Increases with aging and moisture

Moisture does not produce these gases directly, but it accelerates every process that produces them.

TYPICAL TREND: MOISTURE VS TOTAL DGA



Transformers with high moisture show significantly higher total dissolved gases over time.

MOISTURE – DGA – INSULATION LIFE CONNECTION

REALITY CHECK

Low gas levels + high moisture = WARNING (aging has started)
High gas levels + high moisture = HIGH RISK (failure probability high)
Fixing moisture reduces gas levels and slows aging

INTERPRETATION GUIDELINES

- ✓ Always evaluate DGA along with moisture.
- ✓ High moisture can mask early warning signs in DGA.
- ✓ A sudden increase in gases with high moisture is more dangerous.
- ✓ Use trend analysis, not single test results.
- ✓ Low moisture + stable gases = healthy.
- ✓ High moisture + rising gases = act early!

BEST PRACTICES

- ✓ Monitor moisture and DGA together.
- ✓ Maintain moisture at safe levels (< 40% RS or as per transformer design).
- ✓ Reduce moisture continuously.
- ✓ Keep oil clean and free from oxidation.
- ✓ Control temperature and loading.
- ✓ Investigate any abnormal gas trend.
- ✓ Act early to prevent major faults.

Moisture management = Gas management = Life management

STANDARDS & REFERENCES

- IEC 60599 – Mineral oil-impregnated electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis
- IEEE C57.104 – Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers
- IEC 60422 – Mineral insulating oils in electrical equipment – Supervision and maintenance guidance

Always follow standard interpretation methods and consider moisture as a major influencing factor.

THE BOTTOM LINE

> DGA tells you what is happening. Moisture tells you why it is happening.

Control moisture.
Reduce gases.
Increase reliability.
Extend transformer life.

DryTrans keeps moisture low, insulation strong and DGA stable. Continuous Moisture Management for Reliable Transformers.

CONTACT DRYTRANS

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DRYTRANS INSIGHT

Moisture is the hidden driver behind most insulation problems. Managing moisture continuously is the most effective way to control gases and extend life.

RELATED DRYTRANS SOLUTIONS

- TRS / TRS0 – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

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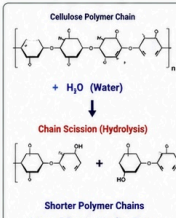
SECTION 38

HYDROLYSIS OF CELLULOSE

The primary aging mechanism of paper insulation in transformers.

Cellulose paper is the structural backbone of transformer insulation. In the presence of moisture and heat, cellulose molecules undergo hydrolysis, causing the polymer chains to break. This reduces the Degree of Polymerization (DP), weakens the paper and shortens insulation life.

THE HYDROLYSIS REACTION

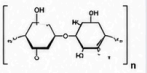


KEY MESSAGE

- ✓ Hydrolysis is driven by moisture and accelerated by temperature.
- ✓ It reduces DP (Degree of Polymerization).
- ✓ Lower DP means weaker paper and lower mechanical strength.
- ✓ It is the main cause of insulation aging in transformers.
- ✓ Controlling moisture is the only way to slow hydrolysis.

WHAT IS CELLULOSE?

Transformer paper is made of cellulose, a natural polymer composed of long chains of glucose units.



- High DP = Strong paper
- Low DP = Weak paper

HOW HYDROLYSIS OCCURS

Water molecules penetrate the paper.

↓

Heat provides energy for the reaction.

↓

The glycosidic bonds in cellulose chains break.

↓

Polymer chains become shorter (DP decreases).

FACTORS THAT ACCELERATE HYDROLYSIS

Factor	Effect
Moisture	Essential for the reaction. Higher moisture = faster hydrolysis.
Temperature	Reaction rate doubles for every 6–8 °C increase (Arrhenius rule).
Time	Longer exposure = more aging (lower DP).
Acids (TAN)	Acidic conditions catalyze hydrolysis.
Oxygen	Promotes oxidation which also weakens cellulose.

EFFECT ON INSULATION

Degree of Polymerization (DP) decreases

↓

Tensile strength decreases

↓

Paper becomes brittle

↓

Less mechanical withstand

↓

Higher risk of failure

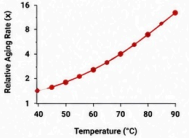
DP AND INSULATION LIFE

DP (Approx.)	Paper Condition	Insulation Life
> 1,000	New / Very Good	> 30 years
600 – 1,000	Good	20 – 30 years
300 – 600	Fair	10 – 20 years
200 – 300	Poor	5 – 10 years
< 200	Very Poor	High failure risk

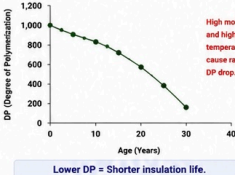
* Life expectancy depends on moisture, temperature, loading and design.

ARRHENIUS RULE (TEMPERATURE EFFECT)

The rate of hydrolysis approximately doubles for every 6–8 °C rise in temperature.



TYPICAL DP DEGRADATION CURVE



Lower DP = Shorter insulation life.

HOW TO DETECT HYDROLYSIS

- ✓ Furan Analysis (2-FAL)
- ✓ DP Testing (Direct / Estimation)
- ✓ Paper Moisture Estimation
- ✓ Moisture Trend Analysis
- ✓ Temperature Monitoring

Rising furans or falling DP indicate hydrolysis is active.

BEST PRACTICES TO SLOW HYDROLYSIS

- ✓ Keep moisture as low as possible (< 40% RS).
- ✓ Maintain cool operating temperature.
- ✓ Remove acids and oxidation by-products.
- ✓ Use continuous moisture management.
- ✓ Monitor DP / furans regularly.
- ✓ Avoid overload and hot spots.

Control moisture + temperature = Control hydrolysis = Extend life.

STANDARDS & REFERENCES

- IEC 60422 – Mineral insulating oils in electrical equipment – Supervision and maintenance guidance
- IEC 60450 – Guide to the sampling of mineral insulating liquids
- ASTM D4243 – Test Method for Measurement of Average Polymerization Degree of New and Aged Electrical Paper and Paperboard

Standards provide methods to assess paper aging and remaining insulation life.

DRYTRANS INSIGHT

Hydrolysis cannot be stopped, but it can be slowed dramatically. Continuous moisture management keeps paper dry, slows DP loss and preserves mechanical strength. This is the most effective way to extend transformer life.

Moisture control today, reliability for tomorrow.

CONTACT DRYTRANS

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DRYTRANS SOLUTIONS

- TR5 / TR50 – Continuous Moisture Management
- MM590 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

ABOUT DRYTRANS

DryTrans provides innovative moisture management solutions that remove moisture continuously, protect insulation, improve reliability and extend the life of power transformers.

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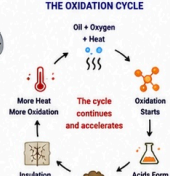
SECTION 39

OXIDATION, ACIDS AND MOISTURE

Moisture and oxygen create a destructive partnership.

Moisture accelerates oil oxidation, which produces acids and sludge. These by-products attack insulation, reduce dielectric strength and shorten transformer life.

THE OXIDATION CYCLE



KEY MESSAGE

- ✓ Moisture accelerates oil oxidation.
- ✓ Oxidation produces acids.
- ✓ Acids attack cellulose insulation.
- ✓ Sludge and deposits reduce cooling and insulation performance.
- ✓ Higher temperature increases oxidation rate.
- ✓ Controlling moisture slows oxidation.
- ✓ Control moisture + temperature + oxygen = extend transformer life.

HOW OXIDATION OCCURS

- Moisture dissolves in oil.
- ↓
- O_2 Oxygen dissolves in oil.
- ↓
- Heat breaks oil molecules.
- ↓
- Reactive molecules form.
- ↓
- Acids and sludge are produced.

ROLE OF MOISTURE

- Increases oil conductivity and ionic activity.
- Promotes oxidation chemical reactions.
- Helps acids to dissolve and spread.
- Increases rate of cellulose hydrolysis.

More moisture = Faster oxidation
= More acids = Faster aging

COMMON ACIDS IN TRANSFORMER OIL

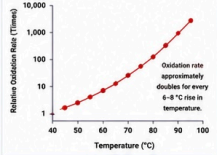
Acid	Source	Effect
Carboxylic Acids (e.g. Formic, Acetic)	Oil oxidation	Increase TAN, corrode metals
Sulfuric Acid	Oxidation of sulfur compounds	Highly corrosive, damages paper
2-Furfuroic Acid	Degradation of paper	Indicator of paper aging

ⓘ Total Acid Number (TAN) is a key indicator of oxidation and acid build-up.

EFFECTS OF ACIDS & OXIDATION

- Attack cellulose insulation (hydrolysis + depolymerization)
- Reduce dielectric strength and BDV
- Increase oil acidity and corrosiveness
- Form sludge and deposits, clog radiators and valves
- Shorten transformer life and reliability

OXIDATION RATE VS TEMPERATURE



Higher temperature + moisture = Rapid oxidation

TAN (ACIDITY) VS TRANSFORMER CONDITION

TAN (mg KOH/g)	Condition	Action	Risk Level
< 0.1	Very Good	Continue Monitoring	Very Low
0.1 – 0.3	Good	Monitor Trend	Low
0.3 – 0.7	Fair	Investigate & Reduce	Moderate
0.7 – 1.0	Poor	Take Corrective Action	High
> 1.0	Very Poor	Immediate Action Needed	Very High

ⓘ Values are typical guidance only. Refer to manufacturer limits.

MOISTURE + OXYGEN = ACCELERATED AGING

Factor	Low Level	High Level
Moisture	Slow oxidation	Fast oxidation
Oxygen	Less reaction	More reaction
Temperature	Lower rate	Rapid rate
Result	Longer Life	Shorter Life

All three factors must be controlled to break the aging cycle.

BEST PRACTICES

- ✓ Keep moisture as low as possible (< 40% RS).
- ✓ Maintain oil temperature within design limits.
- ✓ Minimize oxygen ingress (proper sealing, breather maintenance).
- ✓ Use DryTrans continuous moisture management.
- ✓ Monitor TAN, moisture and temperature regularly.
- ✓ Keep oil clean and free from contaminants.
- ✓ Filter and dehydrate oil when required.

Good oil care = Less oxidation
Less oxidation = Longer transformer life

WHAT TO DO IF TAN IS HIGH

- ⚠ Check moisture level and %RS.
- ⚠ Check oil temperature and loading.
- ⚠ Verify breather performance.
- ⚠ Investigate oxygen ingress.
- ⚠ Test for sludge and acidity.
- ⚠ Perform oil filtration and dehydration.
- ⚠ Increase moisture management.
- ⚠ Monitor trend until improvement.

⚠ High TAN is a warning.
Act early to prevent insulation damage.

MONITORING PARAMETERS

- Moisture (ppm, %RS)
- Temperature
- O_2 TAN (mg KOH/g)
- DGA (CO, CO_2, H_2)
- Furan (2-FAL)

Trend analysis is more important than single readings.

THE BOTTOM LINE

“Moisture feeds oxidation.
Oxidation creates acids.
Acids destroy insulation.

**Control moisture.
Control oxidation.
Extend transformer life.**”

DryTrans keeps moisture low, reduces oxidation and protects your investment.

CONTACT DRYTRANS

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DRYTRANS SOLUTIONS

- TRS / TRS0 – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60422 – Mineral insulating oils in electrical equipment
- IEC 60567 – Oil-impregnated paper and pressboard – Determination of water by Karl Fischer method
- ASTM D974 – Acid and Base Number of Petroleum Products

SCAN TO LEARN MORE

Visit our website for more knowledge articles, case studies and technical resources.

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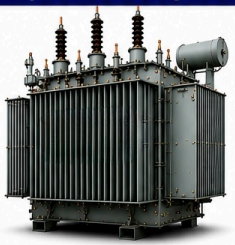
SECTION 40

MOISTURE AND TRANSFORMER RELIABILITY

Moisture is a reliability issue, not just a maintenance issue.

High moisture weakens insulation, accelerates aging, increases the risk of failure and reduces the overall reliability of the transformer. Controlling moisture is controlling reliability.



KEY MESSAGE

- ✓ Moisture directly reduces insulation strength.
- ✓ Moisture accelerates aging and degradation.
- ✓ Moisture increases the risk of partial discharge.
- ✓ Moisture increases the probability of failure.
- ✓ Lower moisture = Higher reliability.
- ✓ Reliability improvement starts with moisture management.

HOW MOISTURE AFFECTS RELIABILITY

Lower Dielectric Strength
Moisture reduces breakdown strength of oil and insulation.

Higher Partial Discharge Risk
Moisture lowers insulation resistance and promotes PD activity.

Faster Aging
Moisture accelerates hydrolysis, oxidation and acid formation.

Higher Failure Probability
Weakened insulation leads to faults, outages and catastrophic failures.

Shorter Service Life
High moisture significantly reduces expected transformer life.

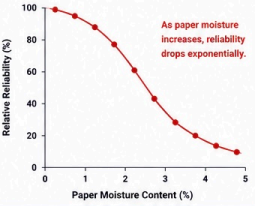
RELIABILITY EQUATION

Reliability ∝ Insulation Strength

High Moisture ↓
Insulation Strength Decreases ↓
Failure Probability Increases ↑
Reliability Decreases ↓

Lower moisture improves insulation strength and increases reliability.

RELIABILITY VS MOISTURE LEVEL



Keeping paper moisture below 2% is critical for long-term reliability.

MOISTURE IMPACT ON KEY RELIABILITY FACTORS

Reliability Factor	Low Moisture	High Moisture	Impact
Dielectric Strength	High	Low	↓
Partial Discharge	Low Risk	High Risk	↑
Aging Rate	Slow	Fast	↑
Thermal Endurance	High	Reduced	↓
Expected Life	Long	Short	↓
Failure Probability	Low	High	↑

RELIABILITY IMPROVEMENT THROUGH MOISTURE MANAGEMENT

Moisture Management = Reliability Management

THE COST OF POOR RELIABILITY

High moisture leads to:

- **Unplanned Outages** — Production loss and revenue impact.
- **Emergency Maintenance** — High cost and resource mobilization.
- **Equipment Damage** — Repairs or replacement of components.
- **Reduced Asset Life** — Early replacement and lost investment.
- **Safety and Environmental Risk** — Risk to personnel and environment.

Good reliability starts with low moisture.

RELIABILITY TARGETS

- ✓ Paper Moisture: < 2%
- ✓ Relative Saturation (20 °C): < 60%
- ✓ Water Activity (a_w): < 0.5
- ✓ Low Partial Discharge Activity
- ✓ Stable DGA with low gas levels
- ✓ Good dielectric strength (BDV, Tan δ)
- ✓ Healthy insulation and long service life

Meet these targets for reliable operation.

BEST PRACTICES

- Monitor moisture continuously.
- Keep oil clean and dry.
- Control temperature and loading.
- Maintain good sealing.
- Use online moisture monitoring.
- Manage moisture proactively.
- Act early, long before failure.

Proactive actions ensure reliable assets.

MONITOR, TREND, ACT

MONITOR
Moisture, Temp, RS, DGA, PD

↓

TREND
Identify changes and risks early

↓

ACT
Reduce moisture and mitigate risk

Early action = Higher reliability

RELIABILITY AT A GLANCE

Moisture ↓
↓
Insulation Strength ↓
↓
Failure Probability ↑
↓
Reliability ↓

Control moisture. Control reliability.

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DRYTRANS SOLUTIONS

- TRS / TR50 – Continuous Moisture Management
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- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60422 – Mineral insulating oils in electrical equipment
- IEC 60076 – Power transformers
- IEEE C57.104 – Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers

ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protect your investment.

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SECTION 41

MEASURING MOISTURE IN POWER TRANSFORMERS

You can't manage what you don't measure.

Accurate moisture measurement is the foundation of an effective moisture management program. It helps you understand the condition of the insulation, track changes over time and take proactive action before problems occur.

WHERE IS MOISTURE MEASURED?

- **Oil** (Dissolved moisture)
- **Paper** (Solid insulation moisture)
- **Ambient Air** (Relative humidity & temperature)

KEY MESSAGE

- ✓ Measure moisture in oil, paper and air.
- ✓ Use the right method for the right measurement.
- ✓ Regular measurements reveal trends and risks.
- ✓ Accurate data enables better decisions and longer asset life.
- ✓ Measurement frequency should match the risk and operating conditions.

OIL MOISTURE MEASUREMENT (DISSOLVED MOISTURE)

Moisture in oil is measured as parts per million (ppm) or mg/kg.

Karl Fischer Titration (IEC 60814)	Reference method. High accuracy. Laboratory test.
Capacitive Moisture Sensor (Online)	Continuous online measurement. Fast and reliable.
Infrared / Optical Sensors	Online monitoring. Requires calibration and compensation.
Lab Quick Test Kits	Field screening. Quick indication.

PAPER MOISTURE MEASUREMENT (INSULATION MOISTURE)

Moisture in paper is measured as Percentage Moisture in Paper (%MP).

Oven Dry Method (IEC 60414)	Reference method. Accurate but destructive (sampling required).
Equilibrium Relative Humidity (ERH) Method (IEC 61439)	Moisture estimated from oil ERH at equilibrium. Non-destructive.
Dielectric Response Analysis (DRA)	Online or offline. Estimates paper moisture profile.
Frequency Domain Spectroscopy (FDS)	Advanced method. High accuracy and insight into aging.

AMBIENT AIR MEASUREMENT

Ambient conditions influence moisture ingress and drying.

Relative Humidity (RH)	Measured using digital hygrometers or transmitters.
Temperature	Measured using RTDs or digital sensors.
Dew Point	Critical for assessing moisture risk and drying potential.

MOISTURE UNITS AND CONVERSIONS

Parameter	Common Units	Notes
Oil Moisture	ppm (mg/kg)	1 ppm = 1 mg water per kg of oil
Paper Moisture	%MP	% of dry paper weight
Oil ERH	%	Equilibrium Relative Humidity
Relative Humidity	%RH	Moisture in air
Dew Point	°C	Temperature at which air is saturated

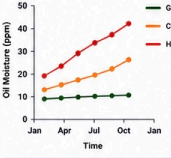
ⓘ Always record temperature with moisture measurements. Moisture is temperature dependent.

TYPICAL MOISTURE LEVEL GUIDELINES

Parameter	Good	Caution	High Risk
Oil Moisture (ppm)	< 20	20 – 30	> 30
Paper Moisture (%MP)	< 1.5	1.5 – 2.5	> 2.5
Oil ERH (%)	< 40	40 – 60	> 60
Ambient RH (%)	< 60	60 – 80	> 80
Dew Point (°C)	< -10	-10 to 0	> 0

ⓘ Guidelines vary by manufacturer, design, and service conditions. Always follow asset-specific limits.

MOISTURE TRENDING – WHY IT MATTERS



Trending helps you detect problems early and validate the effectiveness of drying.

MEASUREMENT BEST PRACTICES

- ☑ Use calibrated and reliable instruments.
- ☑ Follow standard test methods (IEC/ASTM).
- ☑ Sample from the correct location.
- ☑ Control sampling and handling procedures.
- ☑ Record temperature, load and oil condition.
- ☑ Take measurements at regular intervals.
- ☑ Trend results and investigate changes.
- ☑ Act on data, not just on single readings.

Good measurement = Good decisions

HOW OFTEN SHOULD YOU MEASURE?

- **New Transformer:** Baseline before energization.
- **Normal Operation:** Every 3 – 6 months.
- **High Moisture or High Risk:** Monthly or as needed.
- **After Maintenance / Drying:** Frequent until stable.

More risk = More frequent measurement

TOOLS THAT HELP

- Online Moisture Monitors
- SCADA / DGA Platforms
- Data Loggers
- Analytics & Trending Software

Use data and analytics to stay ahead of moisture problems.

THE BOTTOM LINE

> Measurement turns uncertainty into knowledge.
> **Knowledge** drives action.
> **Action** ensures reliability.

Measure it right.
Manage it smart.
Keep it dry.
Keep it reliable.

CONTACT DRYTRANS

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www.drytrans.com

DRYTRANS SOLUTIONS

- TRS / TRSO – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60814 – Determination of water in insulating liquids
- IEC 60414 – Determination of water in solid electrical insulation
- IEC 61439 – Determination of the equilibrium relative humidity

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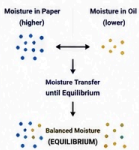
SECTION 42

EQUILIBRIUM RELATIVE HUMIDITY (ERH)
THE KEY TO UNDERSTANDING MOISTURE IN PAPER

ERH defines the moisture content that paper will reach when in equilibrium with surrounding oil and temperature.

It is the most accurate way to assess the moisture condition of transformer insulation and the effectiveness of drying.

THE EQUILIBRIUM CONCEPT



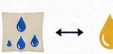
At equilibrium, there is no net moisture transfer between paper and oil.

KEY MESSAGE

- ✓ ERH represents true moisture condition.
- ✓ ERH is temperature dependent.
- ✓ ERH is more accurate than DGA or Karl Fischer alone.
- ✓ Low ERH = Dry insulation = Long life.
- ✓ High ERH = Wet insulation = High risk.
- ✓ Use ERH to set drying targets and monitor progress.

WHAT IS ERH?

Equilibrium Relative Humidity (ERH) is the relative humidity inside paper when it is in equilibrium with oil at a given temperature.



ERH (%) = 100 × (Actual Moisture Content in Paper / Saturation Moisture Content at that Temperature)

ERH vs RELATIVE HUMIDITY (AIR)

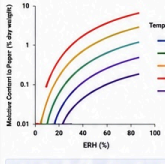
Do not confuse ERH with ambient Relative Humidity (RH). They are different.

Parameter	Refers To	Medium
RH	Moisture in Air	Air
ERH	Moisture in Paper (at equilibrium)	Paper/Oil System

ERH is the correct parameter for paper insulation assessment.

ERH – MOISTURE CONTENT RELATIONSHIP

ERH increases with moisture content and temperature.



For the same ERH, higher temperature means higher moisture content in paper.

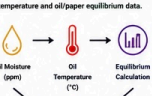
TYPICAL ERH TARGETS

Insulation Condition	ERH (%) Target	Status
New / Very Dry	0 – 20	Excellent
Good	20 – 40	Good
Acceptable	40 – 60	Fair
Wet / High Risk	60 – 80	Poor
Very Wet	> 80	Very Poor

Lower ERH targets extend insulation life and improve reliability.

HOW ERH IS MEASURED

ERH is calculated using oil moisture content, temperature and oil/paper equilibrium data.



Modern monitoring systems calculate ERH continuously and accurately.

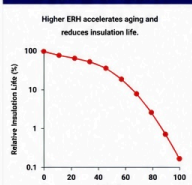
FACTORS AFFECTING ERH

- **Oil Moisture Content** — Higher moisture = Higher ERH
- **Temperature** — Higher temperature = Higher ERH
- **Time** — Equilibrium takes time to reach
- **Oil Type & Condition** — Affects saturation and transfer rate
- **Paper Condition** — Aged paper holds more moisture

All factors must be considered for accurate evaluation.

ERH AND INSULATION AGING

Higher ERH accelerates aging and reduces insulation life.



Keeping ERH low is one of the most effective ways to extend transformer life.

ERH IN PRACTICE

- ✓ Measure oil moisture and temperature regularly.
- ✓ Calculate or monitor ERH continuously.
- ✓ Track ERH trends over time.
- ✓ Set ERH targets based on asset criticality.
- ✓ Take action if ERH is above target.
- ✓ Verify drying effectiveness with ERH.

Good data + ERH = Smart decisions
Better decisions = Reliable transformers

BEST PRACTICES

- ✓ Use online moisture monitors.
- ✓ Maintain oil and paper in equilibrium.
- ✓ Keep oil moisture as low as possible.
- ✓ Control temperature and loading.
- ✓ Dry the transformer systematically.
- ✓ Monitor ERH trend, not just single value.
- ✓ Document and act on results.

Consistent practices deliver consistent reliability.

ERH TARGETS BY TRANSFORMER TYPE

Transformer Type	Recommended ERH Target
Power Transformers (General Service)	< 40%
Power Transformers (Critical / High Reliability)	< 30%
Instrument Transformers	< 40%
Shunt Reactors	< 40%
New Transformers	< 20%

Adjust targets based on service conditions and risk assessment.

TOOLS & TECHNOLOGIES

- Online Moisture Monitors (ERH Calculation)
- SCADA / Asset Management Integration
- Moisture Sensors (Capacitive / FOS)
- Data Analytics & Trending Software

Technology enables visibility. Visibility enables reliability.

THE BOTTOM LINE

> ERH puts moisture in perspective. It tells you the true condition of your insulation, not just what is in the oil.
>
> **Measure ERH.**
> **Manage ERH.**
> **Maximize Life.**

Low ERH today.
High reliability tomorrow.

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ABOUT DRYTRANS

DryTrans provides innovative moisture management solutions that improve reliability, extend transformer life and protect your investment.

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SECTION 43

MOISTURE MIGRATION
THE INVISIBLE RISK

Moisture moves. Unchecked, it causes damage.

Moisture migration is the movement of moisture within transformer insulation due to concentration differences, temperature gradients or pressure changes. It can lead to wet spots, reduced dielectric strength and premature failure.

HOW MOISTURE MIGRATES

- From high concentration to low concentration
- From high temperature to low temperature
- From high pressure to low pressure
- Through paper, barriers, voids and interfaces

Moisture follows the path of least resistance until equilibrium is reached.

KEY MESSAGE

- ✓ Moisture migration is natural and continuous.
- ✓ It can create wet spots and reduce dielectric strength.
- ✓ Temperature and concentration differences drive migration.
- ✓ Good design, drying and sealing reduce the risk.
- ✓ Monitor and manage moisture throughout the transformer life.

DRIVERS OF MOISTURE MIGRATION

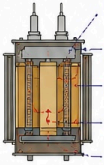
Concentration Gradient
Moisture moves from wet area to dry area.

Temperature Gradient
Moisture moves from hot area to cold area.

Pressure Gradient
Moisture moves from high pressure to low pressure.

Time
Over time, migration continues until equilibrium is reached.

WHERE MIGRATION OCCURS



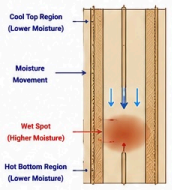
Poorly dried areas or design weak points become moisture traps.

EFFECTS OF MOISTURE MIGRATION

- Creates wet spots
- Reduces dielectric strength
- Increases risk of partial discharge
- Accelerates aging and paper degradation
- Leads to unexpected failures and outages

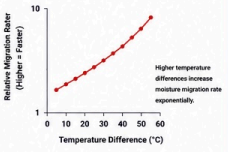
Migration can undo good drying if not controlled.

EXAMPLE: WET SPOT FORMATION



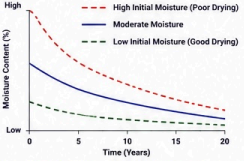
Moisture migrates downward and creates a wet spot at a cooler location.

TEMPERATURE EFFECT ON MIGRATION



Control temperature gradients to control migration.

MIGRATION OVER TIME



Even well-dried insulation can absorb moisture over time if exposed to humidity or leaks.

FACTORS: THAT INCREASE MIGRATION RISK

- High Initial Moisture
- Large Temperature Gradients
- Poor Sealing / Leaks
- Long-Term Operation
- Poor Drying or Vacuum Processing
- Frequent Overloads

Address the causes to reduce the risk.

BEST PRACTICES TO MINIMIZE MIGRATION

- ✓ Dry insulation thoroughly to low moisture levels.
- ✓ Maintain oil in good condition and sealed.
- ✓ Control temperature gradients in design and operation.
- ✓ Use high-quality barriers and insulation systems.
- ✓ Avoid overheating and overloading.
- ✓ Monitor moisture and trends regularly.

Good design + Good drying + Good sealing = Low risk

SIGNS OF MOISTURE MIGRATION

- ⚠ High moisture in bottom insulation
- ⚠ Rising moisture trend over time
- ⚠ Deterioration in dielectric strength
- ⚠ Increased partial discharge activity
- ⚠ Hot spots during thermal scan
- ⚠ Unexpected insulation failures

Detect early. Act early. Prevent failure.

TOOLS TO DETECT MIGRATION

- Moisture Monitors (Online)
- Oil & Paper Moisture Analysis
- Partial Discharge Monitoring
- Temperature Monitoring
- Trend Analysis & Diagnostics

Use data. Understand trends. Take action.

THE BOTTOM LINE

> Moisture migration is silent but dangerous.
> You can't stop it, but you can control it.
> Control moisture.
> Control temperature.
> Protect your transformer.

Awareness today.
Reliability tomorrow.

CONTACT DRYTRANS

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DRYTRANS SOLUTIONS

- TRS / TRS0 – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60422 – Mineral insulating oils in electrical equipment
- IEC 60414 – Determination of water in solid electrical insulation
- IEC 61439 – Determination of the equilibrium relative humidity

ABOUT DRYTRANS

DryTrans provides innovative moisture management solutions that improve reliability, extend transformer life and protect your investment.

SCAN TO LEARN MORE

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Moisture Under Control

DryTrans Knowledge Series

SECTION 44

MOISTURE INGRESS PATHWAYS IN POWER TRANSFORMERS

Moisture finds a way in.
Your job is to keep it out.

Understanding how moisture enters a transformer is essential to prevent insulation deterioration, avoid failures and extend transformer life.

THE IMPACT OF MOISTURE INGRESS

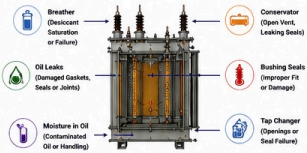
- Reduces dielectric strength
- Accelerates insulation aging
- Increases risk of partial discharge
- Leads to sludge and acid formation
- Results in failures and outages

Prevention is always better than cure.

KEY MESSAGE

- Moisture ingress is continuous if not controlled.
- Multiple pathways exist—sealing is critical.
- Small leaks = big moisture problems over time.
- Good design, sealing and maintenance stop moisture at the source.
- Keep moisture out to keep your transformer reliable and your investment safe.

MAJOR MOISTURE INGRESS PATHWAYS



Every pathway, no matter how small, can allow moisture in.

BREATHER – A CRITICAL ENTRY POINT

Breather removes moisture from air entering the conservator.

When desiccant is saturated or blocked, moist air enters freely.

Check breather regularly.

Replace or regenerate desiccant on time.

A failed breather = Open door for moisture.

SEALS AND GASKETS MATTER

Damaged, hardened or poorly installed seals allow moisture entry.

Inspect and replace seals during maintenance.

Use high-quality materials and proper torque.

Good sealing keeps moisture out and performance in.

TAP CHANGER AND BUSHINGS

Tap Changer

Tap changer compartments can "breathe" if seals are worn or pressure relief devices are not working.

Ensure proper sealing and maintenance.

Bushings

Poorly fitted or cracked bushing seals allow moisture along the conductor path.

Check bushing seals and flanges.

Small gaps = Big risks.

OIL HANDLING AND QUALITY

- Moisture in new oil or during handling adds to total moisture.
- Always filter oil and store in sealed, dry tanks.
- Test oil moisture before filling the transformer.

Clean, dry oil = Strong insulation.

ENVIRONMENTAL FACTORS

Factor	How It Contributes	What You Can Do
High Humidity & Rain	Moist air enters through breathers or leaks	Use effective breathers, keep seals intact, avoid open conservator
Temperature Fluctuations	Breathing effect sucks in moist air	Maintain stable oil level, use nitrogen blanketing where possible
Dust & Dirt	Clogs breathers, retains moisture	Keep equipment clean, check breathers regularly

You can't control the weather, but you can control the risk.

MOISTURE INGRESS – THE CHAIN REACTION

Moisture Ingress → Absorbed by Insulation → Reduced Dielectric Strength → Partial Discharge & Aging → Failure & Outage

Stop it at the start. Break the chain.

BEST PRACTICES TO PREVENT MOISTURE INGRESS

- Use high-quality, properly installed seals and gaskets.
- Maintain and test breathers. Replace desiccant on time.
- Keep oil levels within the recommended range.
- Store oil and equipment properly. Keep them sealed.
- Filter and dry the oil before filling.
- Inspect regularly and fix leaks immediately.
- Monitor moisture in oil and insulation.

Prevention today. Reliability tomorrow.

SIGNS OF MOISTURE INGRESS

- Rising moisture in oil and insulation.
- Frequent breather color change or saturation.
- Oil leaks or wet spots.
- Sludge formation in oil.
- Increased partial discharge activity.
- Unexpected insulation failures.

Watch the signs. Act before it's too late.

DESIGN FEATURES THAT HELP

- Hermetically Sealed Design
- Conservator with Nitrogen Blanket
- High-Quality Sealing Materials
- Leak-Proof Welds and Joints
- Effective Breather with Indicator

Good design = First line of defense.

MAINTENANCE CHECKLIST

- Check oil level
- Inspect for leaks
- Check breather and desiccant
- Test oil moisture
- Inspect seals and gaskets
- Review PD (Partial Discharge) trends
- Document and follow up

Routine checks. Long-term protection.

TOOLS THAT HELP

- Moisture Analyzers (Online / Portable)
- Breather Humidity Indicators
- Ultrasonic Leak Detectors
- Infrared Thermography
- Oil Test Kits & Labs

Use the right tools. Get the right insight.

THE BOTTOM LINE

> Moisture enters quietly.
> Damage happens slowly.
> Protection starts with you.

Know the pathways.
Control the entry.
Ensure reliability.

DryTransformers are reliable transformers.
Keep moisture out.
Keep power on.

CONTACT DRYTRANS

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DRYTRANS SOLUTIONS

- TRS / TRSO – Continuous Moisture Management
- MM590 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60076 – Power Transformers
- IEC 60422 – Mineral insulating oils
- IEC 60567 – Oil-impregnated paper and pressboard
- IEEE C57.106 – Guide for the Interpretation of Gases

ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protect your investment.

SCAN TO LEARN MORE

DryTrans – Continuous Moisture Management Solutions for Reliable Transformers

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Moisture Under Control

DryTrans Knowledge Series

SECTION 45

MOISTURE CONTROL STRATEGIES AND SOLUTIONS

You can't eliminate moisture, but you can control it.

Effective moisture control combines good design, quality materials, proper manufacturing, and proactive maintenance to keep transformer insulation dry and reliable.

KEY MESSAGE

- ✓ Moisture control is a lifecycle responsibility.
- ✓ Prevention is more effective and less expensive than cure.
- ✓ Multiple strategies work together.
- ✓ Monitor, maintain, and manage continuously.
- ✓ Dry insulation = Strong insulation = Reliable transformer.

1. PREVENT MOISTURE INGRESS

- Use hermetically sealed or well-sealed designs.
- Ensure high-quality seals and gaskets.
- Use proper drying and vacuum processing during manufacturing.
- Install effective breathers with desiccant.
- Keep conservator sealed and oil level proper.

Good prevention keeps moisture out.

2. REMOVE MOISTURE

- Vacuum drying of active parts and insulation.
- Hot oil circulation and vacuum dehydration.
- Use adsorbents and drying agents.
- Filter and dehydrate oil during processing.
- Re-dry insulation during refurbishment.

Remove moisture before it causes damage.

3. MONITOR MOISTURE

- Measure oil moisture and temperature.
- Track trends over time.
- Monitor ERH or DGA for early warnings.
- Set alarms and alerts for limit exceedance.
- Use online systems for continuous visibility.

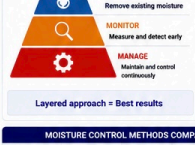
You can't manage what you don't measure.

4. MANAGE MOISTURE

- Schedule regular maintenance and oil testing.
- Replace or regenerate breathers on time.
- Control temperature and loading.
- Repair leaks and address issues promptly.
- Keep records and document moisture activities.

Active management keeps moisture under control.

MOISTURE CONTROL HIERARCHY



Layered approach = Best results

MOISTURE CONTROL OVER TRANSFORMER LIFECYCLE

Moisture control is a continuous journey, not a one-time task.

THE BENEFITS OF MOISTURE CONTROL

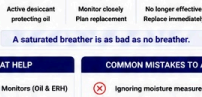
- ✓ Stronger insulation and higher reliability
- ✓ Longer transformer life
- ✓ Lower failure risk and outages
- ✓ Reduced maintenance and costs
- ✓ Better performance and efficiency
- ✓ Protects your investment

Good moisture control pays off in every way.

MOISTURE CONTROL METHODS COMPARISON

Method	Best For	Effectiveness	Cost	Notes
Vacuum Drying	New units, major refurbishment	Excellent	High	Most effective for insulation
Hot Oil Vacuuming	Oil moisture reduction	High	Medium	Removes dissolved moisture
Oil Filtration	Particles & some moisture	Medium	Low	Use with dehydration capability
Breathers	Prevent ambient moisture	Medium	Low	Replace or regenerate regularly
Online Monitoring	Early detection and trends	High	Medium	Enables proactive action

BRESTURE MAINTENANCE GUIDE



A saturated breather is as bad as no breather.

MOISTURE TROUBLESHOOTING QUICK GUIDE

Symptom	Possible Cause	What To Do
High oil moisture	Breather saturated or blocked	Check and replace breather
Rising moisture trend	Leak or high humidity	Inspect for leaks, improve sealing
Hot spots	Wet insulation	Dry insulation, improve cooling
Low dielectric strength	High moisture	Dehydrate oil, dry insulation
Sludge or acids	Moisture + aging	Oil treatment, investigate source

BEST PRACTICES SUMMARY

- ✓ Keep moisture out with good design and sealing.
- ✓ Remove moisture with proper drying methods.
- ✓ Monitor moisture continuously.
- ✓ Manage moisture through maintenance.
- ✓ Act early based on trends, not just limits.
- ✓ Train your team and follow procedures.

Best practices today = Reliable transformers tomorrow.

TOOLS THAT HELP

- Online Moisture Monitors (Oil & ERH)
- Breather Humidity Indicators
- Oil Test Kits and Lab Analysis
- DGA Monitors
- SCADA / Asset Management Systems
- Infrared Thermography

Use the right tools. Get the right insight.

COMMON MISTAKES TO AVOID

- ✗ Ignoring moisture measurements
- ✗ Using poor-quality breathers
- ✗ Skipping maintenance
- ✗ Overlooking small leaks
- ✗ Not controlling temperature
- ✗ Reacting only after a failure

Small mistakes lead to big problems.

THE BOTTOM LINE

Moisture will always try to get in. Your control strategy determines whether it stays out or causes trouble.

Control moisture. Control reliability. Control your future.

Your transformer. Your responsibility. Our solutions.

CONTACT DRYTRANS

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DRYTRANS SOLUTIONS

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- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60076 – Power Transformers
- IEC 60422 – Mineral Insulating Oils
- IEC 60567 – Oil-Impregnated Paper and Pressboard
- IEC 61639 – Determination of Equilibrium Relative Humidity

ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protect your investment.

SCAN TO LEARN MORE

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Moisture Under Control

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SECTION 46

MOISTURE MEASUREMENT TECHNOLOGIES

TOOLS FOR ACCURATE INSIGHTS

Accurate measurement is the foundation of effective moisture management.

Different technologies provide insights into moisture in oil, paper and air. Use the right tool for the right measurement.

KEY MESSAGE

- ✓ No single method measures everything.
- ✓ Each technology has strengths and limitations.
- ✓ Combine methods for a complete picture.
- ✓ Calibrate, maintain and use properly.
- ✓ Accurate data leads to smart decisions and reliable transformers.

OIL MOISTURE MEASUREMENT (DISSOLVED MOISTURE)

Karl Fischer Titration (IEC 60814)

- Reference method
- High accuracy
- Laboratory test

Best Accuracy ★★★★★

Capacitive Sensor (Online)

- Continuous monitoring
- Fast response
- Installed in-line

Best For Trends ★★★★☆

Infrared / Optical Sensor (Online)

- Online monitoring
- No moving parts
- Less maintenance

Best Reliability ★★★★☆

Lab Quick Test Kits

- Field screening
- Quick result
- Easy to use

Best For Screening ★★★☆☆

Measures moisture dissolved in transformer oil (ppm or mg/kg).

PAPER MOISTURE MEASUREMENT (INSULATION MOISTURE)

Oven Dry Method (IEC 60414)

- Reference method
- Accurate, destructive
- Requires sampling

Best Accuracy ★★★★★

Equilibrium RH (ERH) Method (IEC 61439)

- Non-destructive
- Estimates paper moisture profile
- Field or lab use

Best Balance ★★★★☆

Dielectric Response Analysis (DRA)

- Online / offline
- Estimates moisture condition
- Advanced insight

Best Insight ★★★★☆

Measures moisture in solid insulation (cellulose paper) (%MP or ERH).

AMBIENT AIR MEASUREMENT

Relative Humidity (RH)

- Digital hygrometers
- Continuous or spot measurement

Best For Awareness ★★★☆☆

Temperature (°C)

- RTDs or digital sensors
- Essential for calculations

Essential ★★★★★

Dew Point (°C)

- Indicates saturation level of air
- Useful for risk assessment

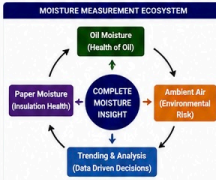
Best For Risk ★★★★☆

Measures ambient conditions that influence moisture ingress and drying.

METHODS COMPARISON GUIDE

Method	Measures	Accuracy	Online	Destructive	Best Use
Karl Fischer Titration	Oil (ppm)	Very High	✗	✓	Lab reference
Capacitive Sensor	Oil (ppm)	High	✓	✗	Continuous monitoring
Infrared / Optical Sensor	Oil (ppm)	High	✓	✗	Online applications
Lab Quick Test Kits	Oil (ppm)	Medium	✗	✗	Field screening
Oven Dry Method	Paper (%MP)	Very High	✗	✓	Reference testing
ERH Method	Paper (%MP/ERH)	High	✗	✗	Condition assessment
DRA	Paper (Moisture Profile)	Medium-High	✓	✗	Advanced diagnostics
RH / Temperature	Air	High	✓	✗	Environmental monitoring
Dew Point	Air	High	✓	✗	Risk assessment

MOISTURE MEASUREMENT ECOSYSTEM



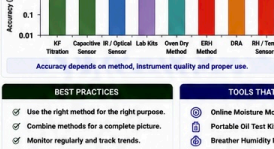
Combine measurements. Understand moisture. Take action. Improve reliability.

ACCURACY IMPROVEMENT TIPS

- ✓ Use calibrated and reliable instruments.
- ✓ Follow standard test methods (IEC/ASTM).
- ✓ Take proper samples from correct locations.
- ✓ Avoid contamination during sampling.
- ✓ Consider temperature when interpreting results.
- ✓ Use multiple methods for cross-verification.
- ✓ Maintain and service instruments regularly.
- ✓ Document results and track trends over time.

Better measurement = Better decisions

TYPICAL ACCURACY RANGE



Accuracy depends on method, instrument quality and proper use.

MEASUREMENT FREQUENCY GUIDELINES

Measurement	Normal Operation	High Risk / Problem
Oil Moisture (Online)	Continuous	Continuous
Oil Moisture (Lab)	Every 3 – 6 months	Monthly
Paper Moisture (ERH/DRA)	Annually	Every 3 – 6 months
Paper Moisture (Oven Dry)	Every 2 – 3 years	Annually
Ambient RH & Temp.	Continuous	Continuous
Dew Point	Weekly	Weekly or more

Adjust frequency based on asset criticality and conditions.

SAMPLE RECOMMENDATIONS (OIL)

Location	Why It Matters
Top Oil	Most exposed to air and moisture ingress
Mid Oil	Represents average condition
Bottom Oil	Shows overall dissolved moisture
Tap Changer Compartment	Critical zone for moisture accumulation
Before & After Filtration	Evaluate filtration effectiveness

Good sampling = Good data = Good decisions.

BEST PRACTICES

- ✓ Use the right method for the right purpose.
- ✓ Combine methods for a complete picture.
- ✓ Monitor regularly and track trends.
- ✓ Act on early warnings and changes.
- ✓ Keep records and analyze data.
- ✓ Train team on proper measurement techniques.

Measure smart. Manage better.

TOOLS THAT HELP

- Online Moisture Monitors (Oil & ERH)
- Portable Oil Test Kits
- Breather Humidity Indicators
- DGA Monitors
- SCADA / Asset Management Systems
- Data Analytics & Trending Software

Use the right tools. Get the right insight.

COMMON MISTAKES TO AVOID

- ✗ Relying on a single measurement.
- ✗ Ignoring temperature effects.
- ✗ Poor sampling or contamination.
- ✗ Using uncalibrated instruments.
- ✗ Not monitoring trends.
- ✗ Delaying action on warnings.

Small mistakes. Big consequences.

THE BOTTOM LINE

"You can't manage what you don't measure. Accurate measurement turns uncertainty into knowledge. Better insight. Better action. Stronger reliability."

Measure it right.
Manage it smart.
Keep it dry.
Keep it reliable.

CONTACT DRYTRANS

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DRYTRANS SOLUTIONS

- TRS / TRSO – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60814 – Oil moisture (KF titration)
- IEC 60414 – Paper moisture (Oven dry)
- IEC 61439 – ERH method
- IEC 60567 – Oil impregnated paper and pressboard
- IEC 60076 – Power Transformers

ABOUT DRYTRANS

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SCAN TO LEARN MORE

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SECTION 47

MOISTURE IN PAPER INSULATION EFFECTS AND CONSEQUENCES

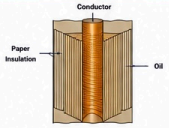
Moisture weakens paper.
Weak paper risks your transformer.

Paper insulation provides mechanical strength and dielectric performance. When moisture increases, paper deteriorates, leading to reduced strength, higher losses and greater risk of failure.

KEY MESSAGE

- ✓ Moisture has a direct negative impact on paper insulation.
- ✓ It reduces dielectric strength and mechanical strength.
- ✓ It accelerates aging and chemical degradation.
- ✓ It increases risk of partial discharge and failure.
- ✓ Keep moisture low to keep paper strong.
- ✓ Strong paper = Strong transformer = Long life.

HOW PAPER INSULATION WORKS

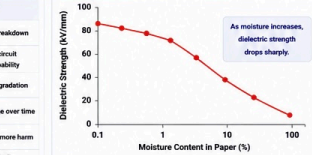


Paper and oil work together.
Paper provides strength.
Oil provides cooling and dielectric support.

EFFECTS OF MOISTURE ON PAPER

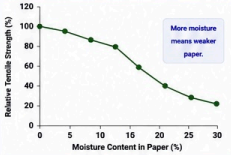
Moisture Effect	Result
Reduces dielectric strength	Higher risk of breakdown
Reduces mechanical strength	Lower short-circuit withstand capability
Accelerates chemical aging	Faster paper degradation
Increases partial discharge activity	Insulation damage over time
Reduces thermal endurance	Hot spots cause more harm
Causes dimensional changes	Can loosen windings and spacers

DIELECTRIC STRENGTH VS MOISTURE CONTENT



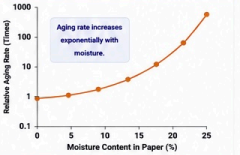
Higher moisture = Lower dielectric strength = Higher failure risk.

MECHANICAL STRENGTH VS MOISTURE



Wet paper is weak paper.

AGING RATE VS MOISTURE



Moisture dramatically shortens transformer life.

TYPICAL CONSEQUENCES

- Breakdown and flashover
- Loss of mechanical strength
- Increased partial discharge
- Higher losses and hot spots
- Reduced transformer life
- Unplanned outages and high costs

High moisture leads to failure and high costs.

MOISTURE CONTENT GUIDELINES (PAPER)

Moisture Content (% by weight)	Condition	Status
<= 1.0	Very Dry	Excellent
1.0 – 2.0	Dry	Good
2.0 – 3.0	Moderate	Acceptable
3.0 – 4.0	High	Poor
> 4.0	Very High	Unacceptable

Lower is always better.

HOW MOISTURE ENTERS PAPER

- From oil (high moisture oil)
- From air (breather saturation or failure)
- From high temperature (accelerates ingress)
- From poor handling and storage
- From leaks and poor sealing

Control the entry. Protect the paper.

PAPER DRYING AND RESTORATION

- Vacuum drying
- Oil filtration and drying
- Dehydrating oil treatment
- Monitor progress (moisture tests)
- Confirm target achieved

Remove moisture. Restore strength.

GOOD PAPER = RELIABLE TRANSFORMER

- ✓ Keep paper dry.
- ✓ Use dry oil.
- ✓ Seal and maintain the system.
- ✓ Monitor and act early.
- ✓ Strong paper. Strong transformer.

Protect the paper today.
Secure your transformer tomorrow.

BEST PRACTICES

- ✓ Keep moisture as low as possible.
- ✓ Use high-quality, dry insulating materials.
- ✓ Maintain oil quality and dryness.
- ✓ Ensure breathers are effective and maintained.
- ✓ Monitor moisture regularly.
- ✓ Act before moisture causes damage.

Good habits protect paper and performance.

TOOLS THAT HELP

- Karl Fischer Titration (Oil Moisture)
- Oven Dry (Paper Moisture)
- ERH Measurement (Insulation Moisture)
- DRA (Dielectric Response Analysis)
- Moisture Sensors (Online/Portable)
- Data Analytics & Trending Software

Use the right tools. Get the right insight.

COMMON MISTAKES TO AVOID

- ✗ Ignoring moisture test results.
- ✗ Using wet oil or wet materials.
- ✗ Poor sealing and leaks.
- ✗ Skipping regular maintenance.
- ✗ Overheating the transformer.
- ✗ Waiting too long to act.

Small mistakes. Big consequences.

THE BOTTOM LINE

Moisture weakens paper silently.
It steals strength. It shortens life.
Control moisture.
Protect the paper.
Protect your transformer.

Dry paper today.
Reliable power tomorrow.

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SCAN TO LEARN MORE

DryTrans – Continuous Moisture Management Solutions for Reliable Transformers

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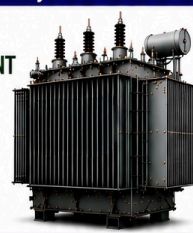
SECTION 48

MOISTURE IN OIL
EFFECTS AND MANAGEMENT

Moisture in oil is unavoidable.
Its impact is not.

Moisture in transformer oil reduces dielectric strength, accelerates aging and increases the risk of failure. Understanding its effects and controlling it effectively is essential for reliable transformer operation.



KEY MESSAGE

- ✓ Moisture in oil lowers dielectric strength.
- ✓ It accelerates insulation aging and increases failure risk.
- ✓ Monitor regularly. Dry proactively.
- ✓ Keep oil dry = Strong insulation = Reliable power.
- ✓ Small moisture, big impact. Don't ignore it.

WHERE DOES MOISTURE IN OIL COME FROM?

- Breathing: Air enters conservator as oil volume changes.
- Condensation: Temperature drops cause moisture to condense.
- Oil handling: Exposure during maintenance or filling.
- Leaks: Leaky seals and gaskets allow moist air ingress.
- Wet paper: Moisture migrates from paper to oil.

Control the sources. Reduce the moisture.

EFFECTS OF MOISTURE IN OIL

- Reduces dielectric strength
- Increases risk of breakdown
- Accelerates oil and paper aging
- Increases partial discharge activity
- Forms sludge and corrosive by-products
- Reduces overall transformer life
- Leads to unplanned outages and high maintenance cost

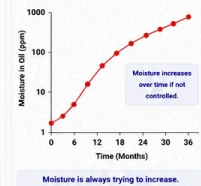
Moisture today, failure tomorrow.

WARNING SIGNS OF HIGH MOISTURE

- Low dielectric strength readings
- Increased partial discharge
- High moisture in oil test results
- Sludge formation in tank
- Breather saturation or color change
- Rising oil temperature
- Frequent alarms and outages

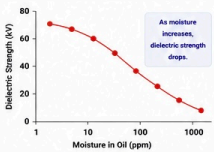
Watch the signs. Act in time.

MOISTURE CONTENT vs TIME (TYPICAL)



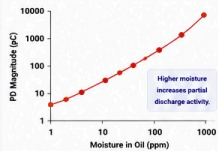
Moisture is always trying to increase.

DIELECTRIC STRENGTH vs MOISTURE CONTENT



Dry oil = Strong insulation.
High moisture = High risk.

PARTIAL DISCHARGE vs MOISTURE CONTENT



PD today, failure tomorrow.

TYPICAL MOISTURE LIMITS IN OIL (GUIDELINES)

Standard / Reference	Normal Condition (ppm)	High Caution (ppm)	Action Required (ppm)
IEC 60422 (New Oil)	≤ 10	10 – 20	> 20
IEC 60422 (In Service)	≤ 20	20 – 35	> 35
IEEE C57.106 (Guide)	≤ 15	15 – 30	> 30
CIGRE TB 445	≤ 10	10 – 20	> 20

Lower is always better. Keep moisture at the lowest practical level.

BEST PRACTICES

- ✓ Keep conservator sealed and oil level optimal.
- ✓ Use effective breathers and replace desiccant regularly.
- ✓ Dry oil before filling using vacuum dehydration.
- ✓ Filter oil continuously during maintenance.
- ✓ Minimize oil exposure during handling.
- ✓ Store and transport oil in sealed conditions.
- ✓ Monitor moisture regularly.
- ✓ Act before moisture causes damage.

Good habits keep oil dry and transformers reliable.

TOOLS TO MEASURE MOISTURE

- Karl Fischer Titration (Lab Method)
- Capacitive Moisture Sensor (Online)
- Infrared / Optical Sensor (Online)
- Portable Moisture Meter
- Lab Test Kits
- DGA (Indirect Indicator)

Use the right tool for accurate insights.

COMMON MISTAKES TO AVOID

- ✗ Ignoring moisture test results.
- ✗ Using poor-quality or expired breathers.
- ✗ Opening conservator unnecessarily.
- ✗ Skipping oil filtration and dehydration.
- ✗ Mixing moisture with oil temperature effects.
- ✗ Assuming new oil is dry.
- ✗ Not monitoring trends over time.

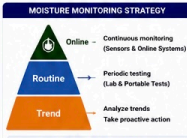
Small mistakes. Big consequences.

THE BENEFITS

- ✓ Higher dielectric strength
- ✓ Lower risk of breakdown
- ✓ Reduced insulation aging
- ✓ Lower maintenance and costs
- ✓ Fewer outages and failures
- ✓ Longer transformer life
- ✓ Better performance and reliability

Dry oil. Strong insulation. Reliable power.

MOISTURE MONITORING STRATEGY



Monitor. Trend. Act. Repeat.

RECOMMENDED ACTIONS BASED ON MOISTURE LEVEL

Moisture Level (ppm)	Condition	Recommended Action
≤ 10	Excellent	Maintain & Monitor
10 – 20	Good	Continue Monitoring
20 – 35	Caution	Increase Monitoring & Check Breathers
35 – 50	High	Dry/Filter Oil, Check Sources
> 50	Very High	Dehydrate Oil Immediately Investigation Required

DEHYDRATION METHODS

- Vacuum Dehydration (Most Effective)
- Thermal Dehydration (Heat & Vacuum)
- Adsorbent Filtration (Clay, Silica Gel, Alumina)
- Continuous Online Drying (For Ongoing Control)

THE BOTTOM LINE

> **Moisture in oil is silent but dangerous.**
> **Measure it.**
> **Manage it.**
> **Control it.**
> **Protect your transformer.**

Dry oil today.
Reliable power tomorrow.

CONTACT DRYTRANS

vishal@drytrans.com
+971 50 679 0417
www.drytrans.com

DRYTRANS SOLUTIONS

- TRS / TRSO – Continuous Moisture Management
- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60422 – Mineral insulation oils in electrical equipment
- IEC 61439 – ERH method
- IEC 60567 – Oil impregnated paper and pressboard
- IEEE C57.106 – Guide for the Interpretation of Gases

ABOUT DRYTRANS

DryTrans provides innovative moisture management solutions that improve reliability, extend transformer life and protect your investment.

SCAN TO LEARN MORE

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Moisture Under Control

DryTrans Knowledge Series

SECTION 49

IMPACT OF MOISTURE ON TRANSFORMER LIFE

LONG-TERM CONSEQUENCES OF IGNORING MOISTURE

Moisture today. Problems tomorrow.
Act now. Protect forever.

Moisture is one of the leading causes of insulation degradation and transformer failure. Understanding its long-term impact helps in making smart decisions that extend transformer life and reduce risk and cost.

KEY MESSAGE

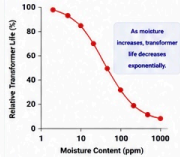
- Moisture causes progressive and irreversible damage.
- It shortens transformer life significantly.
- The cost of ignoring moisture is much higher.
- Prevention and control ensure long, reliable service.
- Dry transformer = Reliable transformer = Lower total cost of ownership.

HOW MOISTURE DAMAGES INSULATION

Reduces dielectric strength	→ Higher risk of breakdown
Accelerates aging	→ Shorter insulation life
Increases partial discharge	→ Progressive insulation deterioration
Forms sludge and acids	→ Corrosion and contamination
Leads to hot spots and overheating	→ Thermal damage and failure

Moisture creates a chain reaction of damage.

MOISTURE vs TRANSFORMER LIFE



Low moisture = Long life.
High moisture = Short life.

COST OF MOISTURE (LONG TERM)

- Higher failure risk and unplanned outages
- Expensive repairs and part replacement
- Shorter service life and early replacement
- Loss of productivity and revenue
- Higher insurance and compliance cost

Prevent moisture. Avoid the cost.

MOISTURE IMPACT TIMELINE

0 – 6 Months
Moisture enters and saturates insulation. No visible damage.

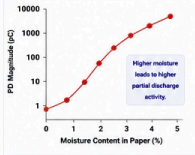
6 – 24 Months
Insulation weakens. PD activity increases. Aging accelerates.

2 – 5 Years
Hot spots, sludge and acids form. Dielectric strength drops.

5 – 10+ Years
High failure risk, outages and major repairs.

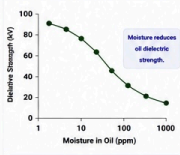
Small moisture today. Big problems tomorrow.

PARTIAL DISCHARGE vs MOISTURE (PAPER)



PD is an early warning of insulation stress.

DIELECTRIC STRENGTH vs MOISTURE (OIL)



Stronger oil. Stronger insulation.

AGING ACCELERATION FACTOR (AAF)

The Aging Acceleration Factor (AAF) shows how moisture and temperature speed up paper aging.

Condition	Typical AAF
Dry Paper (≤ 1% moisture)	1x (Reference)
2% Moisture	2 – 3x
3% Moisture	4 – 6x
4% Moisture	8 – 12x
5% Moisture	16x or more

More moisture = Faster aging.

LIFE EXTENSION THROUGH MOISTURE CONTROL

- Control moisture at every entry point.
- Maintain oil quality and dryness.
- Use online monitoring and alarms.
- Dry and filter oil regularly.
- Keep insulation dry from day one.

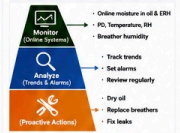
Moisture control can extend transformer life by 2X to 5X or more.

BEST PRACTICES FOR LONG LIFE

- Use hermetically sealed or well-sealed designs.
- Keep breather and conservator systems healthy.
- Use high-quality, dry insulating materials.
- Filter and dehydrate oil before and during operation.
- Monitor moisture in oil and insulation continuously.
- Act early on alarms and trends.
- Train team and follow standard procedures.

Good habits today. Long life tomorrow.

MOISTURE MONITORING STRATEGY



Monitor. Analyze. Act. Repeat.

RECOMMENDED ACTIONS BY MOISTURE LEVEL (OIL)

Moisture (ppm)	Condition	Recommended Action
≤ 10	Excellent	Maintain & Monitor
10 – 20	Good	Continue Monitoring
20 – 35	Caution	Increase Monitoring & Check Breathers
35 – 50	High	Dry/Filter Oil, Check Sources
> 50	Very High	Dehydrate Oil Immediately Investigation Required

Don't wait for failure. Act on the data.

IGNORING MOISTURE CAN LEAD TO

- Insulation breakdown
- Transformer failure
- Fire and safety hazards
- Loss of critical operation
- Reputation damage
- High replacement cost

Ignoring moisture is a risk you don't need.

TOOLS THAT HELP

- Karl Fischer Titration (Oil & Moisture)
- Capacitive Moisture Sensor
- Infrared / Optical Sensor
- DGA (Indirect Indicator)
- ERH Measurement (Insulation)
- Online Moisture Monitors
- SCADA / Asset Management

Use the right tools. Get the right insight.

DRYING & DEHYDRATION METHODS

- Vacuum Dehydration (Most Effective)
- Thermal Dehydration (Heat & Vacuum)
- Oil Filtration and Drying
- Adsorbent Filtration (Clay, Silica Gel, Alumina)
- Continuous Drying Systems

Remove moisture. Restore strength.

COMMON MISTAKES TO AVOID

- Ignoring moisture test results.
- Not monitoring continuously.
- Using poor-quality breathers.
- Skipping oil drying or filtration.
- Assuming new oil is dry.
- Waiting for failure before action.

Small mistakes. Big consequences.

THE BOTTOM LINE

> **Moisture silently destroys insulation. It reduces strength. It shortens life. Control moisture. Protect your transformer. Protect your future.**

Dry today.
Reliable tomorrow.
Power for years.

CONTACT DRYTRANS

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DRYTRANS SOLUTIONS

- TRS / TRSO – Continuous Moisture Management
- MM900 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management

REFERENCE STANDARDS

- IEC 60422 – Mineral insulating oils
- IEC 60414 – Paper-moisture (Oven dry)
- IEC 61439 – ERH method
- IEC 60567 – Oil impregnated paper and pressboard
- IEEE C57.106 – Guide for the Interpretation of Gases

ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protect your investment.

SCAN TO LEARN MORE

drytrans
Moisture Under Control

DryTrans Knowledge Series

SECTION 50
FINAL SECTION

THE ULTIMATE TRANSFORMER MOISTURE FAQ
100 QUESTIONS & ANSWERS
EVERY TRANSFORMER OWNER SHOULD KNOW

Fifty sections. One complete resource.
The answers you need for reliable transformers.

This comprehensive FAQ brings together the most important questions about transformer moisture—covering science, measurement, effects, control, and long-term asset management.

KEY TAKEAWAYS

- ✓ Moisture is the #1 enemy of transformer insulation.
- ✓ Control moisture, extend life, reduce risk and cost.
- ✓ Measure accurately. Monitor continuously.
- ✓ Dct early. Prevention is always better than cure.
- ✓ Dry transformer = Reliable transformer = Lower total cost of ownership.

YOU MADE IT TO THE FINAL SECTION!
You now have master-level knowledge in transformer moisture management.

TOP 100 FREQUENTLY ASKED QUESTIONS

ⓘ Numbers in brackets indicate the primary section(s) where the topic is covered in detail.

WHO SHOULD USE THIS SERIES?

UTILITY ENGINEERS
- ✓ Ensure system reliability
- ✓ Reduce outage risk
- ✓ Improve asset performance
- ✓ Extend transformer life

MAINTENANCE ENGINEERS
- ✓ Understand root causes
- ✓ Apply best practices
- ✓ Use the right tools
- ✓ Take proactive action

ASSET MANAGERS
- ✓ Optimize investment
- ✓ Reduce total cost
- ✓ Extend asset life
- ✓ Improve ROI

PURCHASING TEAMS
- ✓ Specify correct requirements
- ✓ Request right tests
- ✓ Select reliable suppliers
- ✓ Protect long-term value

TRANSFORMER OWNERS
- ✓ Protect your asset
- ✓ Ensure safe operation
- ✓ Reduce risk and cost
- ✓ Build a reliable future

REMEMBER

> **Moisture is silent.**
> **Its damage is not.**
> **Measure it. Manage it.**
> **Control it.**
> **Your transformer depends on it.**
> **Your future depends on it.**

Dry today.
Reliable tomorrow.
Power for years.

EXECUTIVE SUMMARY

- ✓ Moisture is the most critical factor affecting transformer insulation.
- ✓ It reduces dielectric strength and accelerates aging.
- ✓ It increases risk of partial discharge, overheating and failure.
- ✓ It shortens transformer life and increases total cost.
- ✓ Effective moisture management delivers reliability, safety and savings.

Control moisture. Control risk. Control the future.

5 CORE PRINCIPLES OF MOISTURE MANAGEMENT

5↓ PREVENT INGRESS
Good design, quality materials, sealed joints, proper breathers.

MEASURE ACCURATELY
Use the right method, at the right time.

MONITOR CONTINUOUSLY
Track trends. Set alarms. Take action early.

CONTROL PROACTIVELY
Dry, filter, maintain and replace when needed.

PLAN FOR THE LONG TERM
Integrate moisture management into asset strategy.

These principles work together to deliver reliable performance.

BEST PRACTICES AT A GLANCE

- ✓ Keep transformer as dry as possible.
- ✓ Use high quality oil and insulation materials.
- ✓ Monitor moisture in oil and paper regularly.
- ✓ Act early based on trends and alarms.
- ✓ Use vacuum drying for best results.
- ✓ Maintain breathers and seals.
- ✓ Document, review and improve.

Good habits today. Reliability forever.

ESSENTIAL TOOLS

- Karl Fischer Titration (Oil & Moisture)
- Online Moisture Monitors (ERH & OB)
- DGA (Moisture & Key Gases)
- Capacitive Moisture Sensors
- Portable Moisture Meters
- SCADA / Asset Management Systems
- Breather Humidity Indicators
- Lab Test Kits

Use the right tools. Get the right insight.

RECOMMENDED ACTIONS (BY PRIORITY)

HIGH PRIORITY
- High moisture detected
- Rising moisture trend
- High PD or low BDV
- Breather failure

Take Immediate action. Investigate. Dry if needed.

MEDIUM PRIORITY
- Moderate moisture
- Stable but high levels
- Aging transformer
- Environmental change

Increase monitoring. Plan drying. Improve sealing.

LOW PRIORITY
- Low moisture
- Stable and acceptable
- New or well-maintained

Maintain. Monitor. Keep it that way.

RESOURCE MAP (WHAT TO READ NEXT)

Keep learning. Keep improving.

FINAL WORD

> **Knowledge is power.**
> **Action is reliability.**
> **Discipline is performance.**
> **Together, they create transformer excellence.**

Thank you for completing the DryTrans Knowledge Series.
You are now a moisture management expert!

DRYTRANS SOLUTIONS

- TRS / TRSO – Continuous Moisture Management
- MM390 – Moisture Monitoring System
- TRS4PG – Transformer Asset Management
- Breather Management Solutions
- Training & Technical Support

REFERENCE STANDARDS

- IEC 60422 – Mineral Insulating oils
- IEC 60726 / IEEE C57.152 – Guide for Drying
- IEC 61620 – ERH method
- IEC 60567 – Oil Impregnated paper
- IEC 60076 – Power Transformers
- IEEE C57.106 – DGA Guide

ABOUT DRYTRANS

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CONTACT DRYTRANS

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+971 50 679 0417
www.drytrans.com

SCAN TO LEARN MORE

DryTrans — The Complete Transformer Moisture Knowledge Resource
35 Sections. 7,150 FAQs. One Goal: Reliable Transformers For a Better Future.

YOU MADE IT. YOU ARE READY.

drytrans
Moisture Under Control

DryTrans Knowledge Series

SECTION 51
FINAL REFERENCE SECTION

TECHNICAL REFERENCES & STANDARDS

USED THROUGHOUT THE DRYTRANS KNOWLEDGE SERIES

This section provides a consolidated library of international standards, guides, research papers and technical references that form the foundation of all 50 sections of the DryTrans Knowledge Series.

KEY MESSAGE

- ✓ The series is based on internationally recognized standards, research and field experience.
- ✓ These references ensure technical accuracy, credibility and practical relevance.
- ✓ Use the right standard. Apply the right method.
- ✓ Make the right decision. Extend transformer life.

A. INTERNATIONAL STANDARDS (IEC)

			Used in Sections
IEC 60422	Mineral insulating oils in electrical equipment	• Oil condition assessment • Moisture evaluation, %RS • Maintenance recommendations	4, 5, 6, 16, 20, 30
IEC 60814	Determination of water in insulating liquids (Karl Fischer Titration)	• Moisture measurement • Oil moisture analysis • Moisture monitoring	4, 11, 16, 20, 32, 47
IEC 60156	Breakdown voltage of insulating liquids	• BDV discussions • Moisture effects on dielectric strength	8, 33
IEC 60247	Measurement of relative permittivity, dissipation factor and D.C. resistivity	• Tan δ, resistivity • Moisture influence	34, 35
IEC 60567	Oil sampling for dissolved gas analysis	• DGA sampling • Sampling best practices	11, 23, 37
IEC 60599	Interpretation of gases in oil-immersed equipment	• DGA interpretation • Fault diagnosis	11, 37
IEC 61198	Mineral oil-impregnated paper in electrical equipment – Furan analysis	• Paper degradation • Aging assessment	10, 25, 38
IEC 60076 Series	Power transformers	• Design, operation, testing • Insulation systems • General requirements	Throughout series

B. IEEE REFERENCES

			Used in Sections
IEEE C57.91	Guide for loading mineral-oil-immersed transformers	• Loading guides • Temperature effects • Moisture migration	6, 22, 38
IEEE C57.104	Guide for the interpretation of gases generated in oil	• DGA • Moisture & gas generation	11, 37
IEEE C57.106	Guide for acceptance and maintenance of insulating oil	• Moisture limits • Oil condition	4, 8, 16, 30
IEEE C57.143	Guide for transformer condition assessment	• Asset management • Risk assessment	36, 40, 45

C. CIGRE REFERENCES

			Used in Sections
CIGRE TB 761	Condition assessment of power transformers	• Health index • Asset life discussions	14, 36, 40
CIGRE WG A2.49	Transformer ageing	• Ageing rate • Thermal & electrical ageing	9, 14, 38
CIGRE TB 349	Moisture equilibrium and moisture assessment	• Moisture migration • Equilibrium calculations	3, 7, 20, 32
CIGRE TB 445	Transformer drying	• Drying methods • Moisture removal techniques	15, 16, 27

F. BUBBLING REFERENCES

			Used in Section
CIGRE Working Group Papers		• Bubble formation • Moisture limits • Thermal runaway	22
IEEE Bubble Evolution Research		• Wet paper • High temperature operation	22

G. PARTIAL DISCHARGE REFERENCES

			Used in Section
IEEE PD Guides		• PD measurement • Moisture effect	23
CIGRE PD Working Groups		• PD in oil & paper • Insulation defects	23

H. METHANOL REFERENCES

			Used in Section
Jalbert et al.		Methanol as early paper aging indicator	25
Hydro-Québec Research		Methanol monitoring and field experience	25

E. CLASSIC MOISTURE RESEARCH PAPERS

			Used in Sections
Oommen Paper	Moisture equilibrium between oil and paper	• Foundation for equilibrium charts & calculations	3, 20, 32
Fabre and Pichon	Deterioration processes and moisture behaviour		3, 9, 32
Koch & Tenbohlen	Moisture and aging research		9, 22, 38
Emsley & Stevens	Cellulose hydrolysis in power transformers		9, 38

D. TRANSFORMER TEXTBOOKS

			Used in Sections
A. J. Kachler & I. Höhlein	Influence of Moisture on Cellulose Aging in Electrical Insulation		9, 22, 38
S.D. Myers	Transformer Maintenance Guide		14, 40, 45
Martin Heathcote		• Design • Operation • Maintenance • Aging	Throughout series
James H. Harlow (Editor)	Transformer Engineering (2nd Edition)	• Insulation systems • Aging • Reliability	Throughout series

I. OXIDATION & CHEMISTRY REFERENCES

			Used in Sections
ASTM D974	Acid number by potentiometric titration	• Oil oxidation • Acid formation	24, 39
ASTM D971	Interfacial tension (IFT) of insulating fluids	• Oxidation assessment • Paper risk indication	24, 39
IEC 61125	Oxidation stability of insulating oils	• Oxidation resistance • Life estimation	24, 39

J. DRYTRANS TECHNICAL REFERENCES

Field experience and practical observations from DryTrans moisture management solutions worldwide.

DryTrans MMS90	Taiwan Generator Transformer, Singapore FR3 Transformer, UAE Utility Applications
DryTrans TR50	India Utility Applications, Continuous Moisture Management Projects
DryTrans TRAM90	Dual Cylinder Moisture Management Applications

REFERENCES MOST FREQUENTLY USED THROUGHOUT THE SERIES

1	IEC 60422	11	IEEE C57.143
2	IEC 60814	12	CIGRE TB 761
3	IEC 60156	13	CIGRE TB 349
4	IEC 60247	14	CIGRE TB 445
5	IEC 60567	15	Oommen Moisture Equilibrium Paper
6	IEC 60599	16	Fabre & Pichon
7	IEC 61198	17	Emsley & Stevens
8	IEEE C57.91	18	Koch & Tenbohlen
9	IEEE C57.104	19	Jalbert Methanol Research
10	IEEE C57.106	20	J&P Transformer Book

FINAL TAKEAWAY

No single test, no single standard, and no single parameter can fully describe transformer condition.

The DryTrans Knowledge Series combines:

Moisture Science · Transformer Engineering · International Standards · Research Literature · Field Experience

to provide a practical framework for improving transformer reliability, extending insulation life, and managing moisture proactively.

> “Monitoring provides visibility. Moisture Management provides control. Control of moisture is control of transformer life.”

CONTACT DRYTRANS

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www.drytrans.com

DRYTRANS SOLUTIONS

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- MMS90 – Moisture Monitoring System
- TRAM90 – Transformer Asset Management
- Training & Technical Support

ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protect your investment.

REFERENCE STANDARDS

All standards and references listed are the property of their respective owners. Used here for educational and technical reference purposes.

SCAN TO EXPLORE DRYTRANS KNOWLEDGE SERIES

drytrans
Moisture Under Control

DRYTRANS KNOWLEDGE SERIES

THE COMPLETE TRANSFORMER MOISTURE RESOURCE

51 comprehensive sections covering every aspect of transformer moisture—from fundamentals to advanced engineering, from best practices to technical references. Your complete guide to reliability, performance, and asset lifte.

51 SECTIONS
★★★★★
ONE COMPLETE KNØWLEDGE

WHY THIS SERIES MATTERS

- Moisture is the primary driver of insulation aging and transformer failure.
- This series provides the knowledge, science, and practical solutions to take control.
- Designed for utilities, engineers, consultants, asset managers, and decision makers.
- From data to decisions, from insights to action, from testing to continuous moisture management.
- Knowledge is power.
  Moisture management is transformer protection.

THE 6 KNOWLEDGE PILLARS

- **FOUNDATION (1–10)**
  Understanding the Basics
- **MOISTURE SCIENCE (11–20)**
  Science, Behavior & Measurement
- **ADVANCED ENGINEERING (21–30)**
  Diagnostics, Degradation & Chemistry
- **ASSET MANAGEMENT (31–40)**
  Monitoring, Assessment & Life Extension
- **PRACTICAL IMPLEMENTATION (41–50)**
  Best Practices, Protection & Reliability
- **REFERENCE & RESOURCES (51)**
  Standards, Research & References

WHAT YOU WILL ACHIEVE

- Deep understanding of moisture and its impact on insulation life
- Accurate diagnosis and condition assessment
- Better decision making and risk reduction
- Effective moisture management and failure prevention
- Extended transformer life and improved reliability
- Lower cost of ownership and higher asset value

WHO SHOULD USE THIS SERIES?

UTILITY ENGINEERS
Ensure system reliability and reduce outage risk

MAINTENANCE ENGINEERS
Apply best practices and improve maintenance effectiveness

ASSET MANAGERS
Optimize investment, manage risk and extend asset life

PURCHASING TEAMS
Specify the right requirements and protect long-term value

TRANSFORMER OWNERS
Protect your asset, ensure safe operation and build a reliable future

BUILT ON TRUST. PROVEN IN THE FIELD.

- Proven in utilities and industries around the world
- Trusted technologies for reliability and performance
- Field experience. Engineering excellence. Customer success.

THE DRYTRANS COMMITMENT

FOCUS ON MOISTURE
We focus on the #1 driver of insulation aging and failure.

ENGINEERED SOLUTIONS
Advanced systems designed for continuous moisture control.

CUSTOMER SUCCESS
Your reliability goals are our commitment.

SUSTAINABLE RELIABILITY
Extending asset life, reducing waste, improving sustainability.

KNOWLEDGE LEADERSHIP
Sharing knowledge to build a more reliable power future.

CONTACT DRYTRANS

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- www.drytrans.com
- Dubai, United Arab Emirates

ABOUT DRYTRANS

DryTrans provides advanced moisture management solutions that improve reliability, extend transformer life and protect your investment. Our solutions are proven in utilities, industries and critical infrastructure around the world.

**DRY TODAY. RELIABLE TOMORROW.
POWER FOR YEARS.**

> Control moisture.
> Protect your transformer.
> Protect your future.

SCAN TO EXPLORE THE SERIES

KNOWLEDGE IS POWER.
MOISTURE MANAGEMENT IS TRANSFORMER PROTECTION.

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