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UNDERSTANDING FURAN ANALYSIS

RELEVANCE TO MOISTURE

Why Furan Analysis is a Critical Indicator of Insulation Aging and the Impact of Moisture on Transformer Life

INTRODUCTION

Transformer insulation is primarily composed of cellulose paper and mineral oil. While transformer oil can be replaced or treated, the paper insulation cannot be economically replaced and therefore largely determines transformer life expectancy.

One of the most widely accepted methods for assessing paper insulation aging is Furan Analysis, particularly the measurement of 2-Furfuraldehyde (2-FAL) dissolved in transformer oil.

Furan analysis provides a valuable window into the condition of the paper insulation system. More importantly, it helps reveal the long-term impact of moisture on transformer aging.

WHAT ARE FURANS?

Cellulose paper consists of long-chain glucose molecules linked together through polymer bonds.

When cellulose degrades, these chains break down through:

- Hydrolysis (moisture-driven aging)
- Oxidation
- Thermal degradation

As the cellulose structure decomposes, several chemical compounds known as **furans** are produced and migrate into the transformer oil.

The most commonly measured compound is:

2-Furfuraldehyde (2-FAL)

Other furanic compounds include:

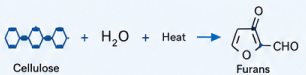
- 5-Hydroxymethyl-2-Furaldehyde (5-HMF)
- 2-Furfuryl Alcohol (2-FOL)
- 2-Acetylfuran (2-ACF)
- 5-Methyl-2-Furaldehyde (5-MF)

Among these compounds, 2-FAL is the most stable and widely used indicator of paper degradation.

WHY MOISTURE IS CLOSELY LINKED TO FURAN GENERATION

Moisture is one of the most destructive contaminants in transformer insulation systems.

Water molecules attack cellulose polymer chains through a process called **hydrolysis.**



As moisture content increases:

- Hydrolysis accelerates
- Cellulose depolymerization increases
- Mechanical strength decreases
- Furans are generated at a faster rate

In practical terms:
A transformer operating at 3–4% paper moisture may generate furans **significantly faster** than a transformer operating below 1% paper moisture under similar loading conditions.

WHAT FURAN ANALYSIS TELLS US

1	**Paper Aging**	Higher furan concentrations generally indicate greater cellulose degradation.
2	**Remaining Life**	Furan levels can be correlated with Degree of Polymerization (DP), which is a direct indicator of paper mechanical strength.
3	**Aging Rate**	Trend analysis reveals whether insulation degradation is accelerating.
4	**Moisture-Driven Damage**	Increasing furan trends often indicate ongoing hydrolysis caused by excessive moisture.

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MOISTURE → HYDROLYSIS → FURAN GENERATION → DP REDUCTION

Moisture
Water enters the insulation system through oil or direct ingress.

Hydrolysis
Water and heat attack cellulose polymer chains causing hydrolysis.

Furan Generation
Cellulose chains break down and furanic compounds (e.g., 2-FAL) are produced and dissolve in oil.

DP Reduction
Degree of Polymerization decreases, leading to loss of mechanical strength and insulation life.

2-FAL CONCENTRATION VS. INSULATION CONDITION

2-FAL Concentration (ppb)	General Interpretation	Insulation Condition	Indicative DP Range (Approx.)
< 100	Very good	New to lightly aged	> 800
100 – 500	Normal aging	Good	600 – 800
500 – 1000	Significant aging	Moderate	400 – 600
1000 – 2500	Advanced degradation	Poor	200 – 400
> 2500	Severe deterioration	Very poor	< 200

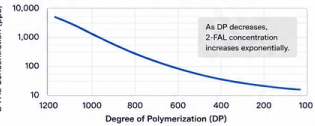
Note: Interpretation should consider transformer age, design, load history, oil history, temperature, and other diagnostic results.

FURANS AND DEGREE OF POLYMERIZATION (DP)

The Degree of Polymerization (DP) represents the average length of cellulose chains. As cellulose degrades, DP decreases.

Furan concentration (especially 2-FAL) has a strong inverse correlation with DP and is widely used to estimate remaining insulation life without opening the transformer.

Typical Correlation between 2-FAL and DP (Example Trend)



Typical DP values:
New Paper: 1000 – 1200 | **Aged Paper:** 500 – 700 | **End of Life:** < 200–250

LIMITATIONS OF FURAN ANALYSIS

Furans Measure Historical Damage
Furans indicate degradation that has already occurred. They do not directly measure current moisture content.

Furans Do Not Identify the Root Cause
High furans may result from moisture, excessive temperature, oxidation, overloading, or localized overheating. Additional diagnostics are required to identify the underlying cause.

Oil Processing Effects
Oil replacement or regeneration can temporarily reduce measured furan concentrations without reversing paper aging. Therefore, trend analysis is often more valuable than a single test result.

COMPLEMENTARY DIAGNOSTICS: MOISTURE, FURANS & METHANOL

	Moisture Measurement	Furan Analysis	Methanol Analysis
What it Indicates	Current moisture level in oil and paper system	Cumulative cellulose degradation (historical aging)	Degradation of lignin (paper/board) and oil oxidation
Primary Driver	Moisture ingress, temperature, breathing, leaks, ambient humidity	Moisture, temperature, oxidation, overload, electrical stress	High temperature, oxidation, moisture, overheating
What It Helps Answer	How wet is the insulation right now? What is the risk of hydrolysis and failure?	How much life has been consumed? What is the remaining life?	Is additional chemical degradation occurring? Is oil oxidation active?
Typical Units	ppm (mg/kg), %RS, aw, % paper moisture	ppb (µg/L)	ppb (µg/L)
Action Focus	Moisture control & ingress mitigation	Life assessment & aging trend management	Thermal control, oxidation control, oil quality management
Test Standards	IEC 60814, IEC 60247, IEC 60068-7	IEC 61198	IEC 61198 (Annex), ASTM D8277

PRACTICAL ASSET MANAGEMENT STRATEGY

An effective transformer insulation program should include:

- Moisture in oil (IEC 60814)
- Relative Saturation (%RS)
- Water Activity (a_w)
- Furan Analysis (IEC 61198)
- DGA (IEC 60567 / IEC 60599)
- TAN and IFT
- Temperature and load history

By combining these measurements, utilities can understand:

- Current insulation condition
- Future aging risk
- Remaining insulation life
- Need for corrective action

KEY TAKEAWAY

Furan analysis is one of the most powerful tools available for assessing transformer paper insulation health.

However, furans reveal the consequences of aging—not the cause.

Moisture remains one of the primary drivers of cellulose degradation and furan generation.

FURAN ANALYSIS tells us how much life **has been consumed.**

MOISTURE MANAGEMENT helps determine how much life remains.

The most effective asset management strategy is not only monitoring furans, but continuously controlling moisture before irreversible paper degradation occurs.

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