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Why Critical Transformers that are subject to Rigid Condition Monitoring still catch fire and put the lights out?

Lawrie Cleary
Principle Technical Authority
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Why do Transformers Fail?

Discussion Points

- Background
- Transformer Life Cycle
- Statistics
- Design Decisions and Trade-offs, Mineral oil vs. Ester oil
- Condition Monitoring and Testing
- Challenges and Solutions

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Failures that effect every day lives

Townsville South Substation

- Prison adjacent brown-out
- Transformer burnt for 3 days
- Fire fighters exhausted all supplies
- Principle Investigator identified faulty MV cabling

Kings Palace Malaysia

- Failed during a formal function
- Transformer recently serviced
- No identifiable maintenance procedures/ no proof testing
- Grid System Operator (GSO) sacked as outcome of investigation

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… and The Big One

Heathrow Airport Transformer 'Fire Prompts Urgent Enquiry'*

- 57-year-old
- Electrical fault occurred inside the transformer's windings or connections
- Transformer was equipped with multiple layers of protection and safety mechanisms which should have prevented destructive event

The Blame Game

- Very Old Equipment
- Lack of Maintenance Investment
- Loaded at 110% of capacity
- 220,000 passengers left stranded
- £100 million loss

* Daily Mail UK March 2025

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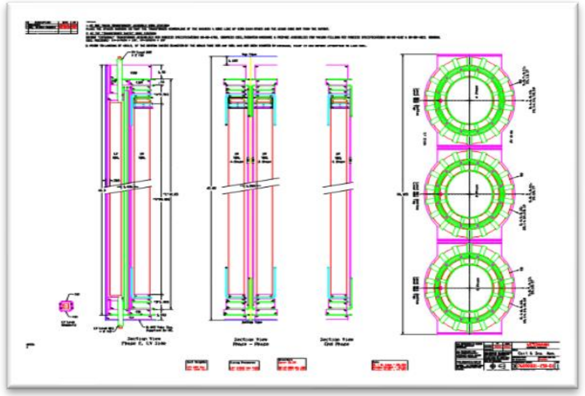
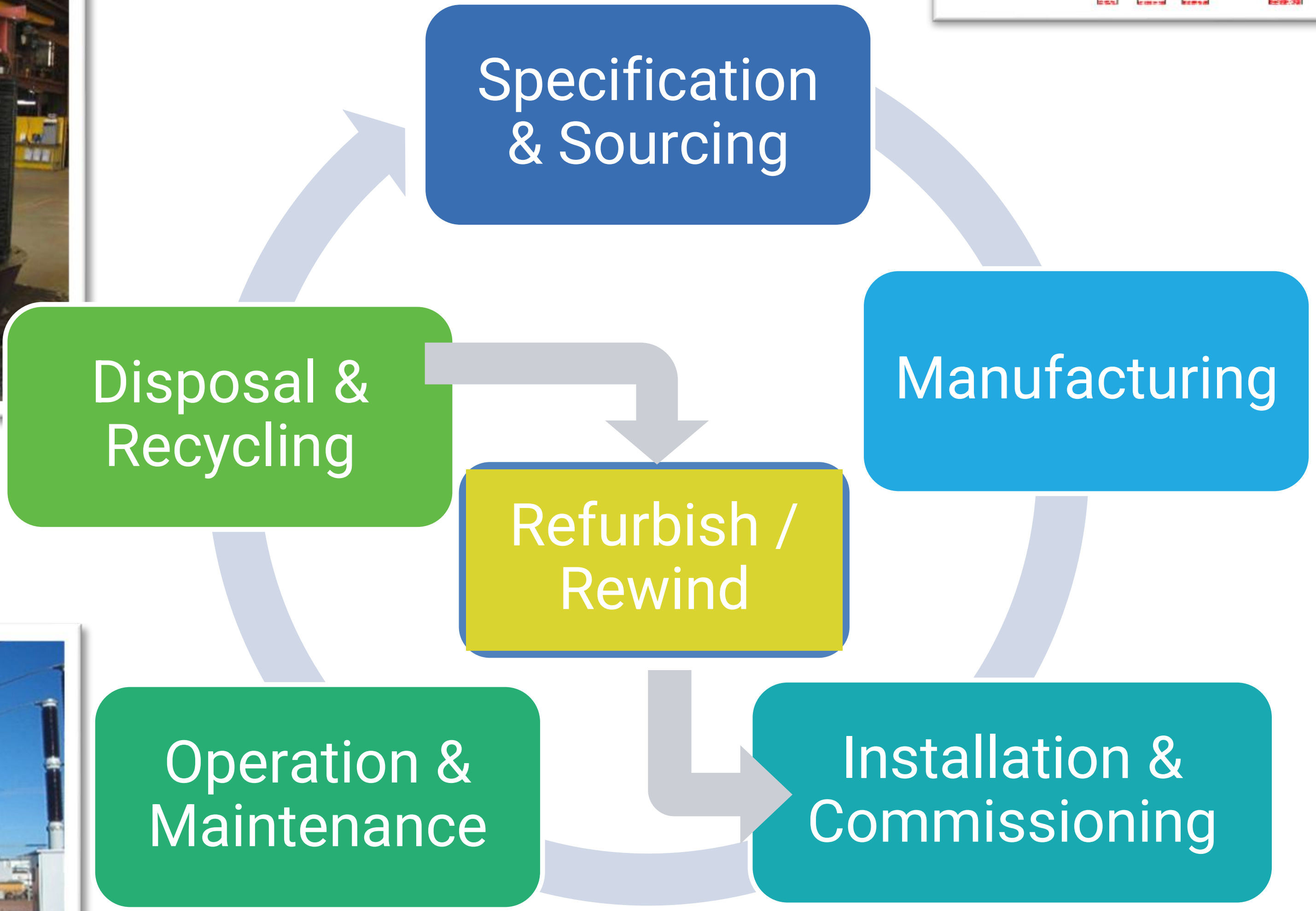
Some facts about mission-critical transformers

- They are inherently reliable
- They are ideally suited to condition monitoring / engineered maintenance approach
- They have finite lives
- Designed life **30+** Years

Transformer Lifecycle





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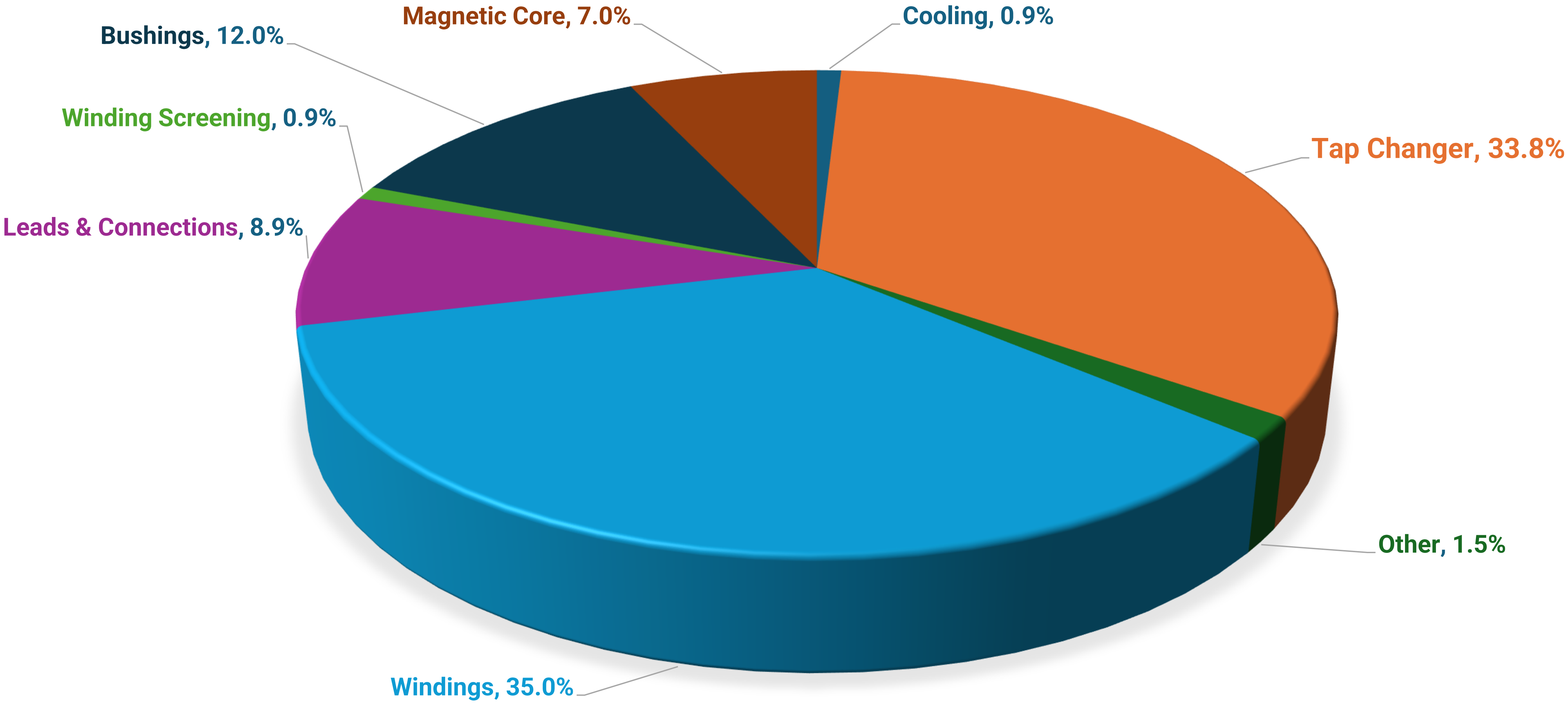
Oil filled transformer failure statistics



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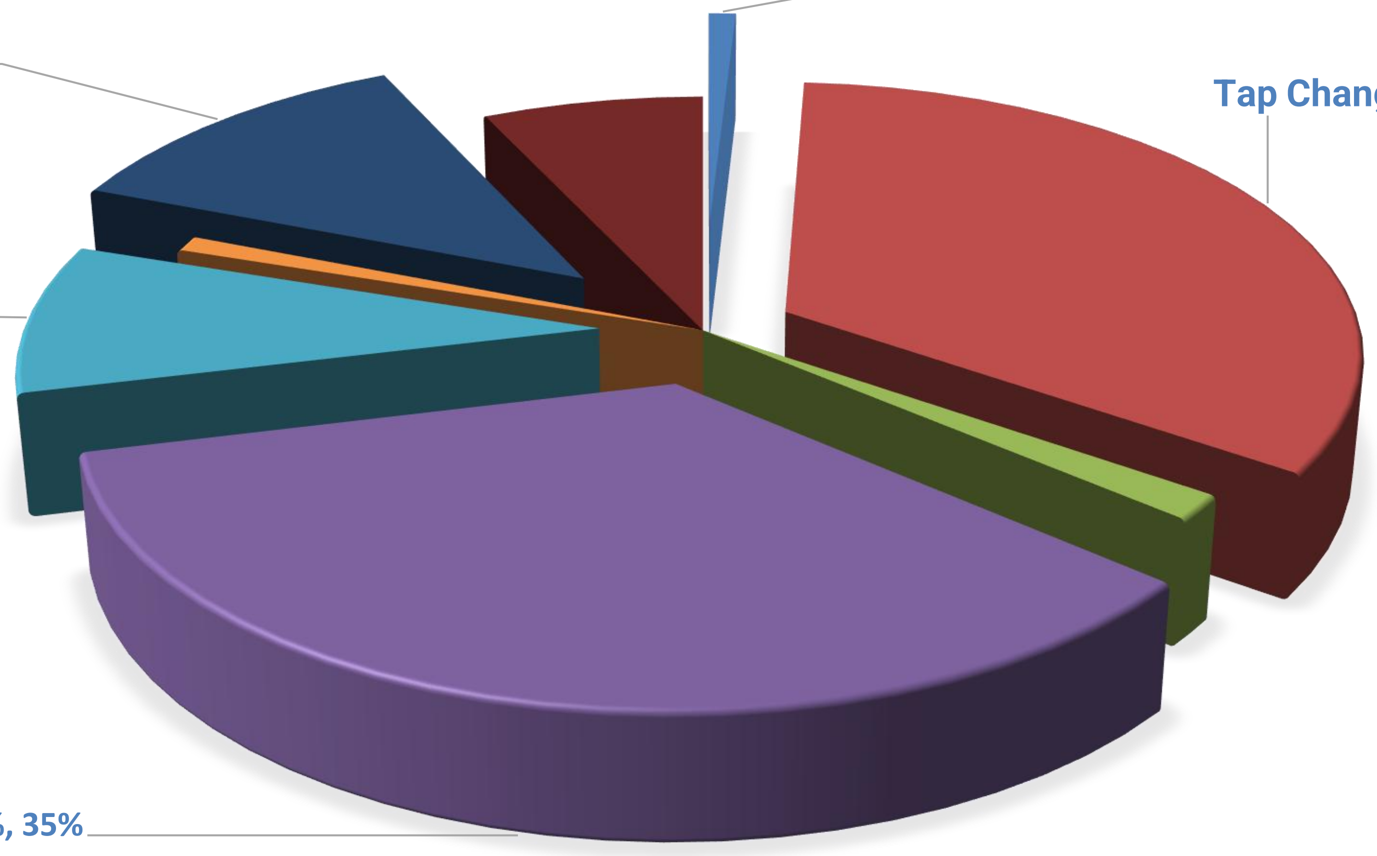
90% of failures are measurable and predictable



Source Machinemonitor® 2024

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"Why do so many critical transformers die early?"

If :

- inherently reliable,
- suited to condition monitoring,
- Maintainable, and
- have a finite design life.

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Winding Failure

Cause

- Insulation Quality
- Specification/ Design
- Preventative Maintenance ???

Tap Selector (Changer) Failure

Cause

- Oil Quality
- Loading
- Preventative Maintenance ???

Connection Failure

Cause

- OEM design
- Miss-Interpretation of Oil DGA results ???
- Preventative Maintenance ???

- Design Specification Fit for Purpose
- FAT SFRA and SAT as installed and every 5y
- Offline Tests (every 2-3y)
  - Ratio, Resistance, IR's, Tan Delta
- Online Testing
  - DGA, Oil Quality, PD
- Monthly Inspections

- Design Specification Fit for Purpose
- Dynamic Resistance (every 2-3y)
- Offline tests (every 2-3y)
  - Ratio, Resistance, IR's, Tan Delta
- Online Testing
  - DGA, Oil Quality, PD
- Monthly Inspections

- Design Specification Fit for Purpose
- DDF, Tan Delta (every 5y)
- Offline tests (every 2-3y)
  - Ratio, Resistance, IR's
- Online Testing
  - DGA, Oil Quality, PD
- Monthly Inspections

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How Can We Minimise Risk of Explosive Failures

🔧 Design & Construction

- Sealed or hermetically sealed units
- Flame-retardant fluids (natural esters oil)
- Pressure relief & explosion-resistant tanks
- Fire barriers

🛠 Preventive Maintenance

- Dissolved Gas Analysis (DGA)
- Moisture and insulation condition monitoring
- Offline Testing
- Thermal imaging for hotspots
- Partial discharge detection

⚠ Protection Systems

- Buchholz and sudden pressure relays
- High-speed fault isolation (breakers/relays)
- Real-time gas monitoring

🔥 Fire Protection & Suppression

- Fire detection & suppression (water spray, gas systems)
- Oil containment pits/bunds
- Site clearance & spacing

📋 Operational Best Practices

- Trained Competent Service Providers

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Mineral Oil vs. Ester Oil – Quick Comparison

Property	Mineral Oil	Ester Oil
Fire Safety	🔥 Low	🔥 🔥 High
Environmental Impact	❌ Poor	✅ Excellent
Moisture Tolerance	❌ Poor	✅ Excellent
Biodegradability	❌ Low	✅ High
Cost	💲 Low	💲 💲 Higher
Maintenance	🛠️ Frequent	🛠️ Less frequent

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Transformer Insulating Oils – Mineral Oil vs. Ester Oil

🛢️ Mineral Oil

- Petroleum-based, widely used
- Low flash point (~140°C) → higher fire risk
- Low biodegradability, environmentally harmful
- Sensitive to moisture → dielectric strength drops
- Lower cost, but requires frequent maintenance

🌱 Ester Oil (Natural/Synthetic)

- Plant-based or synthetic esters
- High flash point (~300°C) → safer operation
- Biodegradable, eco-friendly
- Handles moisture well, maintains dielectric strength
- Higher initial cost but lower lifecycle maintenance

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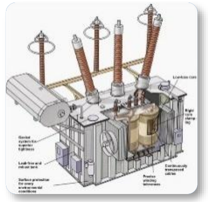
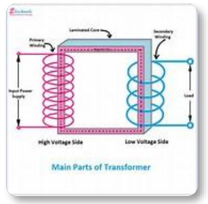
Preventative Maintenance Tests



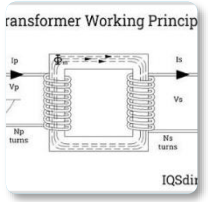
Capacitance and power factor/dissipation factor measurement



DC winding resistance measurement and OLTC verification

Transformer turns ratio (TTR) measurement

Dissolved gas chromatography analysis (DGA)
Physical and chemical oil tests



Excitation current measurement

Short-circuit impedance / leakage reactance measurement

Frequency response of stray losses

Dielectric (frequency) response analysis

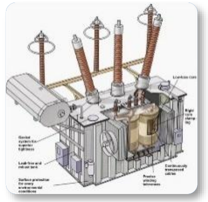
Sweep frequency response analysis (SFRA)

Partial discharge analysis & localisation

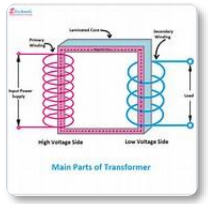
On-line partial discharge measurement & temporary monitoring

Online Inspections, Thermographic analysis

What are we testing for???



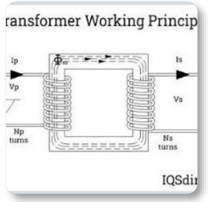
Determine insulation condition in bushings or between windings.



Determine bad connections, open circuits. Tap selector and bushing contact integrity

Detecting winding faults, short circuits, and insulation issues.

Dissolved gas chromatography analysis (DGA)
Physical and chemical oil tests



Turn-to-turn, inter-winding, winding-to-ground insulation quality

Determines impedance, leakage reactance, and power losses

Short-circuits between individual strands within a conductor bundle

Determine moisture content in solid insulation and conductivity of oil

Method for testing the mechanical integrity of transformer cores, windings, and clamping frames

Partial discharge trends over time

Continuous insulation condition in operation and under the influence of deteriorating forces

Identification, leaks, temps, pressure, rust, operating noise and plant identification

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Looking at 'Oil Quality' as a PM Process

Dissolved gas chromatography analysis (DGA)

Physical and chemical oil tests

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Oil Analysis Report

Most recent results

Data history

Transformer Details

Comments & diagnosis

Oil Quality Data

Oil Analysis Report

Report No.: OL8903	Date: 21/Dec[redacted]oup Ltd

Customer Details

Customer: Fortescue Metals Group Ltd Contact: Brendon Lord Email: brelord@fmgl.com.au

Asset Description

Asset Tag:	TF-469	Serial No.:	3000340227-1
Site:	Port Hedland	Area:	SR469
Power Rating:	2.00 MVA	Voltage:	22kV/0.40kV
Oil Volume:		Insulation Fluid:	Mineral Oil
Manufacturer:	ABB	Asset Class:	Power Transformer
Sampling Point:	Bottom Valve	Cooling: / YOM:	2014

TxAnalyser Assessment (This section is not part of the scope of NATA accreditation)

IEEE DGA Interpretation Guidelines (C57.104) (95th percentile)

	Guideline	Result
Hydrogen (PPM)	< 90	3776
Methane (PPM)	< 60	954
Ethane (PPM)	< 30	87
Ethylene (PPM)	< 80	1.5
Acetylene (PPM)	< 7	0.2
Carbon Monoxide (PPM)	< 600	123
Carbon Dioxide (PPM)	< 5000	2460
Total Gas Volume (%)		31.524

IEEE Oil Quality Interpretation Guidelines (C57.106)

	Guideline	Result	Statement of Conformity (For a transformer of this age and voltage class.)
Acidity (mgKOH/g)	< 0.2	0.01	Complies
Colour	< 3.5	<0.5	Complies
Water (PPM)	< 35	12	Complies
Interfacial Tension (mN/m)	> 25	36	Complies
Breakdown Voltage (Avg.kV)	> 40	65	Complies

Comments

This sample is classified as DGA Status 3. Hydrogen, Methane and Ethane gas levels are exceedingly elevated. Exercise extreme caution. Plan outage.

Diagnosis based on Gas Ratios:

CO2/CO ratio: Normal operation
Rogers: Normal deterioration.
IEC 60599 DGA Gas Ratios: T1 => Thermal fault (< 300 oC).

Assessment: Urgent

Next Sampling Date: 25/Jan/2023

TxAnalyser2.5

Additional interpretation of results are available on TxAnalyser Client Login

Assessment Code Legend
Acceptable: Asset is in a healthy/normal condition. The available data does not indicate an active fault mechanism.
Caution: Alert condition. There is an indication of an active fault mechanism in its early stages of development.
Urgent: Alarm condition. An active fault mechanism is highly likely and prompt attention to this asset is required.

Statements of conformity (e.g., Complies/Fails) to standard guidelines are made in this report without taking measurement uncertainty into account except when requested by the customer. Where statements of conformity are made in this report, the following decision rules are applied:
Complies – Results are within standard guidelines
Fails – Results are outside the standard guidelines

Oil Analysis Report

Report No.: OL8903	Date: 21/Dec/2022	[redacted]

Analysis Results (cont. on Page 5) Sample Identification: Latest sample taken by Client

		Sample Date	25/Oct/2022	29/Nov/2021	14/Oct/2020	22/Sep/2020	30/Aug/2019
		Analysis Date	20/Dec/2022	10/Jan/2022			
		Report Date	21/Dec/2022	12/Jan/2022			
		Temp °C *	40	35	36	26	22.00
		Laboratory	TxMonitor	TxMonitor	GE Energy Services	GE Energy Services	GE Energy Services
		Sample ID	OL8903-92	OL8680-21	T2011767	T2011065	T1910050
Dissolved Gas Analysis: ± denotes MU							
Method C - ppm at an STP of 0°C and 760 torr							
ASTM-D3612	Hydrogen (H_2)	PPM (±14)	3776	1220	4	4	8
ASTM-D3612	Methane (CH_4)	PPM (±13)	954	290	<0.5	<0.5	<0.5
ASTM-D3612	Ethylene (C_2H_4)	PPM (±15)	1.5	1.5	<0.5	<0.5	<0.5
ASTM-D3612	Ethane (C_2H_6)	PPM (±16)	87	24	<1	<1	<1
ASTM-D3612	Acetylene (C_2H_2)	PPM (±16)	0.2	<0.2	<0.2	<0.2	<0.2
ASTM-D3612	Carbon Monoxide (CO)	PPM (±272)	123	105	78	102	93
ASTM-D3612	Carbon Dioxide (CO_2)	PPM (±1992)	2460	1890	720	750	690
ASTM-D3612	Oxygen (O_2)	PPM (±294)	12,232	20,618	14,568	14,324	17,712
ASTM-D3612	Nitrogen (N_2)	PPM (±1105)	42,460	52,939	41,017	40,080	45,943
	TDCG	PPM	4,942	1,640	83	105	100
Oil Quality Tests: ± denotes MU							
ASTM-D974	Acidity	mgKOH/g (±0.01)	0.01	0.01	0.00	0.00	0.01
ASTM-D1500	Colour	-	<0.5	<0.5	<0.5	<0.5	<0.5
ASTM-D1533	Water Content	PPM (±6)	12	11	10	13	5
ASTM-D971	Interfacial Tension	mN/m (±6)	36	38	41	41	40
AS1767-2.1	Breakdown Voltage	Avg.kV (±13)	65	71	57	74	82
ASTM-D1524	Visual Examination	-	Clear & Bright	Clear & Bright	Clear	clear	clear
ASTM-D924	Power Factor @ 25°C*	% (±0.01)					
ASTM-D924	Power Factor @ 100°C*	% (±0.30)			0.01	0.01	0.02
	OQIN	-	1500	1500	1500	1500	1500
Furanic Compounds: ± denotes MU							
ASTM-D5837	5-HMF	PPB (±10)			<2	<2	<2
ASTM-D5837	2-FAL	PPB (±13)			<2	<2	<2
ASTM-D5837	2-FOL	PPB (±7)			<5	<5	<5
ASTM-D5837	2-ACF	PPB (±4)			8	8	<8
ASTM-D5837	5-M2F	PPB (±5)			<3	<3	<3
	Calculated D.P.	-			1000	1000	1000
	Calculated Remaining Life	%			100	100	100

Signatory:

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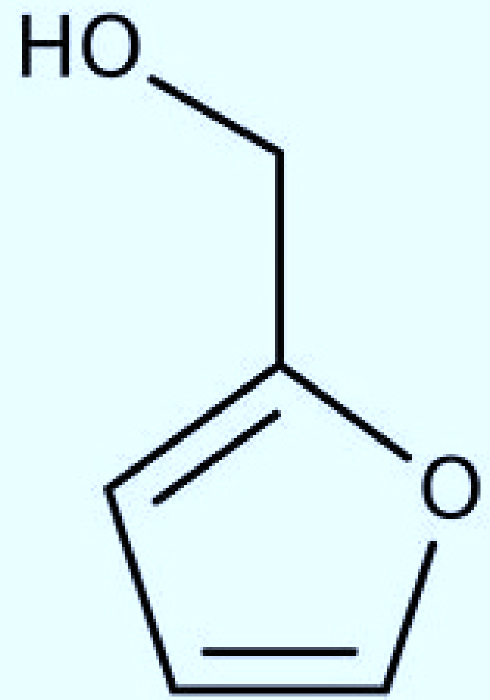
Focus on Furan Analysis

The ASTM lists 33 properties and 55 test methods in its D-117 standard.

- Gas-in-oil analysis by gas chromatography.
- Dielectric Rigidity.
- Humidity Content.
- Neutralization Number (or Acidity Level).
- Interfacial Tension.
- Color.
- Visual Inspection.
- Power Factor.



Furan Analysis derived from oil

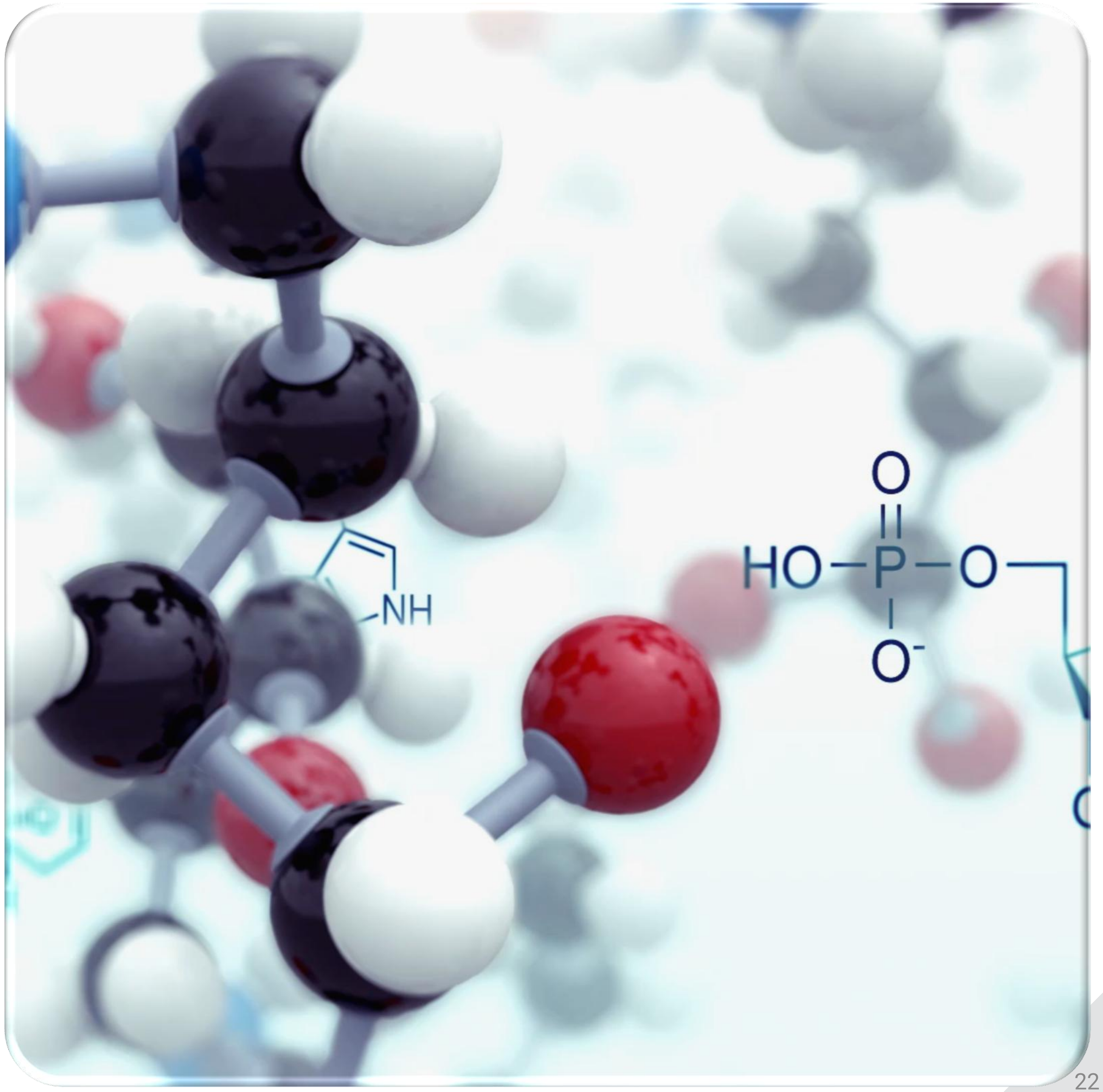
- Monitors **furanic compounds** dissolved in transformer oil.
- used for estimating remaining paCorrelation against laboratory degree of polymerisation.
- per Insulation life.

Purpose of Furan Analysis

- Detects degradation of **cellulose insulation** in oil-filled transformers.
- Monitors **furanic compounds** dissolved in transformer oil.

Key Furan Compounds Detected

- **2-Furfural (2-FAL) — Most indicative of paper degradation.**
- 5-Hydroxymethylfurfural (5-HMF)
- 2-Acetylfuran (2-ACF)
- 5-Methyl-2-furfural (5-MF)



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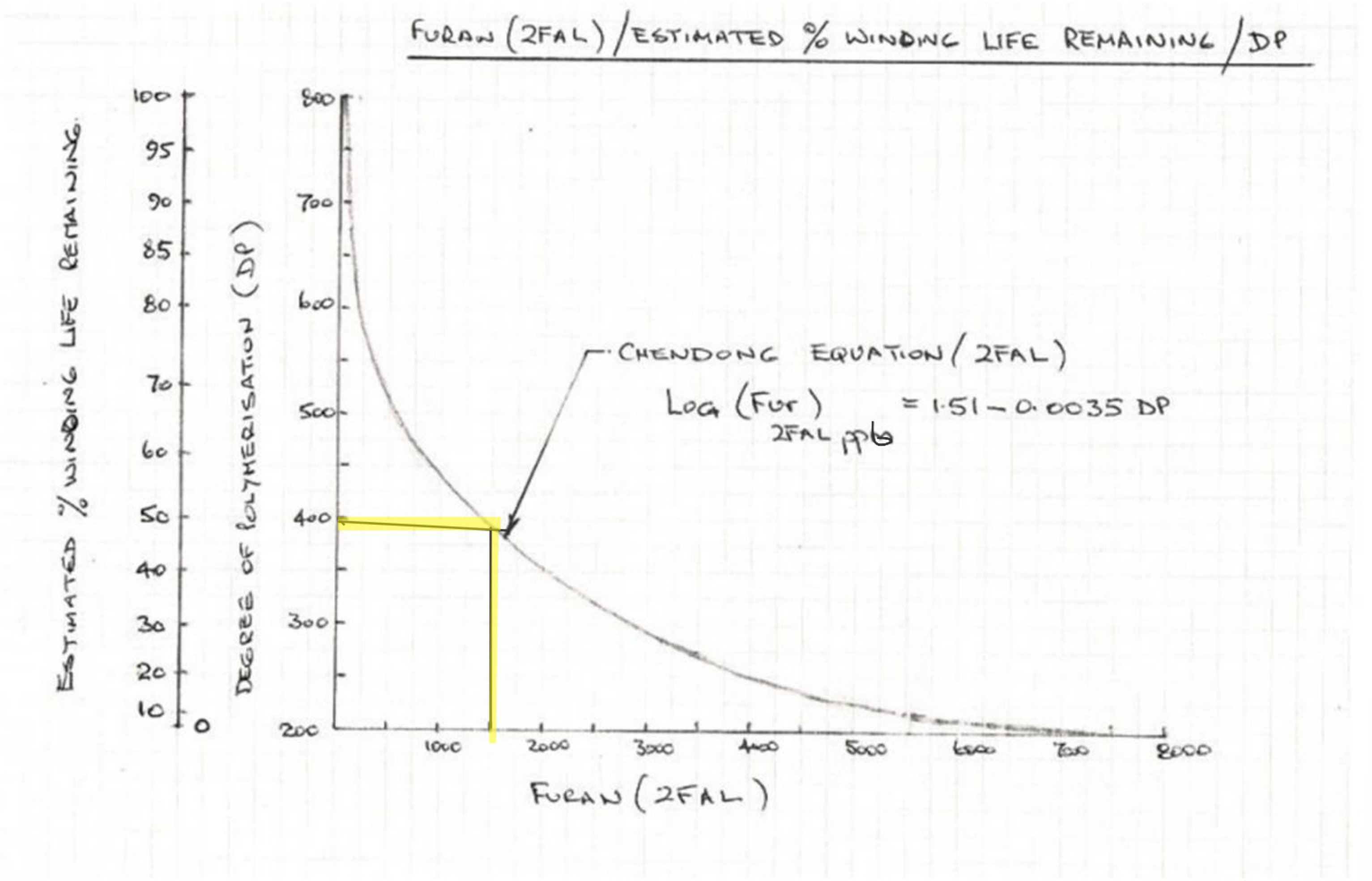
Furans Vs DP – Remaining Life



2FAL (ppb)	DP Value	Estimated percentage of remaining life	Suggested Interpretation
58	800	100	Normal Ageing Rate
130	700	90	
292	600	79	
654	500	66	Accelerated Ageing Rate
1464	400	50	
1720	380	46	
2021	360	42	
2374	340	38	Excessive Ageing Danger Zone
2789	320	33	
3277	300	29	
3851	280	24	High Risk of Failure
4524	260	19	
5315	240	13	End of expected life of paper Insulation and Transformer
6245	220	7	
7337	200	0	

Ideally testing for Furans only needs to be done bi-annually

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Interpretation of Results

2-FAL Concentration (ppb)	Insulation Condition
< 250	Good
250 – 1000	Moderate degradation
> 1000	Severe degradation

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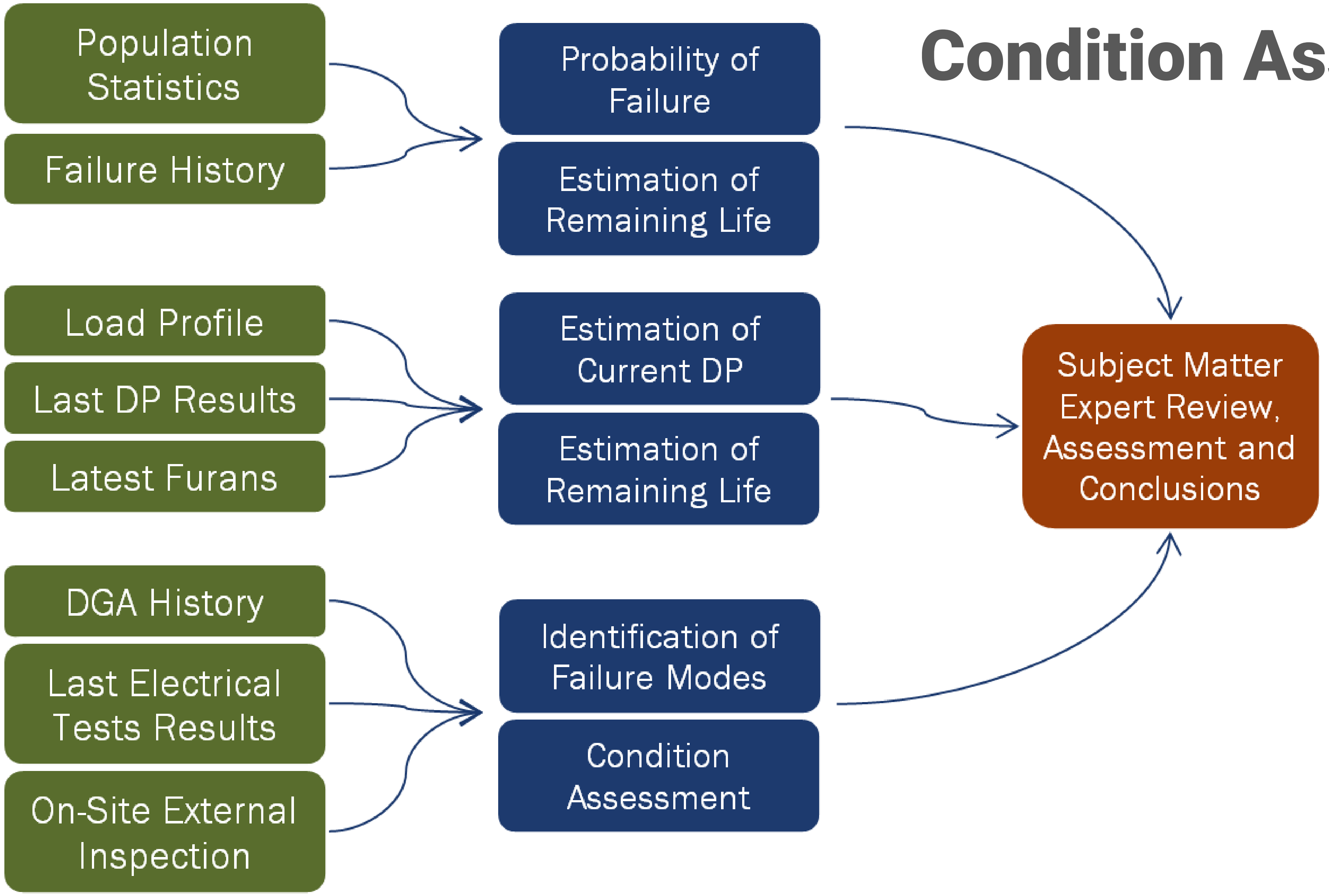
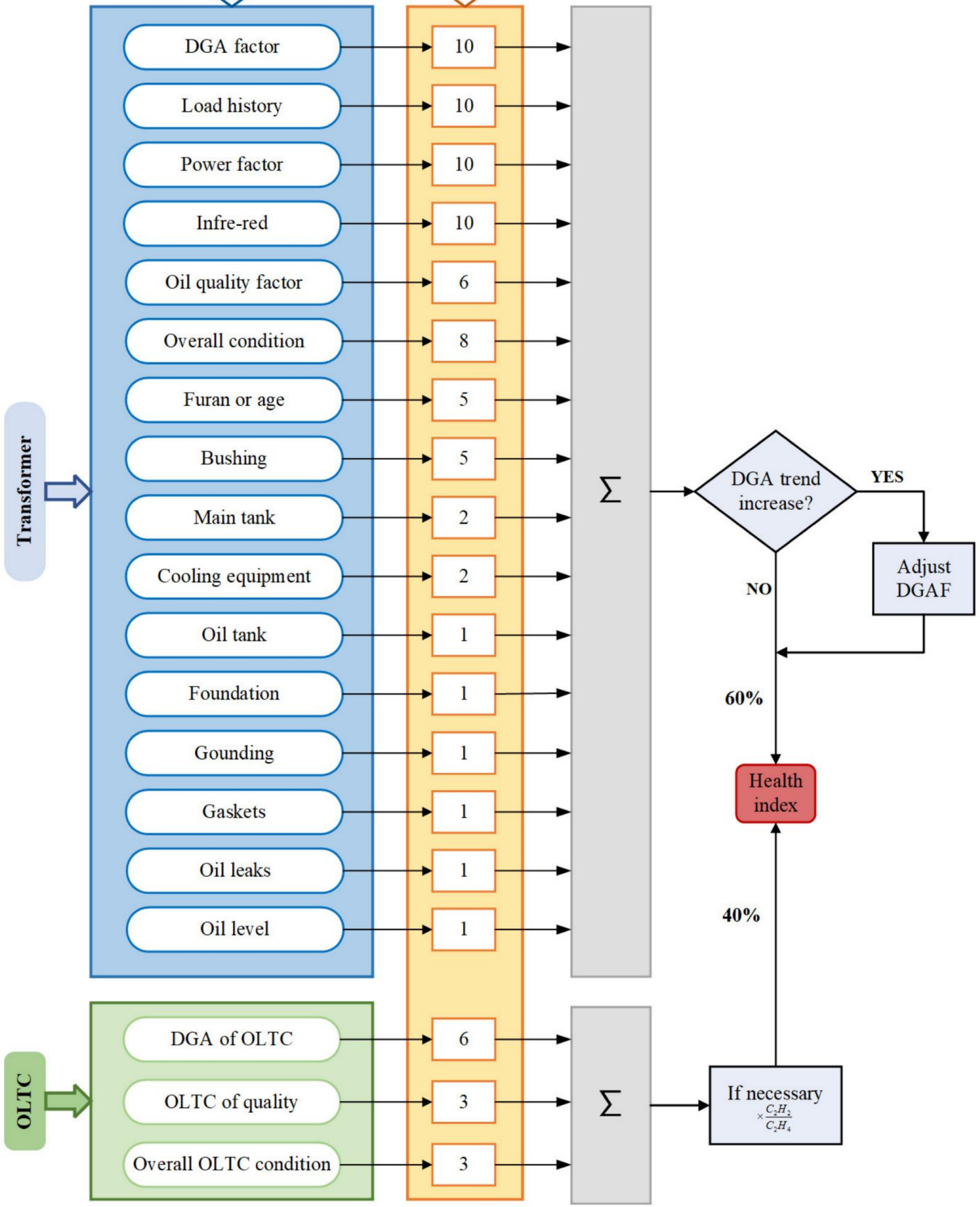
Condition Assessment Process



Create a 'Health Index'



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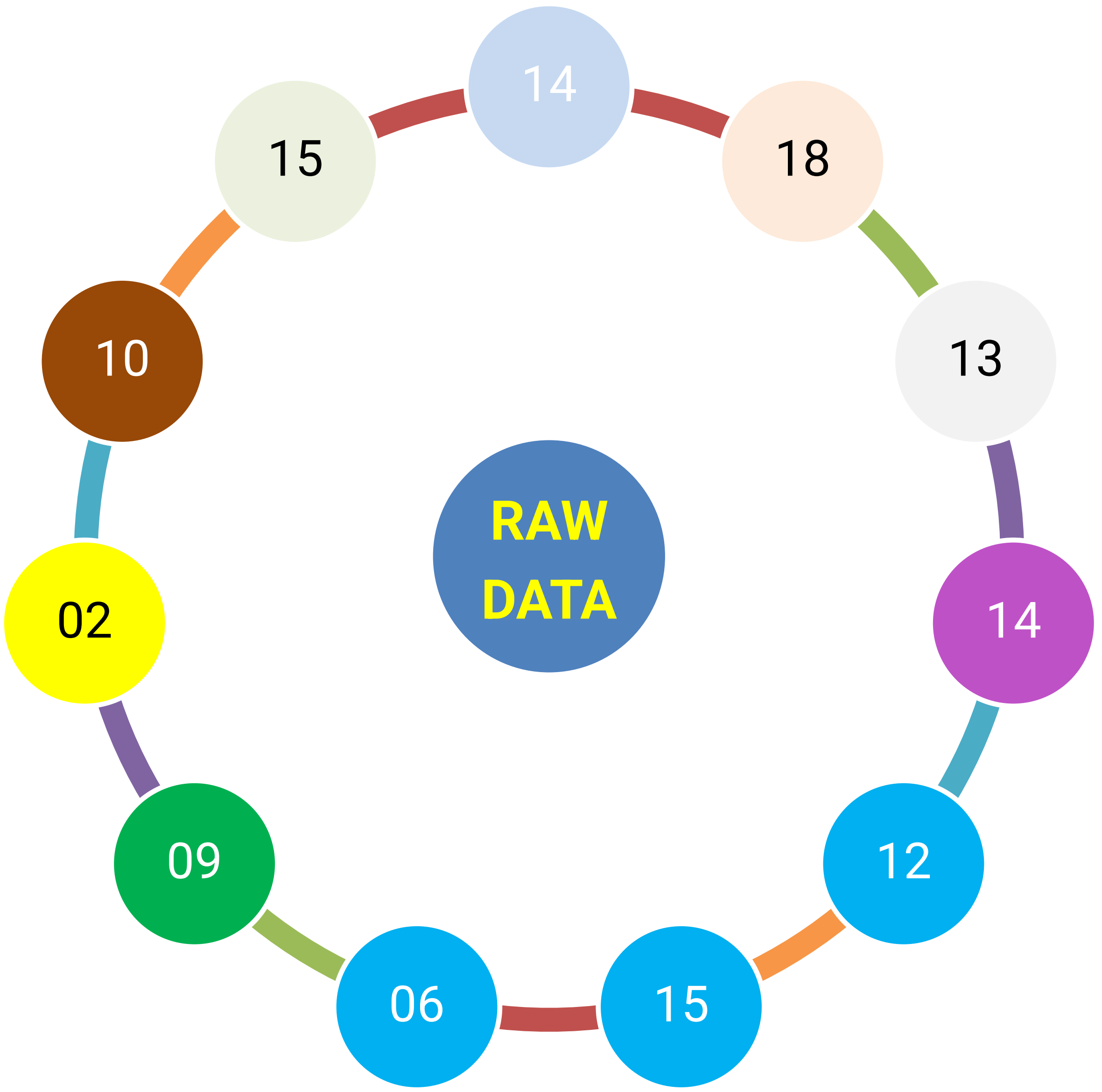
Transformer Component vs. Data Parameters

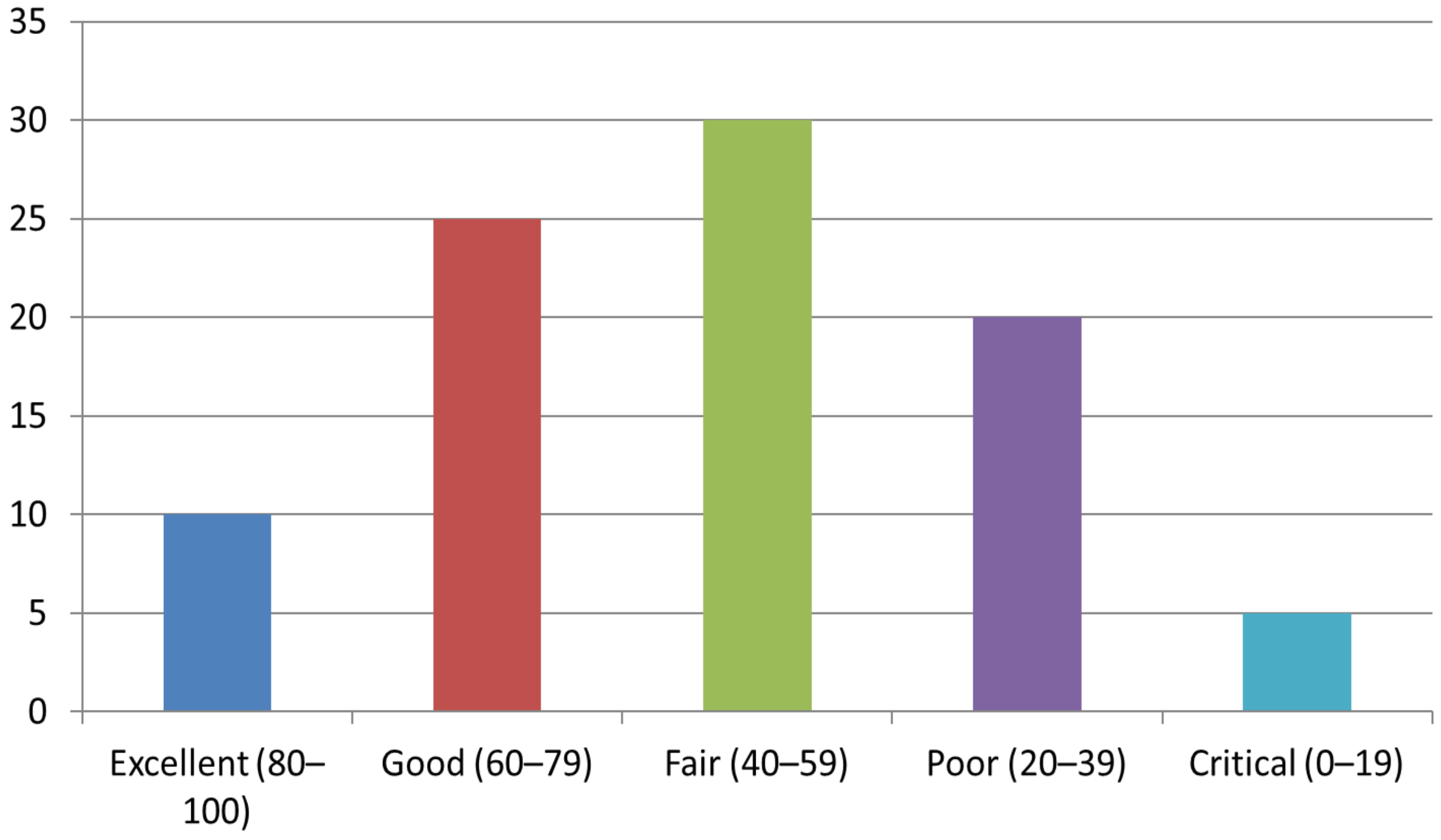
Thermal
Dielectric
Mechanical
Tap Changer
Bushing
Cable Boxes
Insulation Oil Quality - Bushing
Insulation Oil Quality - OLTC
Insulation Oil Quality - Main Tank
Oil DGA
Oil Furans
Electrical Testing



= Health Index Score

“The **Health Index** is not just a metric —

it’s an early warning tool before degradation turns into downtime.”



Transformer Health Index Classification Overview

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Health Indexing Cycle

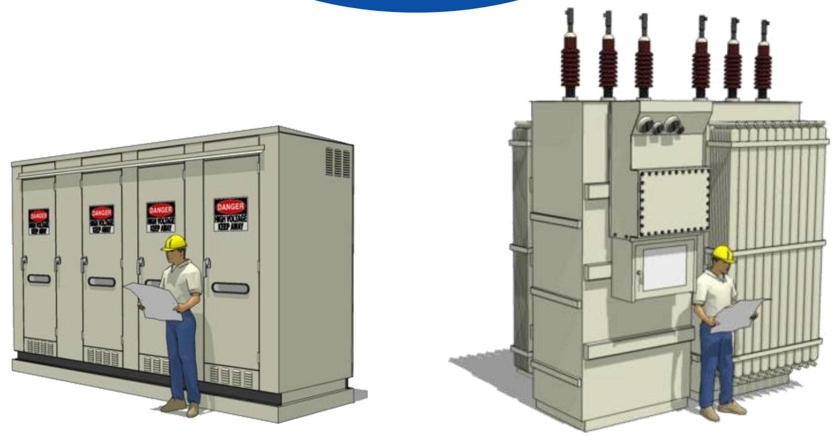
RAW DATA
- Physical Inspections
- Oil Tests: DGA
- Electrical Tests: PI, TAN-Δ, SFRA

Health Index Algorithms

CONDITION
- Individual and Fleet Conditions
- Consistent Ranking System

Risks and Priorities

MAINTENANCE ACTIONS
- Corrective Actions
- Planned Outage
- Refurbishment
- Replacement



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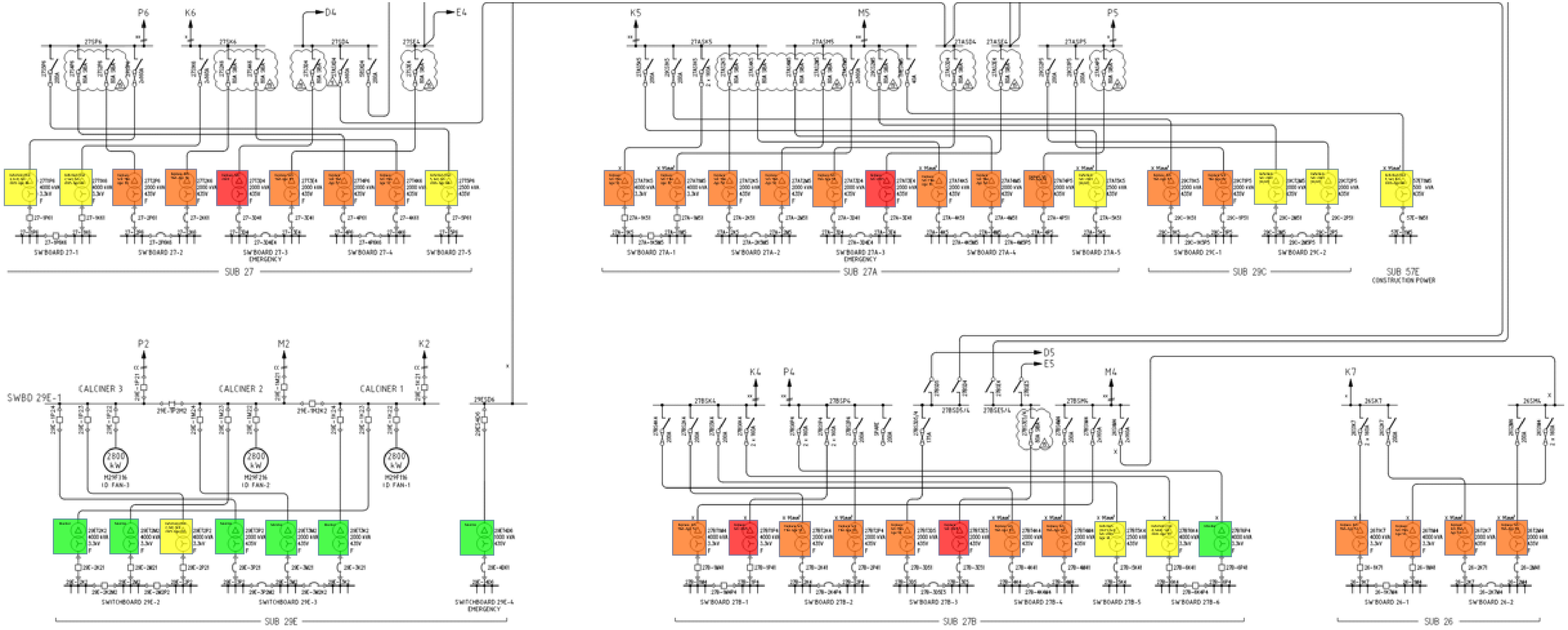
Health Indexing Visual > 60 Critical Transformers



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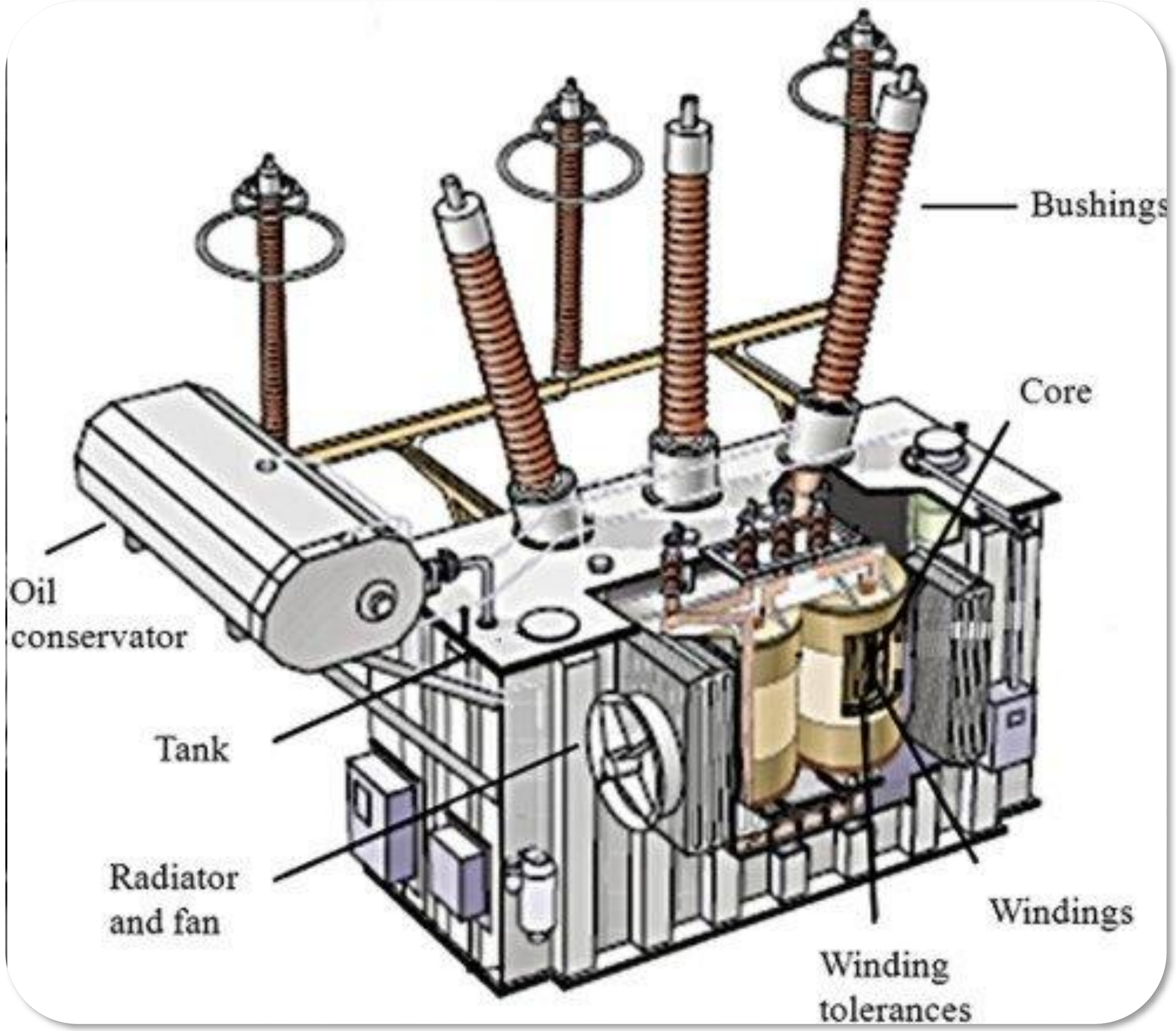
If Engineers and Asset Managers have extensive transformer conditions & algorithmic data at hand

Thermal
Mechanical
Bushing
Insulation Oil Quality
Insulation Oil Quality
Insulation Oil Quality
Oil DGA
Electrical Testing Data

Dielectric
Tap Changer
Cable Boxes
Bushing Condition
OLTC Condition
Main Tank
Oil Furans



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Why do critical transformers that are subject to rigid condition monitoring still catch fire and put the lights out?

Data interpretation lags: Monitoring systems detect symptoms, not root causes. Actionable insights often come too late.

Insufficient engineering diagnostic depth: Subject Mater Experts are becoming scarce. Transformer Design, Operating Conditions, Materials, the Understanding of Symptom Severity is a specialist field

Maintenance vs. Replacement bias: Asset Managers may delay intervention, relying too heavily on HI trending instead of proactive replacement.

Human and organizational factors: work fatigue, Operational Engineers to much going on to interrogate HI data.

Maintenance schedules and technician understanding.

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Challenges and Solutions

- *The condition of a transformer can be ranked to aid in the calculation of risk*
- *The probability of failure replaced with a condition score*
- *Condition score (asset health index) allows the consistent assignment of a number/ colour to the condition of each transformer*
- *Condition score used to track the asset's condition throughout its life*

"Will the use of Asset Health Indexing and Algorithmic Solutions take the eye further off the ball?"

"How do we as Engineers examine the actual Raw Data to decipher preventative decisions?"

"Will we further depend on AI algorithms to prevent Catastrophic Transformer Failures?"

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Thank You, questions?

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