Oil Analysis and Life Extension Considerations

Agenda
• DGA & Oil Quality
• Diagnostic Methods
  • Four Ratio Codes (Doernenburg)
  • Three Ratio Codes (Rogers)
  • Duval Triangle
  • Key Gas Interpretation
  • IEEE Guide
• Sampling Methods
• Oil Preservation Systems
• Condition Assessment
• Inspections
• Components

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Dissolved Gas Analysis – Why Important??

- Transport, installation and intrusive maintenance can damage or compromise a transformer’s electrical insulation system

- In service, transformers are subject to thermal, mechanical and electrical stresses that can cause deterioration and break down solid and liquid insulation

- The degradation of the electrical insulation system generates gases that are characteristics of the material and temperatures involved

- The analysis of types of gas, their concentrations, and the rates of generation can be used to determine the condition of the transformer and plans for maintenance, reconditioning, or replacement.
Transformer Oil Preservation Systems

Sealed System

Inertaire System

Conservator System
Dissolved Gas Analysis – Collection Point

- **Gas blanket or gas accumulation relay**
  - The gas concentration and ratios are different in the gas space than in the oil based at different temperatures and relative solubility in the oil.
  - Gas space concentrations must be converted to oil concentrations before diagnostic techniques can be applied.
  - Gases generated in the oil take time to partition into the gas space and achieve equilibrium, which can delay detection of a problem.

- **Bulk Oil Collection (sample valve)**
  - It does not require a gas blanket and is effective on all mineral oil filled transformer designs.
  - Reasonable equilibrium is required to collect all gases but occurs more quickly in oil than in the gas space.
## Safe Handling Limits

### LEL Limits for Single Gases

<table>
<thead>
<tr>
<th>GAS</th>
<th>LEL in Air, %</th>
<th>ppm in air</th>
<th>ppm in oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>4.00</td>
<td>40,000</td>
<td>2,232</td>
</tr>
<tr>
<td>Methane</td>
<td>5.00</td>
<td>50,000</td>
<td>23,214</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>12.50</td>
<td>125,00</td>
<td>16,625</td>
</tr>
<tr>
<td>Ethane</td>
<td>3.00</td>
<td>30,00</td>
<td>77,700</td>
</tr>
<tr>
<td>Ethylene</td>
<td>2.75</td>
<td>27,500</td>
<td>54,560</td>
</tr>
<tr>
<td>Acetylene</td>
<td>2.50</td>
<td>25,000</td>
<td>30,500</td>
</tr>
</tbody>
</table>

*Source: Doble Engineering*
Extraction of samples are critical to accurate analysis:

- Verify positive head pressure at sample location
- Flush sample location, sampling lines, and collection syringe to get representative sample
- Use new sampling lines for each compartment or piece of equipment
- Verify use of clean, dry and sealed sampling devices required
- Remove all air from sample vessel
- Typically 30 mL samples are required for analysis
- Do not utilize plated or galvanized fittings
Dissolved Gas Analysis

It is possible to diagnose the type of transformer faults with analysis techniques such as:

- Ratio Codes
  - Doernenburg Ratios
  - Rogers Ratios/Three Ratio Code
  - Duval Triangle
- Key Gas Standards
- IEEE Guidelines
Dissolved gas concentrations should exceed the IEEE Condition 1 values when utilizing this analysis technique.

If ratios do not fit within the values given for the diagnostic code, other analytical methods should be considered.
Dissolved Gas Analysis

Rogers Ratio Codes

<table>
<thead>
<tr>
<th>Rogers Ratios</th>
<th>Acetylene ($C_2H_2$)</th>
<th>Methane ($CH_4$)</th>
<th>Ethylene ($C_2H_4$)</th>
<th>Hydrogen ($H_2$)</th>
<th>Ethane ($C_2H_6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 0.1</td>
<td>&gt; 0.1 - &lt; 1.0</td>
<td>&lt; 0.1</td>
<td>0.1 - 3.0</td>
<td>0.1 - 1.0</td>
</tr>
<tr>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial Discharge</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>1.0 - 3.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Arcing</td>
<td>0.1 - 3.0</td>
<td>0.1 - 1.0</td>
<td>&gt; 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slight Thermal Fault</td>
<td>&lt; 0.1</td>
<td>&gt; 0.1 - &lt; 1.0</td>
<td>1.0 - 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Fault &lt;700C</td>
<td>&lt; 0.1</td>
<td>&gt; 1.0</td>
<td>1.0 - 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Fault &gt;700C</td>
<td>&lt; 0.1</td>
<td>&gt; 1.0</td>
<td>&gt; 3.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If ratios do not fit within the values given for the diagnostic code, other analytical methods should be considered.
Dissolved Gas Analysis

Duval Triangle

- Evaluates three gases – Methane (CH\textsubscript{4}), Ethylene (C\textsubscript{2}H\textsubscript{4}), and Acetylene (C\textsubscript{2}H\textsubscript{2}) – as a percentage of the sum of the three gases
- Seven diagnostic triangles exist based upon type of fluid being analyzed and the type of oil compartment

<table>
<thead>
<tr>
<th>Fault Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>Partial discharge</td>
</tr>
<tr>
<td>T1</td>
<td>Low-range thermal fault (below 300 C)</td>
</tr>
<tr>
<td>T2</td>
<td>Medium-range thermal fault (300-700 C)</td>
</tr>
<tr>
<td>T3</td>
<td>High-range thermal fault (above 700 C)</td>
</tr>
<tr>
<td>D1</td>
<td>Low-energy electrical discharge</td>
</tr>
<tr>
<td>D2</td>
<td>High-energy electrical discharge</td>
</tr>
<tr>
<td>DT</td>
<td>Indeterminate - thermal fault or electrical discharge.</td>
</tr>
</tbody>
</table>
Dissolved Gas Analysis – Duval Triangle

**FAULT CODES**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>Partial discharge</td>
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<td>T1</td>
<td>Low-range thermal fault (below 300 C)</td>
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<td>T3</td>
<td>High-range thermal fault (above 700 C)</td>
</tr>
<tr>
<td>D1</td>
<td>Low-energy electrical discharge</td>
</tr>
<tr>
<td>D2</td>
<td>High-energy electrical discharge</td>
</tr>
<tr>
<td>DT</td>
<td>Indeterminate - thermal fault or electrical discharge.</td>
</tr>
</tbody>
</table>
**Key gas interpretation**

Each “key” gas is identified with a certain type of fault

<table>
<thead>
<tr>
<th>Fault Pattern</th>
<th>Key Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Overheating</td>
<td>CO/CO₂ (Carbon Oxides)</td>
</tr>
<tr>
<td>Oil Overheating</td>
<td>C₂H₄ (Ethylene)</td>
</tr>
<tr>
<td>Partial Discharge</td>
<td>H₂ (Hydrogen)</td>
</tr>
<tr>
<td>Arcing</td>
<td>C₂H₂ (Acetylene)</td>
</tr>
</tbody>
</table>

- The “key” gas is frequently the predominant gas
- Occasionally another gas could be in high concentration
- Variations are possible because, over a wide range of temperatures
- Each gas attains a maximum generation rate at a certain temperature
- Depending on the temperature at the fault site, one of the other gasses may be in larger proportion
### Gas Generation Temperatures

#### Dominant Gas Can indicate Type of Fault

<table>
<thead>
<tr>
<th>Dominant Gas</th>
<th>Fault Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (H2)</td>
<td>&gt; 150 C</td>
</tr>
<tr>
<td>Methane (CH4)</td>
<td>&gt;150 C</td>
</tr>
<tr>
<td>Ethane (C2H6)</td>
<td>&gt;250 C</td>
</tr>
<tr>
<td>Ethylene (C2H4)</td>
<td>&gt;350 C</td>
</tr>
<tr>
<td>Acetylene (C2H2)</td>
<td>&gt;500 C</td>
</tr>
</tbody>
</table>

**Combustible Gas Generation vs. Approximate Oil Decomposition Temperature**

**Source:** R.R. Rogers

**Combustible Gas Generation Versus Temperature.**
Dissolved Gas Analysis

- Thermal – Cellulose

Large quantities of carbon dioxide and carbon monoxide are evolved from overheated cellulose (temperatures >110°C). Hydrocarbon gases, such as methane and ethylene, will be formed if the fault involves an oil-impregnated structure.

- Principle Gas: Carbon Monoxide

- Water is often a by-product of the thermal decomposition.
Dissolved Gas Analysis

- Thermal – Oil

Decomposition products include ethylene and methane, together with smaller quantities of hydrogen and ethane. Traces of acetylene may be formed if the fault is severe or involves electrical contacts.

- Principle Gas – Ethylene
Dissolved Gas Analysis

- Electrical – Partial Discharge
  Low energy electrical discharges produce hydrogen and methane, with small quantities of ethane and ethylene. Comparable amounts of carbon monoxide and carbon dioxide may result from discharges in cellulose.

- Principle Gas – Hydrogen
Dissolved Gas Analysis

- Electrical – Arcing
  Large amounts of hydrogen and acetylene are produce, with minor quantities of methane and ethylene. Carbon dioxide and Carbon monoxide may also be formed if the fault involves cellulose. Oil may be carbonized.

- Principle Gas – Acetylene
### Dissolved Gas Analysis

#### IEEE Guide for Interpretation of Gasses C57.104.2008

<table>
<thead>
<tr>
<th>Condition</th>
<th>Dissolved Key Gas Concentration Limits (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H₂</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>101 - 700</td>
</tr>
<tr>
<td>3</td>
<td>701 - 1,800</td>
</tr>
<tr>
<td>4</td>
<td>&gt;1,800</td>
</tr>
</tbody>
</table>

**Condition 1:** TDCG below this level indicates satisfactory operation. Any individual combustible gas exceeding specified levels should prompt additional investigation.

**Condition 2:** TDCG within this range indicates greater than normal combustible gas level. Any individual combustible gas exceeding specified levels should prompt additional investigation. Action should be taken to establish a trend. Fault(s) may be present.

**Condition 3:** TDCG within this range indicates a high level of decomposition. Any individual combustible gas exceeding specified levels should prompt additional investigation. Immediate action should be taken to establish a trend. Fault(s) are probably present.

**Condition 4:** TDCG within this range indicates excessive decomposition. Continued operation could result in failure of the transformer.
## IEEE Guide for Interpretation of Gasses C57.104-2008

<table>
<thead>
<tr>
<th>Condition</th>
<th>TDCG (ppm)</th>
<th>TDCG Rate (ppm/day)</th>
<th>Sampling Interval</th>
<th>Operating Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>&gt;4630</td>
<td>&gt;30</td>
<td>daily</td>
<td>Consider removal from service. Advise manufacturer.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;10</td>
<td>weekly</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 - 30</td>
<td>weekly</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;10</td>
<td>monthly</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 - 30</td>
<td>monthly</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;10</td>
<td>quarterly</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>&lt;=720</td>
<td>&gt;30</td>
<td>monthly</td>
<td>Exercise caution. Analyze for individual gases. Determine load dependence.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 - 30</td>
<td>quarterly</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;10</td>
<td>annually</td>
<td>Continue normal operation.</td>
</tr>
</tbody>
</table>
Important Reminders for Dissolved Gas Analysis

The effectiveness of Dissolved Gas Analysis and of the interpretation of these analyses can be limited by:

- Sampling technique
- Testing – Low precision and repeatability between labs.
- Transformer’s size and oil volume can distort the significance of gas concentration and generation rates.
- Temperature gradient in the active area can produce multiple source symptoms
- Stratification of the oil in the transformer can delay response to an incipient fault
- Lack of trend data
- Residual gas from past events
- Insufficient gas concentration to use ratio analysis
Corrective Measures

• Generated gasses can be removed through degasification process.
• Source of the gassing must be identified and remedied to prevent recurrence of undesired gas generation.
• Important:
  • Degasification will interrupt trend analysis, creating new baseline.
  • Not all oil characteristics can be improved by degasification alone (i.e. IFT)
Degasification of oil is required when elevated levels of dissolved gas concentrations are observed...

- TDCG Concentrations Approaches IEEE Category 4 (4630 PPM)
- TDGC Approaches Solubility Limits for Sealed Systems
- Process Can Be Done on Line or off Line
- Degasification by Recirculation May Not Remove All Gases From Insulation
- Most degasification units incorporate moisture removal means within system

*Leaching of residual gasses (up to 10% of previous values) may occur post processing*
Case Study #1

- 300 MVA
- 345/115kV
- Autotransformer
- 1972 (Recently Remanufactured)
- 15,500 gallons of oil

<table>
<thead>
<tr>
<th>Test Date</th>
<th>Hydrogen (H2)</th>
<th>Methane (CH4)</th>
<th>Ethane (C2H6)</th>
<th>Ethylene (C2H4)</th>
<th>Acetylene (C2H2)</th>
<th>Carbon Monoxide (CO)</th>
<th>Carbon Dioxide (CO2)</th>
<th>Total Combustible Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/11/2013</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>1/11/2013</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>56</td>
<td>15</td>
</tr>
<tr>
<td>1/12/2013</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>39</td>
<td>14</td>
</tr>
<tr>
<td>1/12/2013</td>
<td>12</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>36</td>
<td>22</td>
</tr>
<tr>
<td>1/13/2013</td>
<td>23</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>18</td>
<td>61</td>
<td>49</td>
</tr>
</tbody>
</table>
Case Study #1

Found ungrounded CT circuit upon energization of transformer.
Case Study #2

- 175 MVA
- 345/115kV
- 11,848 gallons of oil

Recently performed Bushing Retrofit
2007 Vintage Unit

<table>
<thead>
<tr>
<th>Dissolved Gas Analysis (DGA)</th>
<th>Hydrogen (H2) (µL/L)</th>
<th>Methane (CH4) (µL/L)</th>
<th>Ethane (C2H6) (µL/L)</th>
<th>Ethylene (C2H4) (µL/L)</th>
<th>Acetylene (C2H2) (µL/L)</th>
<th>Carbon Monoxide (CO) (µL/L)</th>
<th>Carbon Dioxide (CO2) (µL/L)</th>
<th>Nitrogen (N2) (µL/L)</th>
<th>Oxygen (O2) (µL/L)</th>
<th>Total Dissolved Gas (TDG) (µL/L)</th>
<th>Total Dissolved Combustible Gas (TDCG) (µL/L)</th>
<th>Equivalent TCG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Control Number:</td>
<td>7112700</td>
<td>556454</td>
<td>558454</td>
<td>556471</td>
<td>551421</td>
<td>5590164</td>
<td>70900164</td>
<td>548310</td>
<td>19325</td>
<td>23154</td>
<td>20995</td>
<td>16779</td>
</tr>
<tr>
<td>Date Sampled:</td>
<td>03/14/2018</td>
<td>02/09/2018</td>
<td>01/25/2018</td>
<td>12/08/2017</td>
<td>10/21/2017</td>
<td>01/12/2018</td>
<td>03/24/2018</td>
<td>05/06/2018</td>
<td>07/10/2018</td>
<td>10/21/2018</td>
<td>01/12/2018</td>
<td>03/24/2018</td>
</tr>
<tr>
<td>Order Number:</td>
<td>77102543</td>
<td>558454</td>
<td>556471</td>
<td>551421</td>
<td>5590164</td>
<td>70900164</td>
<td>70900164</td>
<td>548310</td>
<td>19325</td>
<td>23154</td>
<td>20995</td>
<td>16779</td>
</tr>
<tr>
<td>Oil Temp:</td>
<td>26</td>
<td>49</td>
<td>60</td>
<td>33</td>
<td>27</td>
<td>26</td>
<td>26</td>
<td>49</td>
<td>60</td>
<td>33</td>
<td>27</td>
<td>26</td>
</tr>
</tbody>
</table>

DGA Keys Gas / Interpretive Method: PER IEEE C57.104-2008
(2007 most recent sample)
- Hydrogen: Condition 3 indications of significant partial discharge activity (700 µL/L).
- Methane within condition 1 limits (120 µL/L).
- Ethane within condition 1 limits (65 µL/L).
- Ethylene within condition 1 limits (50 µL/L).
- Acetylene within condition 1 limits (1 µL/L).
- Carbon Monoxide within condition 1 limits (350 µL/L).
- Carbon Dioxide within condition 1 limits (2500 µL/L).
- TDCG: Condition 2 Levels exceed normal concentrations. Fault may be present (720 µL/L).

DGA TDCG Rate Interpretive Method: PER IEEE C57.104-2008
(2007 most recent sample)

DGA Cellulose (Paper) Insulation: CO2/CO Ratio is only applicable when CO2 greater than 5000 and CO greater than 500.
Case Study #2

- Increasing H2 trend
- Only significant increase H2

- Duval Pentagon suggests PD activity
- Next Steps / Options:
  - Acoustical Analysis
  - Internal Inspection
  - Field Plots
Case Study #2

- Acoustical Analysis performed to identify phase/location generation of PD

*The below screen shot is inserted here as an example of PD.* This transformer was in service and had an 1896 ppm H2 in the DGA.
Case Study #2

- Internal Inspection performed and clearances obtained/measured
- Field Plot generated to identify source

- Utilizing Acoustical Report for locating source, paired with field plot data analyzing local stress levels, source of the PD was able to be determined and remedied
Transformer Life Extension Considerations

• Condition Assessment Ranking Method
• Assessment Condition
  • Visual inspection
  • Electrical Evaluation
  • Oil Analysis
  • Thermal Aging
  • Internal Inspection
  • Components

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May 9, 2019
3 Biggest Enemies of a Transformer

- Heat
- Water
- Oxygen
Assessing and extending the functional life of the transformer involves many activities:

- **Control Of Aging Factors**
  - Oil Quality
  - Cooling
  - Oil Preservation System
- **Clamping System Review**
- **Component Inspection & Testing**
Reactive vs. Proactive

- Take action due to failure
- Take action to prevent failure
Condition Assessment Methodology

Figure 1. Transformer Condition Assessment Methodology

Tier 1 Inspections, Tests, and Measurements
- Oil, Power Factor & Excitation, Routine O&M, Age

Problem?
- YES*
  - Repair, Rehab, Relocate

Problem
- NO
  - Transformer Tripped or Malfunctioned

Tier 2 Tests Below
- Shorted Winding
- Core / Winding Deformation
- Bad Ground Connection & Unintentional Ground
- TC Contacts, Broken Strands, Loose Connections
- Internal Partial Discharge, Arcing, Sparking
- Mechanical Problems
- Nitrogen Leaks
- Core Shield Problems, Loose Parts
- Shifted Windings
- Insulation Condition

TURNS Ratio Test
Short Circuit Impedance (Leakage Reactance)
Core to Ground Resistance Test
Winding DC Resistance Measurements
Ultrasonic & Sonic Contact Fault Detection
Ultrasonic Non-Contact Fault Detection
Vibration Analysis
Frequency Response
Degree of Polymerization

Results of Inspections, Tests, and Measurements are Quantified as Condition Indicators Used to Arrive at a Transformer Condition Factor.

* Severe problems may warrant immediate de-energization.

Return to Routine Inspection & Testing

Problem
NO
YES
Replace Transformer

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Condition Assessment

Level 1
- Routine tests, visual inspections
- No outage Required

Level 2
- More detailed investigations, laboratory analysis
- Outage Required/Non-invasive

Level 3
- Highly sophisticated measurement and analysis techniques
- Outage Required/Invasive
## Condition Assessment – Level 1

### Level I - Base Line (Non Intrusive)

<table>
<thead>
<tr>
<th>Visual</th>
<th>Oil Leaks / Oil Levels / Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Tank</td>
</tr>
<tr>
<td></td>
<td>LTC Tank</td>
</tr>
<tr>
<td></td>
<td>LTC Filtration System</td>
</tr>
<tr>
<td></td>
<td>Coolers / Radiators &amp; Piping</td>
</tr>
<tr>
<td></td>
<td>Conservator</td>
</tr>
<tr>
<td></td>
<td>Bushings</td>
</tr>
<tr>
<td></td>
<td><strong>Temperatures (Current Min / Max)</strong></td>
</tr>
<tr>
<td></td>
<td>Winding</td>
</tr>
<tr>
<td></td>
<td>Top oil</td>
</tr>
<tr>
<td></td>
<td><strong>Load Tap Changer</strong></td>
</tr>
<tr>
<td></td>
<td>Position (Min Max)</td>
</tr>
<tr>
<td></td>
<td>Position Indicator Functional</td>
</tr>
<tr>
<td></td>
<td>Operation Counter -read &amp; verify operating</td>
</tr>
<tr>
<td></td>
<td>Oil Filtration System - differential pressure</td>
</tr>
<tr>
<td></td>
<td><strong>Control Box</strong></td>
</tr>
<tr>
<td></td>
<td>Heaters</td>
</tr>
<tr>
<td></td>
<td>Moisture / Oil Leaking into cabinet</td>
</tr>
<tr>
<td></td>
<td>Corrosion</td>
</tr>
<tr>
<td></td>
<td>Cooling Controls Functional</td>
</tr>
<tr>
<td></td>
<td>LTC Controls Functional</td>
</tr>
<tr>
<td></td>
<td>LTC Filtration Sys Functional</td>
</tr>
<tr>
<td></td>
<td>Wiring / terminal blocks condition</td>
</tr>
<tr>
<td></td>
<td><strong>Accessories</strong></td>
</tr>
<tr>
<td></td>
<td>Breathers - Air Flowing, Desiccant Condition</td>
</tr>
<tr>
<td></td>
<td>Pumps - Operate</td>
</tr>
<tr>
<td></td>
<td>Cooling Fans - Operate</td>
</tr>
<tr>
<td></td>
<td>Flow Gauges</td>
</tr>
<tr>
<td></td>
<td><strong>Power System Factors</strong></td>
</tr>
<tr>
<td></td>
<td>Load Criticality</td>
</tr>
<tr>
<td></td>
<td>Portable Required for Outage</td>
</tr>
<tr>
<td></td>
<td>Load % of Nameplate</td>
</tr>
<tr>
<td></td>
<td>Customer Sensitivity to Outage</td>
</tr>
<tr>
<td></td>
<td>Transformer Age</td>
</tr>
<tr>
<td></td>
<td>Maintenance History</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Infrared Scan</th>
<th>Diagnostic - Historical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTC - Main Tank Temperature Differential</td>
<td></td>
</tr>
<tr>
<td>Cooling Equipment</td>
<td></td>
</tr>
<tr>
<td>Bushings</td>
<td></td>
</tr>
<tr>
<td>Lightning Arrestors</td>
<td></td>
</tr>
<tr>
<td>Tank Hot spots</td>
<td></td>
</tr>
<tr>
<td>Control Box Wiring</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fluid Analysis*</th>
<th>Electrical Test Results**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved Gas Analysis - Main Tank</td>
<td></td>
</tr>
<tr>
<td>Dissolved Gas Analysis - LTC Tank</td>
<td></td>
</tr>
<tr>
<td>Oil Quality - Main Tank</td>
<td></td>
</tr>
<tr>
<td>Oil Quality - LTC Tank</td>
<td></td>
</tr>
<tr>
<td>Power Factor</td>
<td></td>
</tr>
<tr>
<td>Degree of Polymerization</td>
<td></td>
</tr>
</tbody>
</table>
Annual thermographic testing is helpful detecting:

- Bushing Problems/hotspots
- Stray flux heating/shield issues
- LTC/Main tank oil temperature differential
- Oil level problems
- Blocked or closed cooling loops
- Oil pump/fan motor problems
- Control device problems.
**Condition Assessment – Level 2**

**Level II - Investigative Testing (Outage Required)**

<table>
<thead>
<tr>
<th>Infrared Scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTC - Main Tank Temperature Differential</td>
</tr>
<tr>
<td>Cooling Equipment</td>
</tr>
<tr>
<td>Bushings</td>
</tr>
<tr>
<td>Lightning Arrestors</td>
</tr>
<tr>
<td>Tank Hot spots</td>
</tr>
<tr>
<td>Control Box Wiring</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fluid Analysis*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved Gas Analysis - Main Tank</td>
</tr>
<tr>
<td>Dissolved Gas Analysis - LTC Tank</td>
</tr>
<tr>
<td>Oil Quality - Main Tank</td>
</tr>
<tr>
<td>Oil Quality - LTC Tank</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vibration / Sound Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Discharge Testing</td>
</tr>
<tr>
<td>Ultrasonic Testing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical &amp; Material Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Factor</td>
</tr>
<tr>
<td>Core Megger</td>
</tr>
<tr>
<td>Turns Ratio</td>
</tr>
<tr>
<td>Winding / Contact Resistance</td>
</tr>
<tr>
<td>Turns Ratio</td>
</tr>
<tr>
<td>Leakage Reactance</td>
</tr>
<tr>
<td>Sweep Frequency Response Analysis</td>
</tr>
<tr>
<td>Degree of Polymerization</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Visual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Inspection -Main Tank</td>
</tr>
<tr>
<td>Internal Inspection - LTC Tank</td>
</tr>
</tbody>
</table>

---

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Level 3 diagnostics can include testing methods to detect operating difficulties and pinpoint repair activities

- Internal Inspections
- Materials and Oil Testing
  - Metal in Oil Testing
  - Particle count
  - Degree of Polymerization Testing
- Advanced Diagnostics
  - FRA Measurements
  - Field Induced Testing
  - Acoustics
Design Assessment considers original design parameters

- Thermal Performance
- Short Circuit Withstand
- Dielectric Design

Without a design analysis, it is difficult to accurately evaluate loss of insulation life of individual transformers or transformer's operating capability.

Figure 4. Transformer Hot Spot Rise for 80 Different Large Network and Generator Transformers.
A typical condition ranking will involve a number of assessment parameters as defined by evaluator:

- **Typical Parameters**
  - Age
  - O&M History
  - Oil Condition & DGA
  - Electrical Condition
  - Component Evaluation
  - Design Assessment

- **Transformer Condition Index**
  - \( \text{TCI} = \sum (w_1P_1 + w_2P_2 + \ldots + w_nP_n) \)
  - Normalized index to standard score
Life Cycle Decisions

Options
- Perform Corrective Maintenance
- Retrofit/Refurbish
- Operate As–Is (some loaded beyond nameplate)
- Re-Locate
- Retire

Condition Assessment ➔ Life Assessment (Profiling) ➔ Design Assessment
Visual Inspection (Level 1)
Transformer Maintenance

- **Gauges & Devices (cont.)**
  - **Levels & Indicators (Reset)**
    - Winding Temperature
    - Oil Levels
    - LTC Position(s)
Transformer Maintenance

- Gauges & Devices *(cont.)*
  - Alarms *(Indicators)*
  - Gas Accumulators
  - Bushing Sight Glasses
Transformer Maintenance

- Gauges & Devices
  - Pumps & Fans
  - N2 Systems
  - Breathers
Transformer Maintenance

- Surface Conditions
  - Paint/Galvanizing/Plating
  - Rust
  - Water collection
Transformer Maintenance

- Oil Leaks – Identify Location & Severity
Transformer Maintenance

- Controls & Wiring
  - Degradation/Insulation
  - Infestation
  -Disconnected/loose wires
  - Proper labeling
  - Overheating
Transformer Maintenance

Assessment Over!
## Electrical Test Condition Ratings

<table>
<thead>
<tr>
<th>Test</th>
<th>Type of Faults Detected</th>
<th>Good</th>
<th>Caution</th>
<th>Concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bushing Power Factor (% at 20C)</td>
<td>Bushing insulation defect</td>
<td>&lt;0.5%</td>
<td>0.5%-1%</td>
<td>&gt;1%</td>
</tr>
<tr>
<td>Bushing Capacitance</td>
<td>Shorted condenser or test tap problems</td>
<td>&lt;10% Change from Baseline</td>
<td></td>
<td>&gt;10% change from baseline</td>
</tr>
<tr>
<td>Winding Power Factor (% at 20C)</td>
<td>Defects in winding insulation or moisture</td>
<td>&lt;0.5%</td>
<td>0.5%-1%</td>
<td>&gt;1%</td>
</tr>
<tr>
<td>Winding Capacitance</td>
<td>Winding deformation / Open core ground</td>
<td>&lt;10% Change from Baseline</td>
<td></td>
<td>&gt;10% change from baseline</td>
</tr>
<tr>
<td>Leakage Reactance/LV Impedance</td>
<td>Winding deformation / Through fault damage</td>
<td>&lt;3% Change from Baseline</td>
<td></td>
<td>&gt;3% change from baseline</td>
</tr>
<tr>
<td>Transformer Turns Ratio</td>
<td>Open or shorted windings / improper polarity</td>
<td>&lt; 0.5% standard deviation</td>
<td>&gt;0.5% standard deviation</td>
<td></td>
</tr>
<tr>
<td>Winding Insulation Resistance</td>
<td>Defects in winding insulation or moisture</td>
<td>&lt; 1000 MΩ</td>
<td></td>
<td>&lt; 1000 MΩ</td>
</tr>
<tr>
<td>DC Winding Resistance</td>
<td>Poor connections - winding, bushings, tap changer</td>
<td>&lt;2% phase to phase deviation</td>
<td>2-5% phase to phase deviation</td>
<td>&gt;5% phase to phase deviation</td>
</tr>
<tr>
<td>Winding Excitation</td>
<td>Core problems /shorted turns</td>
<td>&lt;10% Change from Baseline</td>
<td></td>
<td>&gt;10% change from baseline</td>
</tr>
<tr>
<td>Frequency Response Analysis</td>
<td>Winding deformation</td>
<td>&lt; 2 dB amplitude deviation / resonant point shift from baseline</td>
<td>&gt; 2 dB amplitude deviation / resonant point shift from baseline</td>
<td></td>
</tr>
</tbody>
</table>
Test References

- IEEE Guide for Maintenance and Acceptance of Insulating Oil in Equipment (C57.106-2006)
- IEEE Guide for Interpretation of Gasses Generated in Oil Immersed Transformers (C57.104-2008)
- IEEE Guide for Dissolved Gas Analysis in Transformer Load Tap Changers (C57.139-2010)
- IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids (C57.147-2008)
- IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester Immersed Transformers (C57.155-2014)
Oil Quality (Level 1)
## Classification of Service Aged Oils

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Unit</th>
<th>Voltage</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Breakdown</td>
<td>ASTM-D1816 w/ 1mm gap</td>
<td>min, kV</td>
<td>&lt; 69 kV</td>
<td>23</td>
<td>&lt;23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>69 - 288 kV</td>
<td>28</td>
<td>&lt;28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 345 kV</td>
<td>30</td>
<td>&lt;30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Neutralization Number</td>
<td>ASTM-D974</td>
<td>max, mg KOH/g</td>
<td>&lt; 69 kV</td>
<td>0.2</td>
<td>-</td>
<td>&gt;0.2</td>
<td>&gt;0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>69 - 288 kV</td>
<td>0.15</td>
<td>-</td>
<td>&gt;0.15</td>
<td>&gt;0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 345 kV</td>
<td>0.1</td>
<td>-</td>
<td>&gt;0.10</td>
<td>&gt;0.5</td>
</tr>
<tr>
<td>Interfacial Tension</td>
<td>ASTM-D971</td>
<td>min, Dynes/cm</td>
<td>&lt; 69 kV</td>
<td>25</td>
<td>-</td>
<td>&lt;25</td>
<td>&lt;18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>69 - 288 kV</td>
<td>30</td>
<td>-</td>
<td>&lt;30</td>
<td>&lt;18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 345 kV</td>
<td>32</td>
<td>-</td>
<td>&lt;32</td>
<td>&lt;18</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>ASTM-D1533</td>
<td>max, PPM @60°C Avg. Oil Temp.</td>
<td>&lt; 69 kV</td>
<td>35</td>
<td>&gt;35</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>69 - 288 kV</td>
<td>20</td>
<td>&gt;20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 345 kV</td>
<td>12</td>
<td>&gt;12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power Factor</td>
<td>ASTM-D921</td>
<td>max, %</td>
<td>&lt; 69 kV</td>
<td>0.5</td>
<td>-</td>
<td>&gt;0.5</td>
<td>&gt;1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>69 - 288 kV</td>
<td>0.5</td>
<td>-</td>
<td>&gt;0.5</td>
<td>&gt;1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 345 kV</td>
<td>0.5</td>
<td>-</td>
<td>&gt;0.5</td>
<td>&gt;1.0</td>
</tr>
</tbody>
</table>

*Group I.* Oils that are in satisfactory condition for continued use  
*Group II.* Oils that required only reconditioning for further service  
*Group III.* Oil in poor condition. Such oil should be reclaimed or disposed of depending upon economic considerations  
*Group IV.* Oils in such poor condition that it is technically advisable to dispose of them
Moisture lowers the dielectric strength of solid insulation.

Source: Tom Prevost, EHV Weidmann, 2006
Moisture lowers the lowest hot-spot temperature range for possible bubble formation.

Comparison of “critical” bubble temperature vs. water content in paper by three researchers

Source: TV Oommen, EPRI Reports: EL-6761, March 1990; EL-7291, March 1992
Moisture accelerates thermal aging of paper insulation.

*IEEE Std C57.91-1995*
Reconditioning of oil is required to improve moisture content or dielectric breakdown of the oil.

- Accomplished with vacuum purification equipment
- Process can be completed on-line or off-line
- Reducing moisture concentration of oil by recirculation of oil within transformer tank has limited improvement of moisture content of the cellulose insulation
Reclamation is intended to remove polar and acidic contaminates from the oil. Use of fullers earth filtration is required. The treatment requires...

- Oil should be passed through a moisture filter to prevent wetting of clay
- Oil exiting clay should pass through vacuum oil purification unit
- Oil entering fullers earth tower should be heated to 70°C
- Addition of oxidation inhibitor to reclaimed oil is recommended
Oil Handling Associated with Repairs

Often repairs and component changes will require the handling of oil. Some repairs can be completed with only partial draining of the transformer.

- Oil should only be stored in clean and dry containers
- Oil should not be lowered below active part of transformer
- Do not pull vacuum of partially filled transformer.
- Transformer should be refilled at atmospheric pressure.
- Bleed all vent openings
- Allow transformer to remain idle for specified time
- EHV transformers often require complete draining for any intrusive maintenance.
Corrosive Sulfur

Issue:

- Corrosive sulfur from oil interacts with copper and silver to form metal sulfides
- Dielectric strength is reduced potentially resulting in strand to strand or disk to disk failure
- Inspection is only method of detection
- Oil testing can determine potential risks

Solution:

- Existing damage cannot be reversed
- Future damage can be controlled
  - Oil replacement
  - Partial oil replacement
  - Passivation with metal deactivators
Insulation Aging Estimates
# Insulation Aging & Expected Life

## Table 2—Normal insulation life of a well-dried, oxygen-free 65 °C average winding temperature rise insulation system at the reference temperature of 110 °C

<table>
<thead>
<tr>
<th>Basis</th>
<th>Normal insulation life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hours</td>
</tr>
<tr>
<td>50% retained tensile strength of insulation</td>
<td>65 000</td>
</tr>
<tr>
<td>(former IEEE Std C57.92-1981 criterion)</td>
<td></td>
</tr>
<tr>
<td>25% retained tensile strength of insulation</td>
<td>135 000</td>
</tr>
<tr>
<td>200 retained degree of polymerization in insulation</td>
<td>150 000</td>
</tr>
<tr>
<td>Interpretation of distribution Transformer functional life test data (former IEEE Std C57.91-1981 criterion)</td>
<td>180 000</td>
</tr>
</tbody>
</table>

**NOTES:**

1. Tensile strength or degree of polymerization (D.P.) retention values were determined by sealed tube aging on well-dried insulation samples in oxygen-free oil.
2. Refer to 1.2 in annex I for discussion of the effect of higher values of water and oxygen and also for the discussion on the basis given above.
Theoretical Aging Calculation

- **Service Age**
- **Hot Spot Temperature**
  - Real time recording
  - Loading profile
  - Approximation from ambient, average winding rise and hot spot gradient
- **Aggregate Aging Factor**
- **Moisture Content Consideration**

<table>
<thead>
<tr>
<th>UNIT DESIGNATION</th>
<th>SERIAL NUMBER</th>
<th>Estimated Time in Service, Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB</td>
<td>7001535</td>
<td>376,680</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Avg. Ambient Temp (°C)</th>
<th>Avg. Ambient Temp (°F)</th>
<th>Number of Hours/Year</th>
<th>Est. Hot Spot Temp (°C)</th>
<th>Aging Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5</td>
<td>&lt; 41</td>
<td>0</td>
<td>&lt;75</td>
<td>0.0195</td>
</tr>
<tr>
<td>5 to 10</td>
<td>41-50</td>
<td>0</td>
<td>75-80</td>
<td>0.0358</td>
</tr>
<tr>
<td>10 to 15</td>
<td>51-59</td>
<td>3624</td>
<td>80-85</td>
<td>0.0649</td>
</tr>
<tr>
<td>15 to 20</td>
<td>60 to 68</td>
<td>4416</td>
<td>85-90</td>
<td>0.1156</td>
</tr>
<tr>
<td>20 to 25</td>
<td>69 to 77</td>
<td>720</td>
<td>90-95</td>
<td>0.2026</td>
</tr>
<tr>
<td>25 to 30</td>
<td>78 to 86</td>
<td>0</td>
<td>95-100</td>
<td>0.3499</td>
</tr>
<tr>
<td>30 to 35</td>
<td>87-95</td>
<td>0</td>
<td>100-105</td>
<td>0.5957</td>
</tr>
</tbody>
</table>

8760 Total

Avg. Aging Factor 0.1018
Water Content Factor 1.5000

<table>
<thead>
<tr>
<th>UNIT DESIGNATION</th>
<th>SERIAL NUMBER</th>
<th>Total Time in Service</th>
<th>Aging Hours</th>
<th>Percent Loss of Life*</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB</td>
<td>7001535</td>
<td>376,680</td>
<td>57,506</td>
<td>38.34%</td>
</tr>
</tbody>
</table>
Degree of Polymerization

- Test Method is ASTM-4243
- New insulation measures 1000-1200
- End of life considered to be 200
- Direct measure of insulation aging.
- Paper is most aged at the hot spot location.
- Often impractical to retrieve sample from optimal location.
Theoretical Aging vs. Direct Measurements

- Theoretical Aging predicted DPv of 680.

Challenges with Direct Measurement:
- Sample location often not at point of most severe aging (hot spot).
- Sample extraction in invasive and difficult to obtain.
Theoretical Aging vs. Indirect Measurements

Theoretical Aging predicted DPv of 680.

Challenges with Indirect Measurement:

- Oil maintenance/processing or replacement will remove aging compounds.
- Must track cumulative effects of aging between maintenance cycles.

Theoretical Aging predicted DPv of 680.
Internal Inspections (Level 3)
Internal Inspection

- Inspect tightness and alignment of coil spacers and blocks
- Inspect for shifting of core and coils
- Inspect for broken fiber or permali hardware
- Inspect phase barriers, oil boxes, and tank shielding
Clamping Systems

- Short circuit withstand capabilities can be compromised by less than designed clamping force. Clamping force can be reduced through:
  - Aging
  - Materials utilized
  - System Faults
  - Drying Operations
  - Transportation
GE Mark II Clamping System

**Issue:**
- Prior to 1975, GE applied a static clamping system.
- Insulation shrinks causing the transformer to lose clamping pressure.
- Extreme risk of failure during short circuit event with loss of clamping pressure

**Solution:**
- Reblock current clamping structure
- Factory retrofit to Dyna-Comp™ system
Key Accessories & Components
Cooling Systems

Issue:

- High liquid & winding temperatures
- Generation plant repowering or uprate
- Combustible gas generation
- Fouled cooling equipment and/or mineral deposits
- Air recirculation against firewalls or other obstructions

Solution:

- Cleaning of cooling equipment
- Addition of louvers
- Cooling retrofit
  - Fans,
  - Radiators
  - Coolers and/or pumps
- Factory rewind
Natural Ester Fluid Retrofill

- Insulating paper aging rate reduced – 5 – 8 times aging rate reduction compared to mineral oil
- Essentially no sludge precipitate
- Reduction of paper moisture levels
- Much lower gassing tendency value
- Reduced coking on bare copper
Visual Comparison vs. Aging Time

- Natural Ester
  - Sealed Tube Test - ML 152-2000
  - Upgraded Paper 500 hr @ 170°C

- Natural Ester
  - Sealed Tube Test - ML 152-2000
  - Upgraded Paper 1000 hr @ 170°C

- Natural Ester
  - Sealed Tube Test - ML 152-2000
  - Upgraded Paper 2000 hr @ 170°C

- Natural Ester
  - Sealed Tube Test - ML 152-2000
  - Upgraded Paper 4000 hr @ 170°C

- Mineral Oil

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May 9, 2019
Sealed and Nitrogen Blanket Systems

Issue:
- High moisture content and/or oxidation byproducts from improper operation of oil preservation systems
  - Plugged bleeders
  - System leaks
  - Defective regulator

Solution:
- Component Addition/Replacement
  - Silica Breather
  - Nitrogen System
- Retrofit to expansion system
Gas Bubble Evolution

Issue:

- Supersaturation of nitrogen in oil releases free nitrogen gas when transformer oil cools causing oil bubbles, partial discharge, and potential dielectric failure.
- Older transformers particularly Generator Step Up transformers and EHV (above 230 kV) are susceptible to this problem

Solution:

- Special Start-up/Shut Down procedures
- COPS Tank Retrofit
- Cooling Control Modifications
Expansion Tanks

Issue:

- Expansion Tank Elevation
  - Low profile conservator tank (rectangular and elliptical) is mounted below highest tank point
  - Leak in cover gaskets, gas detector piping, upper cooling can cause free gas leak, moisture intrusion, and possible loss of oil in turrets
  - Can cause gas detector alarm operation and possible supersaturation of gas in oil

Solution:

- Elevation of current conservator tank
Solution:

- Elevation of current conservator tank
- Examination of bladder for fungal attack and degradation
  - Retrofit to different bladder
  - Retrofit breather with regenerating silica style (eliminate maintenance)
Surge Arresters

- Transformer should be protected from overvoltages resulting from external or internal events such as lightning, switching, faults, resonance, or loss of ground

- Consider
  - Replacement of rod gap or silicon carbide arresters
  - If not present, addition of arresters at transformer terminals
  - Coordination of remote mounted arresters with the transformer terminal winding BIL
Bushings

Condition Awareness

- **Service Advisories:**
  - Trench COTA Bushings (34.5 kV and above)
  - GE Type U Bushings
  - ABB O+C Bushings (2000 and 2013)

- Mean-time-to-failure is typically a short period
- Power factor monitoring
- Infrared scanning
GE Type U Bushings

Action Limits:

- Refurbish or replace bushing if power factor doubles nameplate value or capacitance increases to 110% of nameplate.

- Infrared scan of top terminals. If temperature exceeds 70°C, investigate and re-torque top terminal.
Load Tap Changers

Issue:
- Lack of spare parts
- High maintenance costs or excessive maintenance schedules
- Obsolete equipment

Solution:
- Tap Changer Retrofit
  - Reduced Maintenance Intervals
  - Vacuum Conversion
  - Updated equipment & controls
LTC Filtration

Issue:
- Resistive/Reactive Tap Changers
  - Moisture
  - Arcing By-Product
  - Wear By-products

Solution:
- LTC Filtration
  - Removal of Arc By Production
  - Removal of moisture
  - Removal of metallic particles
  - Extended maintenance intervals
  - Reduce wear and arc erosion
Oil Analysis and Life Extension Considerations

- DGA & Oil Quality
- Diagnostic Methods
  - Four Ratio Codes (Doernenburg)
  - Three Ratio Codes (Rogers)
  - Duval Triangle
  - Key Gas Interpretation
  - IEEE Guide
- Sampling Methods
- Oil Preservation Systems
- Condition Assessment
- Inspections
- Components

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References

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- IEEE Guide for Maintenance and Acceptance of Insulating Oil in Equipment (C57.106-2006)
- IEEE Guide for Interpretation of Gasses Generated in Oil Immersed Transformers (C57.104-2008)
- IEEE Guide for Dissolved Gas Analysis in Transformer Load Tap Changers (C57.139-2010)
Questions?

Thank you!