Introduction

• This paper will discuss the effects of water and oxygen content in transformer oil and how this directly correlates with its aging.

• It will compare the three possible transformer maintenance approaches:
  - Run-to-Failure
  - Predictive Maintenance
  - Proactive Maintenance.

• A case study will show how the “best practice” approach actually saves money on all ends: operation, maintenance and reliability (production)
Chapters

1) Aging as a Function of Oxygen and Water
   • The Presence of Oxygen (and its consequences)
   • The Presence of Water (and its consequences)

2) Maintenance approaches
   • Run-to-Failure
   • Predictive Maintenance
   • Proactive Maintenance (Zero Downtime Maintenance)

3) Case Study “Best Practice”: Zero Downtime Maintenance

4) Summary
1) Aging as a function of Oxygen and Water

Hypothesis

$O_2$ → Oil

Acids are formed by oxidation

Acids → Oil reclaiming

Transformer refurbishment

$H_2O$ → Paper ageing:

Water & acids accelerates ageing.

Water is formed

$H_2O$
Interrelation of Water, Oxygen and Cellulose

1. Ageing is caused by the oxidation process. Oxygen is introduced into the transformer through:
   - the venting pipe of the expansion reservoir and
   - naturally in the cellulose.

2. Water is one of the end products of the cellulose and oil ageing processes and is generated in vast quantities inside transformers. Over 98% of dissolved water in a transformer is bound in the cellulose - which, incidentally, is where it harms it the most.

3. Acids are formed in certain steps of the oxidation process of oil and cellulose, leading to the end-products CO2 and water.
Oxygen and Water in Oil
= a dangerous cocktail

Acid generation accelerates when water and oxygen are present. Acid in turn causes acid-hydrolysis.
Goals / Important Data

• **0.2 % Water content in the insulation** (arbitrary number: basically as little water content as possible, but below 1%)

• **2 ppm Water content in the transformer oil** (arbitrary number: basically as little water content as possible, but below 10 ppm)

• **20 years** Life extension of the transformer (arbitrary number, but very much achievable – see calculations)

• **200 DP (Degree of Polymerization):** End of life for the insulation is considered at or below 200 DP. The lower the DP, the further the degradation of the insulation, caused by oxygen and water (acid)

• **2,000 ppm Oxygen content or less in the transformer oil**
The presence of Oxygen

Lowering the Oxygen Concentration slows Down Oxidation

Depolymerisation of Cellulose. Accelerated Ageing (130 C) (270 F)
With/Without Presence of Oxygen

Oxygen
No Oxygen
The presence of Water

Life Expectancy can be Calculated from Water Content and Temperature.

\[
\text{Expected Life} = \frac{1}{\frac{\text{DP}_{\text{End}}}{A} + \frac{1}{24 \times 365} \times \frac{13350}{T^{\frac{1}{273}}}} \text{ year}
\]

Source: L. Lundgaard, SINTEF Energiforskning AS
The presence of Water

Oil/Cellulose Humidity Correlation
- at different oil temperatures

![Graph showing the correlation between water in cellulose (W%) and water in oil (ppm) at different oil temperatures (20°C, 30°C, 50°C, 70°C, 90°C).]
The presence of Water

Just how fast is the moisture moving in the core?
The presence of Water

Not very fast at all!
Graph 1: Transformer Temperatures Under Changing Load Conditions (see C57.91-1995, p. 82)
2) Maintenance approaches

- Run-to-Failure
- Predictive Maintenance
- Proactive Maintenance (Zero Downtime Maintenance)
Run-to-failure
Run-to-failure costs/benefit

• “Maintenance” costs of US$ 0.00...

• Shortest transformer life/lowest return on invest

• Unpredictable time of failure

• Loss of revenues until replacement is installed (months?)
Predictive Maintenance

Oil Regeneration & Reclaiming on demand during outages

• Will remove water from the oil and some moisture from paper. But with oil in the transformer the moisture transport takes time.

• Will remove Oxygen from the oil and some from the paper.

• Will remove some acids from paper. Oil acidity is reported to be stable and low after treatment.
Predictive Maintenance: cost/benefit

- Outage $ 0.00 to $ 1,000,000.00 per service
- Oil Service ~ $ 350.00 per hour
- More predictable time of failure
- Increased life time of the transformer / higher return on invest
Proactive Maintenance (Zero Downtime Maintenance)

Oil Regeneration during operation

• Will remove water from the oil and moisture from paper.

• Will remove Oxygen from the oil and from the paper.

• Will remove acids from the oil and paper.
Proactive Maintenance
cost/benefit

- One time Investment: US$ 20,000.00 to US$ 60,000.00 (depending on size and equipment)
- Predictable time of failure
- Longest life time of the transformer/highest return on invest
Technical Data

<table>
<thead>
<tr>
<th>Type</th>
<th>3 x 27/108/S/MZ/S/AMJT/G</th>
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<tbody>
<tr>
<td>Pump capacity</td>
<td>325 l/h</td>
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<tr>
<td>CJC Fine filter insert</td>
<td>2 x AM, 1 x JT</td>
</tr>
<tr>
<td>Power consumption</td>
<td>0.18 kW</td>
</tr>
<tr>
<td>Weight</td>
<td>approx. 230 kg</td>
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<tr>
<td>Maximum pressure</td>
<td>2.2 bar</td>
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<tr>
<td>Viscosity range</td>
<td>ISO VG 20</td>
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<tr>
<td>Dirt holding capacity, app.</td>
<td>8 l</td>
</tr>
<tr>
<td>Water holding capacity, app.</td>
<td>16 l</td>
</tr>
<tr>
<td>Connections</td>
<td>Inlet: 1/2&quot;, Outlet: 1&quot;</td>
</tr>
</tbody>
</table>

Function

The warm humid insulation oil is pumped through two filters containing a molecular sieve and through a cellulose fine filter insert. The molecular sieve and the cellulose not only draw the water out of the oil, but also the solid contamination. Dried and cleaned, the insulation oil is lead back to the transformer. There, it picks up further humidity from the paper insulation. This steady process ensures a drying of the transformer's paper insulation which is as smooth as possible.
3) Case Study “Best Practice”: Zero Downtime Maintenance

<table>
<thead>
<tr>
<th>Fecha</th>
<th>Inlet °C</th>
<th>Outlet °C</th>
<th>Inlet ppm</th>
<th>Outlet ppm</th>
<th>Runtime hrs</th>
<th>Water/hour ml</th>
<th>Total water l</th>
<th>Temp. Aceite Tr °C</th>
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<tr>
<td>6/8/2011</td>
<td>29</td>
<td>24</td>
<td>38</td>
<td>1</td>
<td>0</td>
<td>12</td>
<td>0.12</td>
<td>50</td>
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<tr>
<td>6/9/2011</td>
<td>32</td>
<td>31</td>
<td>33</td>
<td>1</td>
<td>24</td>
<td>11</td>
<td>0.9</td>
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<tr>
<td>5/10/2011</td>
<td>32</td>
<td>31.5</td>
<td>30</td>
<td>1</td>
<td>48</td>
<td>10</td>
<td>1.66</td>
<td>55</td>
</tr>
<tr>
<td>5/13/2011</td>
<td>32</td>
<td>31</td>
<td>24</td>
<td>1</td>
<td>119</td>
<td>8</td>
<td>3.56</td>
<td>55</td>
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<tr>
<td>5/16/2011</td>
<td>26</td>
<td>26</td>
<td>21</td>
<td>1</td>
<td>137</td>
<td>7</td>
<td>5.26</td>
<td>40</td>
</tr>
</tbody>
</table>
Not only is the water content down to 1ppm removed, but large portions of dissolved gases as well:

Sent: miércoles, 31 de marzo de 2010 03:37 p.m.
To: thomas.riedel@asm-mexico.com.mx
Subject: Resultados de cromatografía TR-1

Buenas tardes Thomas, le envío los resultados de la cromatografía realizada al aceite del Transformador de la subestación costa siete:

Entrada:
CO2 - 84 ppm
C2H4 - 0.86 ppm

Salida:
CO2 - 6 ppm
C2H4 - 0.12 ppm
Inlet °C  29
Outlet °C  24
Inlet ppm  38
Outlet ppm  1
inlet °C  35
outlet °C  34
inlet ppm  36
outlet ppm  1
While we were already there, we prevented an oil change on an online tap changer...
Not necessary to wait for the oil analysis from the lab…
4) Summary

- Transformer life can be extended dramatically simply by controlling the contaminants:
  - water
  - oxygen
  - (thus acids)

- Most efficiently water and oxygen are removed on a continuous basis:
  - it takes very long for these contaminants to migrate from the insulation into the oil.
  - “On-line” is the ideal environment for dehydration
  - “Zero Downtime”

- Best practice approach for ensuring reliable production is the proactive maintenance approach because…:
  - Bottleneck in production
  - Expensive piece of equipment
  - long delivery times and adversely effect on production (electricity)
  - potential for great losses in revenues are being caused
References

1. Justin Stover, CJC. (2006) Zero Downtime Maintenance of Transformer Oil and Insulation Life Extension
2. Kim Kjaer, CJC. (March 2005) Transformer Lecture