Evaluation of transformer solid insulation

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Liquid impregnated cellulose materials in the form of insulation paper are used in power transformers as electrical insulation and as mechanical support for the windings and leads. The mechanical strength of these materials will reduce over time. The thermal performances of these materials are of interest both for assuring a high quality of new units, and also for estimating remaining life for asset management.

Managing an ageing transformer population requires decisions regarding life extension activities, e.g., transformer condition control, reclamation and drying, and life assessment for reinvestment. Knowledge of transformer ageing can either be based on diagnostic monitoring and ageing markers or by modelling of ageing kinetics.

Direct evaluation

The mechanical properties of insulating paper can be established by direct measurement of its tensile strength or degree of polymerisation (DP). These properties are used to evaluate the end of reliable life of paper insulation. It is generally suggested that DP values of 150 to 250 represent the lower limits for end-of-life criteria for paper insulation; for values below 150, the paper is without mechanical strength. Direct measurement of these properties is not practical for in-service transformers.

Analysis of paper insulation for its DP value requires the removal of a few strips of paper from suspect sites. This procedure can be conveniently carried out during transformer repairs. The results of these tests will be a deciding factor in rebuilding or scrapping a transformer.

Note: Since it is usually not practical (and often dangerous to the transformer) to obtain a paper sample from a de-energised, in-service transformer, an alternative method has been found.

Furan analysis

When a cellulose molecule de-polymerises (breaks into smaller lengths or ring structures), a chemical compound known as a Furan is formed.

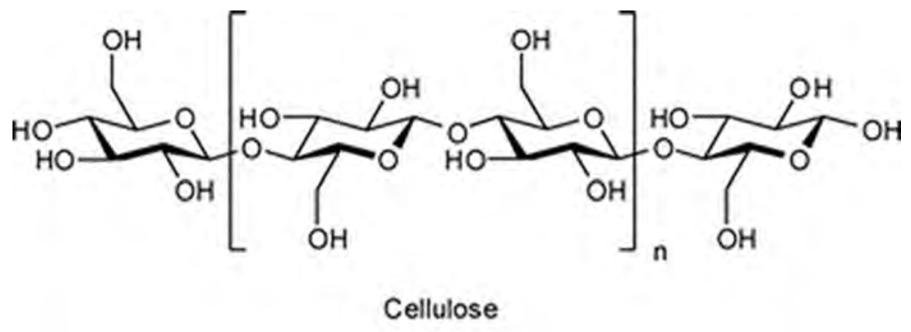

Figure 1: Cellulose molecule consisting of a chain of saccharide rings.

By measuring the quantity and types of furans present in a transformer oil sample, the paper insulation overall DP can be inferred with a high degree of confidence. The types and concentration of furans in an oil sample can also indicate abnormal stress in a transformer, whether intense, short duration overheating or prolonged, general overheating. Furan analysis can be used to confirm dissolved gas analysis where carbon monoxide present indicates problems with solid insulation.

5-Hydroxymethyl-2-furaldehyde	5H2F	Oxidation
Furfuryl alcohol	2FOL	High Moisture
2-Furaldehyde	2FAL	Overheating, old faults
2-Furyl methyl ketone	2ACF	Rare, lighting
5-Methyl-2-furaldehyde	5M2F	Local, severe overheating

Table 1: Results of the presence of certain chemicals within transformers

It has been shown that the amount of 2-furaldehyde in oil (usually the most prominent component of paper decomposition) is directly related to the DP of the paper inside the transformer. Paper in a transformer does not age uniformly and variations are expected with temperature, moisture distribution, oxygen levels and other operating conditions. The levels of 2-furaldehyde in oil relate to the average deterioration of the insulating paper. Consequently, the extent of paper deterioration resulting from a "hot spot" will be greater than indicated by levels of 2-furaldehyde in the oil.

For a typical power transformer, with an oil to paper ratio of 20:1, the 2-furaldehyde levels have the following significance:

Furan content (ppm)	DP value	Significance
0 - 0,1	1200 - 700	Healthy transformer
0,1 - 1,0	700 - 450	Moderate deterioration
1 - 10	450 - 250	Extensive deterioration
>10	<250	End of life criteria

Table 2: Significance of Furan content in a transformer

Furan measurements have gained popularity in the past 20 years because they offer measurements of specific chemical compounds such as 2-FAL, which can be directly correlated with the ageing of the transformer's paper insulation. Several equations describing a degree of polymerisation (DP) as a function of $\log_{10}$ (2-FAL) for kraft paper have been developed, and it is shown that accurate DP estimation is not always possible. It is advisable not to apply any Furan-DP correlation without proper analysis directly. Additionally, certain actions may affect the Furan concentration in the oil, such as oil reclamation and oil treatment, among others.

Comparing various models in predicting DP from 2-FAL

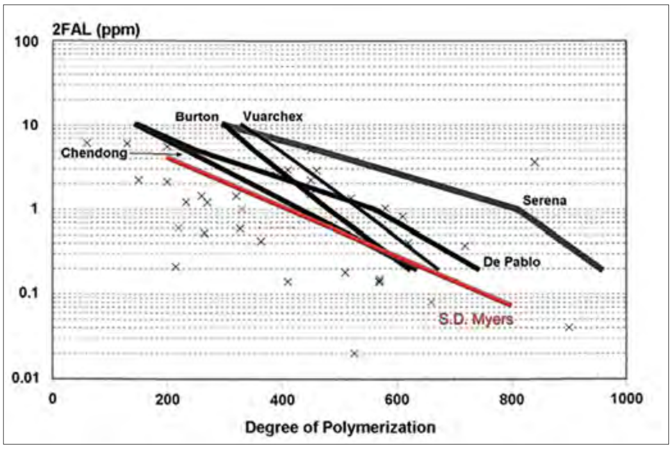

Figure 2: Comparing Furan-DP models [Courtesy of SD Myers]

Ageing rates of insulation paper

There are three main processes of degradation: Hydrolysis, Oxidation, Pyrolysis

In a real transformer all these processes – hydrolysis, oxidation and pyrolysis act simultaneously, resulting in a non-linear Arrhenius plot.

Temperature (pyrolysis)

Ageing rates increase with operating temperature. The ageing of cellulose can be described by the equation:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = A \cdot e^{\frac{-E_A}{RT}} \cdot t \quad \rightarrow \quad \frac{1}{DP_0}\left(\frac{DP_0}{DP_t} - 1\right) = A \cdot e^{\frac{-E_A}{RT}} \cdot t$$

This equation describes how the DP-value decreases from the start value (DP_0) to a value DP_t after a time t by a so-called Arrhenius relation.

Oxidation

In a similar way to hydrolysis, oxygen is a highly reactive element which causes the breakage of cellulose bonds to form by-products such as water, carbon monoxide and carbon dioxide. These three mechanisms, oxidation, hydrolysis and pyrolysis normally do not act in isolation but rather as a group of reactions that reinforce each other.

Acids (oxidation by-products)

Various organic acidic compounds are also released as by-products of oxidation. These acids in turn also attack the cellulose. In particular, the degradation of insulation due to acidic reactions has the consequence of producing sludge. As this sludge is produced, it could be deposited in areas critical for the cooling processes of the coils, such as cooling ducts, that would block the free circulation of oil, which in turn increases the temperature and accelerates the whole ageing cycle once again. As we can see, there are a variety of mechanisms that cause degradation of the insulation system which effectively "ages" the transformer.

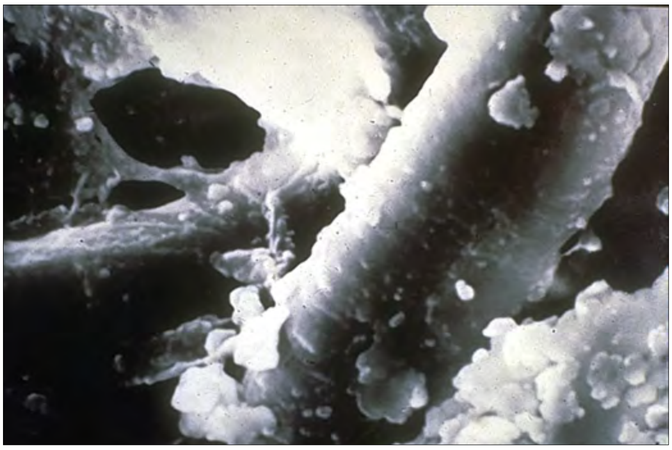

Figure 3: Electron microscope picture of paper aged in oil (Acid value 0,15 mg/kg) Courtesy of SD Myers

Water (hydrolysis)

The presence of water will increase the rate of cellulose degradation. At the beginning of a transformer's life, the Kraft insulation contains less than 0,5% water, and the mineral oil is also dried. The water content levels within the transformer (in the paper insulation) may increase up to 5% during its lifetime. The rate of degradation of the paper, starting from an initial water content value of 4%, was 20 times greater than that at 0,5%. So, in principle as the transformer ages, the rate at which the insulation deteriorates is expected to increase.

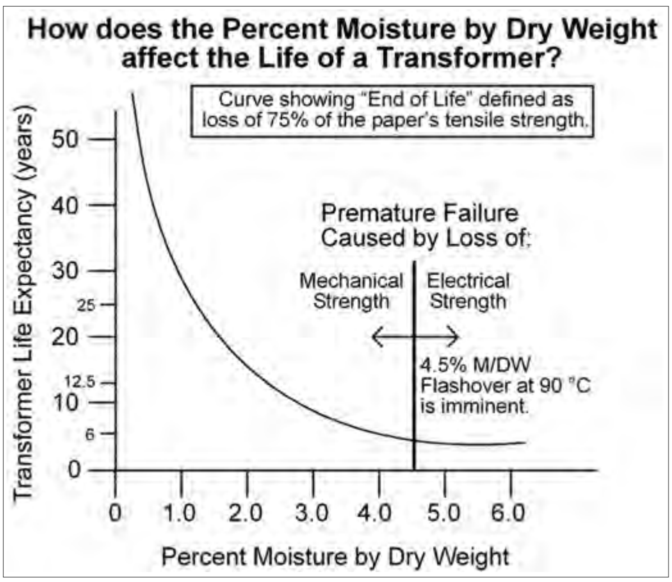

Figure 4 - Influence of (Hydrolysis) water in oil on ageing of Kraft paper

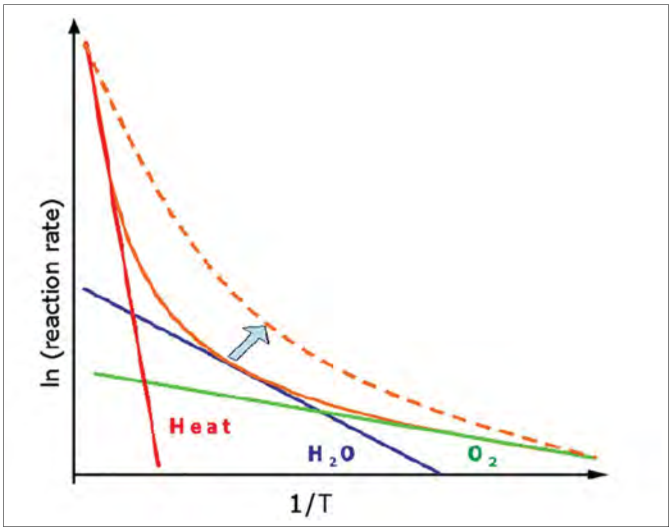

Figure 5 - Sketch of ageing rates due to different ageing mechanisms

Paper ageing and transformer risk assessment

The "predicted" DP (degree of polymerisation) indicates an average paper condition over the whole transformer (subject to factors such as effective circulation). New Kraft paper has a DP in excess of 1200, and paper with a DP of 200 or less is considered to be unfit (subject to interpretation). The values can be optimistic if the oil has been regenerated within the last two years.

This data should be evaluated in conjunction with routine chemical analysis and transformer history.

The reduced strength of paper that results from abnormal ageing may be a direct or indirect cause of a failure. An understanding of the progression of cellulose ageing, and the risks associated, enables an asset manager to make an informed decision regarding the condition in a real transformer, the real situation being always more complex: temperature and water content varies along the winding, there are several different qualities of paper (e.g., thermally upgraded or normal Kraft paper), and the paper is present in many layers with temperature and water content gradients.

Also, cellulosic materials like pressboard and wood are used. Simple formulas may give insight in ageing mechanisms but are never sufficient for assessing the condition of a whole winding. Even so, it is still believed that one should base the analysis on the weakest link, which will be the condition around the hotspot region in the transformer.

Ageing will be most pronounced in this region within the top end of the winding, and electro-mechanical forces will be strongest here. If the tensile strength in this region is insufficient to withstand these forces, this will be the most likely place for a failure to occur.

Furthermore, even if there was an agreed end-of-life criterion for the strength of the paper or the degree of polymerisation of the cellulose, there remains the question of how large the stresses are. The risk of a failure is different for transformers operating in different circumstances. The risk is lower for those operating in grids where the transformer rarely experiences a short circuit or where the short-circuit currents are lower than what the transformer is designed for. But the risks are higher for those transformers exposed to frequent and high short-circuit stresses from, for example, line-to-ground failures on power lines due to lightning, or when moved from one place to another.

Finally, in asset management an engineer will not only consider failure probability, but also the consequence of that failure to gain a more complete picture of the risk involved with a specific transformer or a larger fleet of transformers.

Other diagnostic compounds

The presence of phenols and cresols in concentrations greater than 1 ppm indicate that solid components containing phenolic resin (laminates, spacers, etc.,) are overheating.

Methanol (MeOH) and ethanol (EtOH)

It has been demonstrated over several years that the ageing of impregnated paper in insulating liquid, which results in cellulose degradation, produces molecules of light alcohols, methanol (MeOH) and ethanol (EtOH).

In laboratory experiments, a good correlation has been established between the increase of the methanol content in insulating liquid and the decrease of the degree of polymerisation of the cellulose, irrespective of the type of paper, standard Kraft or thermally upgraded. Further, at the early stages of paper ageing, i.e., of cellulose degradation, the methanol content is always higher than that of furanic compounds (mainly 2-furfural), so this behaviour suggests that methanol could be a relevant in-oil marker to detect early paper ageing in transformers and to assess its evolution.

Case study: insulation failure

Overiew

The transformer failed in service while undergoing Power-On purification to remove moisture from the insulating oil.

Transformer details

Primary voltage:	11 kV
Secondary voltage:	500 V
VA rating:	500 kVA
Vector group:	Dyn11
Impedance:	4,1%
Tap changer:	Off load
Make:	CAWSE & MALCOLM
Year manufactured:	Unknown
Conservator:	No
Breather size:	CHG2
Oil volume:	600 litres

Transformer oil analysis-diagnosis

The dissolved gas analysis indicated a Partial discharge of low energy density (IEC 599) with the CO_2/CO ratio of 16,5 indicating insulation paper degradation. (The normal ratio is between >3 and <11).

The Furan analysis of 8,97 ppm indicated extensive paper deterioration. (Optimistic value as the oil purification process

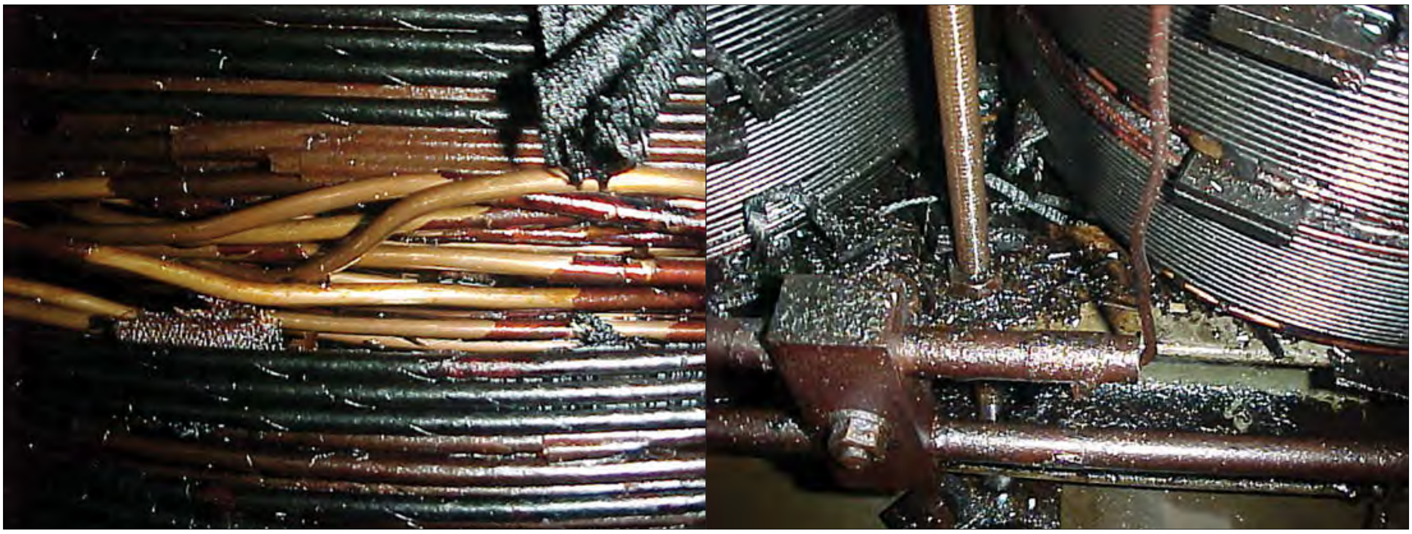

Figure 6: End of life criteria (Degree of polymersiation DP <200): 75% tensile strength loss

removes furan compounds).

The maintenance history of the transformer revealed that oil replacement and purification took place on 12 March 2000. The Furan production rate was 160 ppb (parts per billion) per month (ppb/month). The Morgan Schafer Company reports that a Furan production rate of 25 ppb/month is cause for concern.

The transformer oil analysis indicated a case of advanced paper insulation deterioration. (See Table 3)

Findings

The transformer was removed to a works facility and inspected. The paper insulation clearly was at End of life criteria.

Risk assessment to plan remedial actions:

A transformer with a low DP can continue to operate normally providing it does not experience any external events.

In a situation where the load is suddenly changed, or the

SampleDate	H2	02	N2	CH4	CO	CO2	C2H4	C2H6	C2H2	%Gas	H20	kV	Acidity	Temp	Furan	SampleType
13-Dec-2004	434	2340	64873	16	355	5863	15	0	0	8,63	64	20	0,10	40	8,97	
7-Sep-2004	0	0	0	0	0	0	0	0	0	0	10	87	0,09	60		Purification
9-Jul-2004	167	2500	55983	15	324	6322	0	0	0	8,01	52	34	0,09	56		
15-Feb-2004	0	0	0	0	0	0	0	0	0	0	10	83	0,09	50		Purification
19-Nov-2003	40	8547	70970	9	351	4259	17	19	0	8,38	65	23	0,09	61		
28-Aug-2003	0	0	0	0	0	0	0	0	0	0	16	72	0,07	65		Purification
23-Jun-2003	21	19370	65345	5	114	2116	0	0	0	8,53	43	35	0,07	52		
31-Mar-2003	0	0	0	0	0	0	0	0	0	0	12	82	0,08	60		Purification
3-Feb-2003	0	0	0	0	0	0	0	0	0	0	13	69	0,08	60		Purification
9-Dec-2002	120	21162	73130	7	124	2601	0	10	0	8,63	45	25	0,08	49		
23-Oct-2002	23	20525	56656	0	55	1189	0	0	0	8,01	38	35	0,09	45		
11-Oct-2002	24	5878	46760	1	63	4297	0	0	0	6,22	10	70	0,09	40		Purification
2-Oct-2002	45	9531	61661	11	237	4833	15	17	0	8,74	78	17	0,08	63		Suspect Fault
27-Dec-2001	0	0	0	0	0	0	0	0	0	0	10	82	0,07	67		Purification
6-Nov-2001	102	11165	53340	10	236	3729	11	11	0	7,03	52	19	0,07	54		
28-Nov-2000	0	24042	59971	9	207	2281	19	0	0	8,58	52	22	0,05	55		
12-Mar-2000	0	0	0	0	0	0	0	0	0	0	11	14	0,05	60		Oil rep/pur
9-Dec-1999	53	13284	59226	7	159	3754	18	19	0	8,8	78	18	0,05	66		
23-Feb-1999	0	0	0	0	0	0	0	0	0	0	34	48	0,18	70		Purification
8-Dec-1998	50	8079	69484	5	429	4872	10	0	0	8,49	65	26	0,18	60		
26-Feb-1998	0	0	0	0	0	0	0	0	0	0	14	71	0,17	46		Purification
30-Jan-1998	19	18445	68637	7	359	6250	9	0	0	10,97	100	24	0,17	60		
9-Dec-1996	58	15222	72938	17	425	9269	18	15	0	9,71	94	46	0,15	64		
4-Jul-1996	19	19031	67861	10	244	6588	5	0	0	9,5	68	43	0,13	57		
14-Nov-1995	16	4377	44646	6	351	6777	8	2	0	5,99	68	40	0,13	40		

Table 3: Spreadsheet of transformer oil analysis and maintenance history

transformer is subject to mechanical shock or there is a through-fault on the system, this transformer has a higher risk of failing.

It should be noted that aggressive oil reconditioning when the mechanical strength of the paper is so low can do more harm than good.

It is strongly advised that exposure to fault risk should be managed carefully and plans for end of life developed.

Note: Oil reconditioning can remove the evidence of paper degradation but the degradation itself is irreversible.

Review of maintenance history

The transformer had undergone oil purification on ten occasions since 1995 in an attempt to remove moisture and improve the dielectric, with oil replacement on 12-03-2000. The oil purification had no effect in improving the oil condition.

Economic consideration

Accessing the state of the paper insulation is vitally important when considering a maintenance plan for a transformer. In this case a more cost-effective maintenance plan would be to remove the transformer to a works facility for refurbishment.

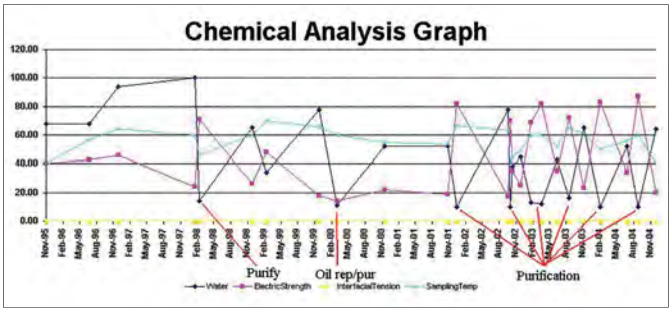

Figure 7: Chemical analysis graph

The assumed average maintenance cost for this transformer was R 25 000 since 1995 with no benefits i.e., there had been no improvement in fluid insulation condition with a deterioration in solid (paper) condition.

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