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Report

Transformer Windings

Ageing, diagnosis and asset management

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ABSTRACT

This report addresses transformer ageing and diagnostics, with emphasis on advising end-users regarding transformer asset management and transformer specification. The basis is results generated during two projects focusing on degradation of mineral oil impregnated cellulose insulation, and also some studies on service aged transformers.

Ageing is governed by thermally activated processes and accelerated from presence of contaminants like water, lighter carboxylic acids and oxygen. It is found that commercially available thermally upgraded papers used for limiting ageing rates may vary a lot in quality, mainly due to varying nitrogen content.

Two schemes for assessing the present and future ageing condition are possible:

- Monitoring by-products formed during ageing, using these as ageing indicators. The recommended indicators are furans, methanol, water and CO and CO_2.
- Calculation based on ageing kinetic algorithms using thermal conditions, contamination and materials used as input parameters.

Schemes are proposed for calculation of ageing condition and expected remaining life estimation. Qualified thermal analysis of service history is necessary for carrying out qualified estimations.

Three different rigs for studying the condition of transformers in service have been tested.

An experimental rig has been built to study temperature dependent partitioning of water and ageing markers in order to estimate condition of cellulose in the windings from oil samples.

Partitioning curves for water, acids and furans in aged transformer insulation are developed.

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1 EXECUTIVE SUMMARY

Background
The infrastructure of the European electricity supply is ageing; hence plans for reinvestments are important to secure regularity. Transformers are critical components for the function of the production plants and the grids. One important issue is long unavailability and replacement time in case of severe failure for these components. A failure mode and criticality analysis has identified the transformer winding as the most critical subcomponent in the transformers. Winding faults, including short circuits and earth faults will impose risk of tank rupture with potential severe collateral damage and will render the apparatus useless for a long time. The identification of failure and ageing processes and conditions of a transformer is essential for making decisions on maintenance actions and timely replacement.

Ageing of cellulose
Ageing of windings has been studied with emphasis on deterioration of the cellulose insulation with time and temperature, considering the contamination condition of the transformer and its design, with cooling system and potential sealing.

Ageing kinetic formulas of Arrhenius type seem to describe the ageing of the cellulose quite well, at least in the first period of the ageing. Parameters were derived from laboratory experiments on *new paper in new oil*. The parameters for calculating ageing under different conditions are suggested both for normal kraft cellulose and for thermally upgraded cellulose. These allow for estimation of remaining life. Micro-calorimetric studies support the hypothesis that the hydrolytic degradation of cellulose is more temperature dependent than oxidation.

Hydrolysis of cellulose is accelerated by the presence of low molecular weight acids dissociated by presence of water. These partly water soluble acids, formed by ageing of both oil and paper, will be absorbed by the paper. A fraction of the acids will react with the cellulose via an esterification process. Consequently these consumed acids will no longer contribute to ageing.

The impact of oxygen partial pressure on the ageing of cellulose has been studied. It was found that the ageing rate dropped slowly as partial pressure was reduced down to $1/4^{th}$ of normal pressure, thereafter it dropped more rapidly. This suggests that in order to reduce oxidation of transformers the oxygen content has to be reduced significantly to see positive effects.

Ageing of *service aged cellulose* was studied in laboratory experiments: For kraft cellulose system undergoing a combined oxidative and hydrolytic ageing an activation energy of 111 kJ/mole seem to be a suitable Arrhenius parameter. Then the "environmental" A-factor can be adjusted according to water content by multiplying with a factor of around 2,5 in case of oxygen presence.

Variation of ageing between papers from different manufacturers, including several upgraded paper, was studied. It was found that the effect of the upgrading depended heavily on the nitrogen content of the upgrading agent. Some types of insulating paper had a low content and the content dropped with time, resulting in a negligible effect of the upgrading.

Diagnostics
Monitoring should differentiate between monitoring for early discovery of faulty conditions focusing on gassing (DGA), and monitoring for assessing ageing using a set of oil descriptive parameters, together with temperature logs. Water, acids and oxygen accelerate ageing. Water, acids furanic compounds and alcohols are formed during ageing and can be used as indicators.

A rig to study the partitioning of diagnostic and ageing driving substances between oil and cellulose has been built, allowing for studies of partitioning up to 120 °C. Partitioning of water, acids, furanic compounds and alcohols has been studied in model systems with new materials, and in materials collected from an old scrapped transformer.

Our experiments gave no clear indications of deviations from partitioning curves derived for new materials. It is therefore suggested that the established curves are valid also for old, service aged materials.

Temperature dependence of partitioning of furanic compounds and alcohols from solid insulation into oil is measured. Curves showing increasing concentration with increasing temperature are used to establish "normalisation" factors to correct measured values to a reference temperature as it is done for water.

Low molecular weight, small carboxylic acids will be absorbed into cellulose, where they partially will be bound to the cellulose molecules via an esterification process.

For mapping contaminants (water, ageing drivers and byproducts) in the solid insulation of a transformer in service a mobile rig has been built. Oil is circulated out from the transformer and back again via test cell using an in-house adapter to be fitted to the rotary ball valve on the tank. Water content and temperature in the oil is monitored. The test cell can be set at a temperature representative for the transformer winding (e.g. hot-spot) and filled with cellulose. Then water and contaminants can be extracted from the paper.

A mobile rig for measuring gasses in oil continuously has been tested and a rig for measuring water and conductivity in oil has been built and tested, also using the in-house adapter for simple connection to the tank. Both enable the possibility to follow conditions in more detail for learning more about dynamic changes in levels of contamination in a transformer.

Thermal models and end-of of life estimation
Formulas for estimating present condition and remaining life are suggested, along with parameters that compensate for the contamination condition of the transformers.

Because ageing largely is driven by thermally activated processes the emphasis is on thermal conditions and thermal models for transformers. Correct values of hot-spot factors and good models to estimate yearly average temperature are crucial for ageing modeling to get good estimates of remaining life.

Field investigation of service aged transformers
The condition of the cellulose in five service aged transformers has been investigated. For two transformers the external oil filter for contamination assessment was used and conditions in the filter compared with samples taken from inside the transformer. Even if the filters functioned the investigations ended up inconclusive. More experience with regard to temperature settings for the filter representative for specific areas inside the transformer is needed. Two very thorough investigations of paper from scrapped large transformer were performed. These results showed that ageing was little progressed because of low service temperatures and - in one case - use of thermally upgraded paper.

Scrapping investigations are considered necessary to test the feasibility of the proposed ageing kinetic models and to establish field experience for life assessment of transformers. Procedures for paper sampling from failed and scrapped transformers are suggested, with a focus on evaluating hot-spot conditions and minimizing number of samples.

Maintenance
Oil reclaiming, reinhibiting of oils, and drying of cellulose are all considered viable maintenance actions. To decide on the efficiency of drying one need to know the content of water and acids in cellulose before and after the drying. The paper filter rig developed is considered useful in this context.

Specifications of new transformers
Based on all ageing studies done we can now conclude that thermally upgrading of cellulose suppresses hydrolysis, but does not reduce oxidation. Sealing to reduce oxygen ingress and the usage of upgraded paper with high nitrogen content seem to be good for securing a long transformer life. Good monitoring of temperatures and knowledge of the hot-spot factor is essential to enable later calculations of life consumption.

Continuous monitoring
DGA - also with continuous gas-in-oil monitors - will increase chances for early recognitions of fault situations. Recording life-consumption requires continuous monitoring of temperatures and calculations of yearly average temperatures. When combined with adequate measurement of contamination of the oil and cellulose one has the best basis for an accurate condition assessment of the winding insulation.

2 INTRODUCTION

Transformer availability is important for the performance of power systems. Transformers have an important function, they are costly, and when failing the outage times may become very long. When failing, collateral damage can be severe in case of explosions and fires. On the background of the growing age of many power systems, failure probability and ageing of important apparatus like transformers becomes important for maintenance and reinvestment planning. In power grids there often is redundancy in transformer capacity based on e.g. an “N-1” or “N-2” criterion. This results in reduced loading under normal operation. In the power plants the transformers are designed to fit to the maximum production of the plant, but often turbine/generators are operated at "best point" resulting in loads below nominal values.

Recent studies show that many transformers have potential for long lives (e.g. 80 years) and that such long life times can be utilized with controlled risk provided an adequate condition monitoring scheme is introduced.

For the transformer owner reliability concerns will lead to three different discussions:

- Specification of new transformers to meet specific expectations
- Monitoring of units to reveal potential defects that may lead to failure
- Assessment of ageing condition to decide on proper time for reinvestment

Most major failures that result in internal flashovers and in long outages will originate from the windings, including intake leads. Bushing and tap changer failures can usually be repaired quicker than windings. Therefore quality assurance and monitoring of the insulation system becomes important to secure the reliability of a transformer.

One can split the hazard connected to the transformer insulation into two groups:

- Defects that followed the transformers from the beginning or failures that suddenly occurred during service.
- Normal ageing which will take place gradually and increase possibilities for defects and failures to occur.

The winding defects will typically be arcing, discharges and high temperature spots which to a large extent can be revealed by periodic DGA or continuous gas monitors. The occurrence of such defects will be higher in the start of the transformer life than later due to child “diseases” and then over a long period stochastic until end of life approaches and the probabilities will increase. Presently there are few signs of increase in defect and failure rates from service statistics.

The normal ageing will mainly concern deterioration of oil and paper and pressboard. Several conditions have relevance for evaluation of ageing:

- Which materials are used (cellulose and oil qualities)
- Thermal conditions (design, load and ambient temperatures)
- Cooling equipment; its setting and operation
- Knowledge and models for material ageing
- Tank design with breathers and sealing
- Contamination of oil and cellulose
- Content of ageing markers in oil and in cellulose
- Availability of thermal history and diagnostic data
- Considerations on winding clamping pressure
- Maintenance history; oil reclaiming, drying

Without more detailed knowledge, global statistical data is all a user knows about expected availability of transformers. The natural next step is to establish information about any increased hazards from service, condition and ageing. A population study can then be done to single out units which need special attention based on technical condition or severe consequences. Information from oil and DGA analysis and simple spreadsheets using historical load data and condition measurements can be used for this. Such a study will always show quite large uncertainties. To reduce uncertainties for units where repair, refurbishment or renewal is considered one need improved diagnostic and modeling.

This report will describe present knowledge – both what is developed in this project and what is available from other sources – on transformer winding ageing.

3 WINDING, FAILURE AND AGEING MODES

The winding is stressed both continuously and by transients. The stresses are:

- Dielectric stresses with continuous ac and occasional lightning and switching surges. Moisture reduces the dielectric properties.
- Mechanical stresses originate from inrush and short circuit through current giving rise to high shear stresses in end windings. Reduced tensile strength of winding insulation and reduced winding clamping increase possibilities for damage.
- Thermal stresses come mainly from current heating of windings and will be design and partly manufacturing dependent. One can calculate hotspot for each winding knowing the hotspot factor, ambient temperature and load. Sudden thermal stresses – like for emergency overloading - can be harmful if cellulose has a high water content: Then water vapor bubbles may be formed in the windings when water vapor pressure builds in the cellulose and the oil cannot absorb the excess water. At sudden temperature drops water "mist" may be formed when the oil becomes oversaturated. Both vapor bubbles and mist will potentially result in winding and disc short circuits.
- Chemical stress factors will be water, acids etc. that will accelerate ageing of cellulose. Oxidation of oil may also produce sludge that will reduce winding cooling. Lately copper sulfide formation has become a problem accelerated by high temperature.

From a strategic point of view it is the insulation system of the winding that is of the largest interest, and for the asset manager knowledge of failures and present and future ageing status is what is requested. Most fault conditions are revealed via gas analysis. Our topic here is the irreversible ageing of the oil impregnated cellulose insulation.

The end-of life and failure scenario for the winding is a consequence of irreversible and progressive degradation and reduction of tensile strength of paper. Large through currents from e.g. external short circuit will give large shear stresses particularly in the end windings that, when the paper is weakened and/or clamping pressure is reduced, will result in movement of the windings. This will either directly result in winding or disc short circuits, or this may occur later at the next high current transient, or at switching or lightning overvoltages.

In this context two ageing mechanisms should be considered. One is the possibility of plastic deformation from dynamic thermal stresses and continuous expansion stresses from moisture ingress. The other is the reduction in tensile strength of cellulose; paper around conductors and pressboard used in spacers etc.. The simplest general formula for ageing rate *k* is the Arrhenius relation for a process of 1st order:

$$\boldsymbol{k = Ae^{-E/RT}} \qquad \textbf{(1)}$$

Where *A* – the pre-exponential factor, expressing the probability that a reaction will take place - is determined by the general contamination content of the cellulose (water, acids and oxygen), *E* is the so-called activation energy, which determines the temperature dependence of the material ageing process in question in [kJ/mol], R is the Gas constant [8,314 $JK^{-1}mol^{-1}$] and T is the absolute temperature in Kelvin.

This ageing kinetic formula shows the instantaneous ageing rate, which can be estimated for each ageing process for the relevant material if the E and A values are known and temperature can be determined. To find the ageing over a certain period either one has to integrate the ageing over time based on ageing kinetic formulas or assume some average historical or future conditions from statistics and experience.

The E and A values have to be established experimentally based on influence from various contamination substances for the material in question. Later, if one knows the relation between the content of contaminants and ageing one can determine the A-values from diagnostic measurements of contaminants.

Water is an important ageing accelerator, which also has relevance to other failure and ageing scenarios as dielectric strength of oil and bubbling at high temperatures at overloading. Usually the A values for cellulose ageing are determined from measurement of contaminants in the oil and estimation of cellulose conditions via equilibrium curves. Not to forget, temperature is important also for other failure modes like e.g. copper sulfide formation.

4 TRANSFORMER DESIGNS AND THERMAL AGEING OF WINDINGS

As described above, one can estimate ageing of cellulose material knowing:

- Temperature
- The ageing process for the relevant material
- The contamination

The ageing processes are described as thermally activated; that is because they are accelerated with increasing temperature. In the transformer the oil temperature is higher at the top of the transformer than at the bottom and it is higher inside the winding than in the surrounding oil. The area with the highest temperature – called hot-spot - is usually the second turn or disc from the top of the winding. Here the stray losses are highest and there is heat from turns or discs both below and above[1]. Within IEC community hot-spot temperature at rated conditions is assumed to be 98ºC with 20 °C ambient and 78K temperature rise.

IEC's loading guide 60076-7 describes how the temperature distribution can be described as shown in Figure 1: top and bottom oil temperature can be measured using thermometers, and the average winding temperature can be calculated from resistance measurement on the winding. The hotspot factor *H* is a factor used to calculate the hotspot temperature. This factor is specific for each design, winding and cooling mode and should be requested from the manufacturer when buying a transformer. It is known to vary in the range 1.0 - 2.6 [1]. Since 1990 fiber optic temperature sensors have become available, and knowledge of hotspot conditions and calculations are improved. For older transformers it can be uncertain which value to use. Design has also changed with time with introduction of zig-zag cooling et cetera. If one does not know this factor for the transformer, then the guide suggests using a hotspot factor of 1.3 for large power transformers.

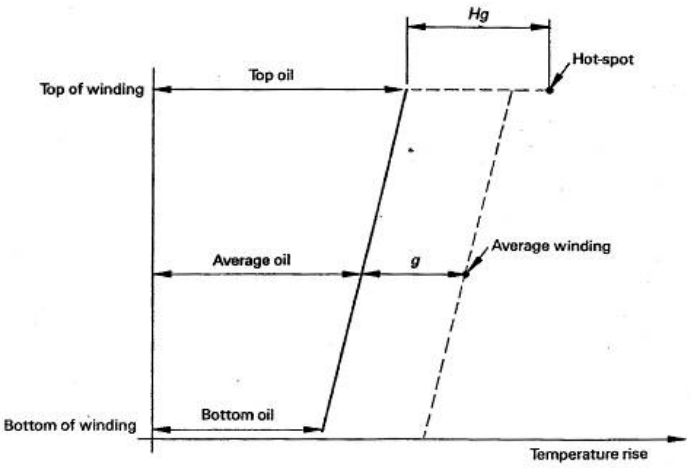

Figure 1: Thermal diagram for transformers.

Hot spot temperature of a transformer at a given load can be calculated based on the data available from the standard heat run test (rated top oil temperature rise – ($\Delta\theta_{or}$), average winding to average oil (g), loss ratio (R) , and oil (x) and winding (y) exponents). For example for an ONAN cooled transformer the simplified formula for the hot spot temperature (θ) for steady state reads:

$$\theta = \theta_a + \Delta\theta_{or}\,[(1+RK^2)/(1+R)]^x + Hg_rK^y \qquad \textbf{(2)}$$

where θ_a is ambient temperature, K is load, Hg_r is hot spot to top oil gradient.

[1] This is only indicative. Variation of cooling duct height, interleaved windnings, oil guiding rings, etc will influence.

For ageing estimation one only needs yearly weighed averages and does not need to include transient conditions. If one knows yearly averages of ambient temperature and daily, weekly and seasonal load variations then estimates can be made of yearly weighted average temperature for use in the ageing kinetic formulae according to the formulas given in the loading guide IEC 60076-7.

The ageing kinetic formula (1) describes ageing for one single process and one specific material. It is a general formula and can be used more or less for any material: oil or cellulose. When it comes to paper there are two main qualities: it is normal kraft paper and thermally upgraded paper where certain nitrogen compounds are used to make the kraft cellulose more resistant to ageing. In Norway all transformers produced by National Industri from about 1967 to 1977 were produced with Insuldur type upgraded paper on a Westinghouse patent. Since 2000 several companies have specified transformers with dicyandiamide treated upgraded paper. Upgrading of paper is a process which is not standardized by IEC. Pressboard is manufactured in different qualities of normal kraft cellulose. Heat pressed high density qualities are used for spaces, ribs and barriers taking up mechanical stress, and low density used for angle rings, snouts and parts that has to be shaped.

The cellulose is exposed to two main ageing processes; oxidation - influence from oxygen - and hydrolysis – influence from water. There is also pyrolysis which becomes significant at temperatures far above normal operating conditions, being more relevant for thermal fault conditions. The constants in the Arrhenius ageing kinetic formulae are specific for each single material and ageing process.

Also oil conditions may play a role. In Norway most oils are naphthenic inhibited mineral oils: these are severely refined oils where most polyaromatics and sulfur compounds are removed and an antioxidant (DBPC – Di-tert-butyl-p-cresol) is added. In other countries oils are often uninhibited: These oils are less hard refined and contain natural antioxidants, of which most are sulfur containing compounds. Information is ambiguous concerning the influence of how the antioxidants influence the cellulose ageing. It is normally assumed that when the oil ages it produces both high and low molecular weight carboxylic acids. The smaller ones will be partly water soluble and will be absorbed by the cellulose where they contribute to hydrolytic ageing.

Most studies on ageing of impregnated cellulose are done using mineral oils as impregnants. For the "new" insulating ester liquids further studies are needed to see if they have other effects on the cellulose ageing than the mineral oils have. However, one thorough study [2] revealed no differences between liquids for the initial ageing period. After a certain time – and mainly at higher temperatures - water in cellulose was reduced due to interaction of water with the ester liquids, which slowed down the ageing. Within normally operating temperatures (<120 °C) the effects were remarkably small.

Types of breathing systems and cooling systems will also influence ageing. Earlier all transformers in Norway were of the open breathing type. They were always equipped with a moisture trap on the air inlet to the conservator, but leakages and malfunctioning filters may have given moisture access to the conservator. Lately several companies specifies transformers with a rubber diaphragm or cushion in the conservator. This diaphragm will reduce concentration of oxygen in the transformer – typically[2] to 24 000 µl/l - and therefore slow down the ageing processes.

Of course the cooling system and the policy of how to operate pumps and fans will influence operating temperatures and thus the ageing. For condition assessment the cooling mode should be logged together with the load and temperatures to allow for use of the correct formulas for temperature estimation.

[2] This refers to modern headspace technique measurement

5 THE AGEING MODELS

Cellulose in transformers consists of kraft cellulose produced from softwood, either in the form of paper or pressboard. The kraft cellulose consists of 75-85% cellulose, 10-20% hemicellulose and 2-6 % lignin. Thermally upgraded paper has been treated with various nitrogen compounds.

The ageing kinetic equation (1) in chapter 3 can be used for any ageing parameter and process. For paper it is the mechanical strength measured as bursting, folding or tensile strength that is impaired with time. This deterioration was earlier described by Montzingers rule, stating that life was halved/doubled for every 6-8 degrees:

$$\textit{Life duration} = e^{-p \cdot \theta} \qquad (3)$$

Where p often is 6 and θ is the temperature in Celsius being 98 ºC for unit life. Equation (3) is simplification of the Arrhenius relation (Equation (1)), and it is only valid within a limited temperature range. The correlation between p and activation energy E_A is seen in Table 1. This table shows the link between an Arrhenius relation of the ageing where the temperature dependence is given by the E_A-value, here in kilojoule per mol, and Monzinger's rule giving the temperature change that will halve or double the life time. For example will an activation energy of 110 kJ/mol correspond to a halving/doubling of the ageing for every 7.2 °C.

Table 1: Correlation between activation energy and temperature shift for halving of life.

E_A [kJ/mol]	50	70	90	110	130	150
p [°C^{-1}] at 98 °C ref.	16.2	11.4	8.8	7.2	6.1	5.2

Measuring tensile strength which is the best parameter to describe the functional need, is not a very reproducible or reliable method for evaluating paper samples from old transformers. Tensile strength will be correlated to the average length of the cellulose molecules – as seen in Figure 2 – hence measuring degree of polymerization has become a method in widespread use. The degree of polymerization (DP) is the average number of saccharide units in a cellulose molecule as sketched in Figure 3. It is measured via the viscosity of a "soup" of dissolved cellulose, where viscosity increases with fiber length. For paper in a newly delivered transformer, after it has been heat treated in the drying process, the DP-value is about one thousand – 1000. From Figure 2 we see that down to a DP of 500- 600 little reduction in mechanical strength has taken place. Commonly one assumes that the transformer life is over when DP reaches 200. Then only 20-30 % of the paper's original tensile strength remains. However, the decision of which end-of-life criterion to use is up to the transformer owner.

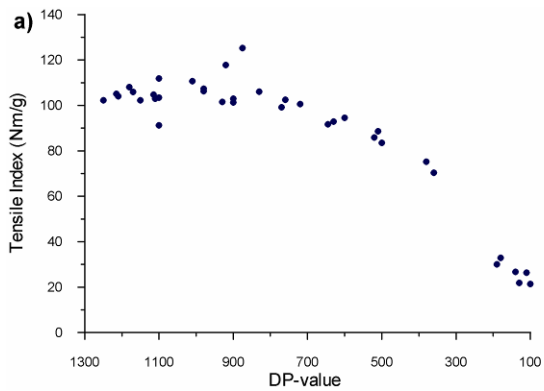

Figure 2: Correlation between tensile index and degree of polymerization for paper.

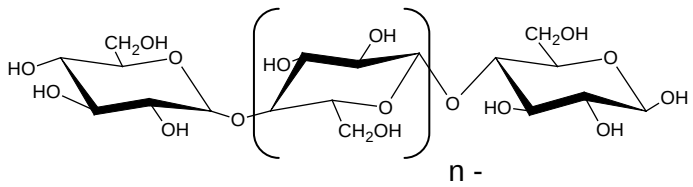

Figure 3: Structural formula of cellulose.

Ageing of pressboard and paper will be influenced by water content, oxygen availability, temperature etc in different deterioration processes called:

- Oxidation, where presence of oxygen and different catalytic processes involving peroxide formation assist in breaking up the cellulose chains.
- Hydrolysis, where water and carboxylic acids, also formed via cellulose ageing assist in chain cleavage in a so-called autocatalytic process.
- Pyrolysis, which will go on without influence of oxygen and water, but at temperature far above the normal operating temperature.

The DP-value falls monotonically with time as chain scissions take place and is accelerated with increasing temperature as shown in Figure 4a. Chain scissions are calculated as $\eta = DP_{new}/DP_{old} - 1$ and develops inversely with the change in DP. As shown in Figure 4b the rate of change in 1/DP is constant in the start of the ageing.

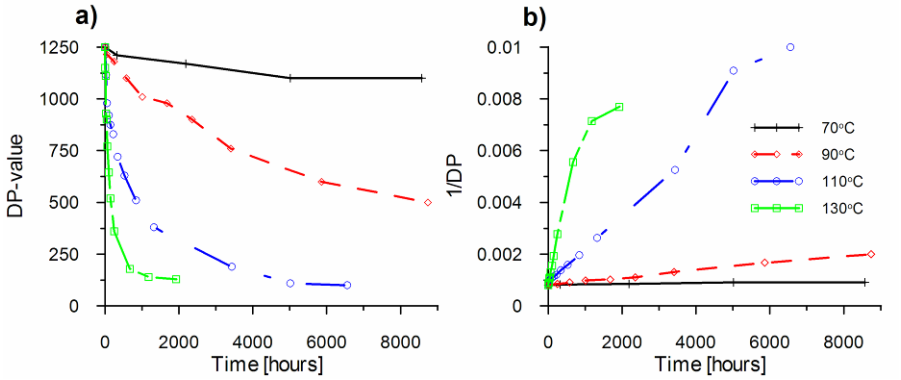

Figure 4: Change in DP and 1/DP with time for kraft paper with 3% moisture.

From Figure 4a one can see that the DP value does not approach zero, but a higher value - probably determined by the microcrystallinity of the cellulose - called the *level-off value*. From Figure 4b we see that the rate of change in chain scissions may fall off with time. These are both deviations from the simple 1st order Arrhenius relation and an alternative ageing formula has been suggested by Emsley et al. [3]. In experiments it is often time-consuming to establish curves down to low DP-values. The initial ageing is easier to study. For the end user any *consideration based on initial ageing rates will yield conservative estimates on the ageing* development and one will therefore be on the safe side.

In 2001 SINTEF published results from a long-term study on ageing of cellulose [4] suggesting that the activation energy is different for hydrolysis and oxidation. Here one attempted to separate the influence of oxygen and water presence. The experiment continued for another three years supporting the hypothesis that the temperature dependence was different for oxidative and hydrolytic ageing. This is also supported by other studies [5, 6]. The extended data has now been processed, and reaction rates for the different

conditions calculated based on the initial ageing up to around one chain scission (DP going from 1250 to 600). In some of the low temperature experiments where ageing was less progressed, the rate was calculated based on the final DP values, being higher than 650. The ageing rates were calculated from a linearization of curves like those in Figure 4b. Then – assuming a 1st order ageing model - these values were plotted in an Arrhenius plot, showing the natural logarithm of the ageing rate versus inverse absolute temperature. Finally, for each ageing experiment the average activation energy over the range from 70°C to 130°C was calculated and corresponding A-values estimated. These E and A values for normal kraft paper and for Insuldur process upgraded cellulose are shown in Table 2 and in Table 3. Figure 5 shows Arrhenius plots of how the experimental values fit with the 1st order ageing model during the initial ageing period.

Table 2: Activation energy (EA) and environment factor (A) for oxidation and hydrolysis of Kraft cellulose.

Parameter	Dry, no oxygen.	1.5%-moisture	3.5%- moisture	Dry, Oxygen. access
E_A-value [kJ/mol]	128	128	128	89
A-value [hour $^{-1}$]	$4.1 \cdot 10^{10}$	$1.5 \cdot 10^{11}$	$4.5 \cdot 10^{11}$	$4.6 \cdot 10^{5}$

Table 3: Activation energy (E_A) and environment factor (A) for oxidation and hydrolysis of Insuldur upgraded Kraft cellulose.

Parameter	Clean system	1.5%-moisture	3.5%- moisture	Dry, Oxygen. access
E_A-value [kJ/mol]	86	86	86	82
A-value [hour $^{-1}$]	$1.6 \cdot 10^{4}$	$3.0 \cdot 10^{4}$	$6.1 \cdot 10^{4}$	$3.2 \cdot 10^{4}$

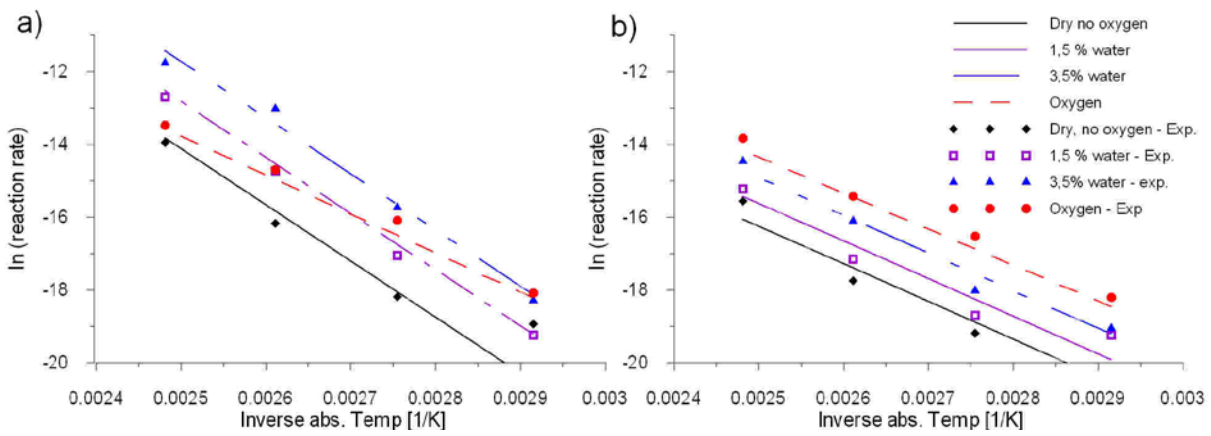

Figure 5: Arrhenius plots of ageing of (a) Kraft paper (Munksjø termo 70) and (b) Thermally upgraded paper (Insuldur).

In a real transformer, oil and cellulose ageing occur in parallel. The fact that cellulose ageing is driven by different processes - hydrolysis, oxidation and pyrolysis – that act simultaneously, hampers the application of one singular activation energy. How ageing rate depends on temperature will vary with regard to which process that dominates in a specific temperature range as suggested in Figure 6. Dominating process will be governed by both temperature and contamination condition. Also synergetic effects take place between the different reactions; e.g. oxidation may activate hydrolysis by producing acids.

However, we will for illustrative purposes assume independent processes. The total degradation – expressed as average number of chain scissions experienced - then being the sum of degradation from each process becomes:

$$\eta_{Tot} = DP_{new}\left(A_{Oxi}\, e^{\frac{-E_{Oxi}}{R \cdot T}} + A_{Hyd}\, e^{\frac{-E_{Hyd}}{R \cdot T}} + A_{Pyr}\, e^{\frac{-E_{Pyr}}{R \cdot T}} \right) \cdot t \qquad \textbf{(4)}$$

where *Oxi*, *Hyd* and *Pyr* are used as subscripts to identify the activation energy *E* and the environment factor *A* for each process mentioned above.

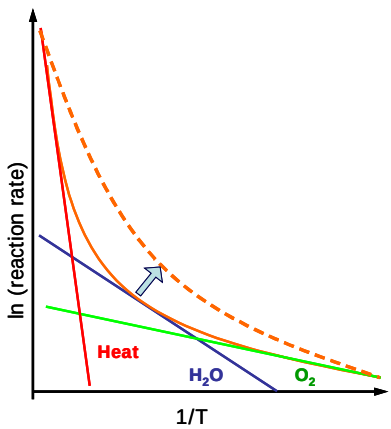

Figure 6: Sketch of ageing rates due to different ageing mechanisms. The arrow shows the effect of increased water content increasing the A-factor for hydrolysis.

5.1 HYDROLYSIS AND DEPENDENCE OF INSULATION CONDITION

The hydrolysis of cellulose is a catalytic process where the reaction rate depends on acidity; that is H^+-ions (or rather H_3O^+, because the proton immediately is associated to a water molecule) from carboxylic acids dissociated by surrounding water molecules. These H^+-ions can easily get into the amorphous zones of the cellulose. This decomposition process needs both water and free acids. Apparently, hydrolysis is the dominant mechanism in the upper range of transformer operating temperatures. The environmental factor (A) depends on the dissociation constant for acids present, the amount of free acids, and the water content. It is also shown that the lower the molecular weight of the carboxylic acids is the more detrimental it becomes [6]. As hydrolytic degradation of cellulose produces water and low molecular acids this process is auto-accelerating.

As explained, for hydrolysis the A factor will depend on several factors. How it depends on the water concentration in paper is shown in Figure 7a. For new transformers the water content is in the 0.5% range. The quantitative effects on ageing rates from the acids are more uncertain. Figure 7b shows that large oil-like carboxylic acids as stearic and naphthenic acids hardly change the ageing, while the water soluble low molecular weight acids accelerate ageing. Also one should be aware that quantification of acids in paper is a difficult task. One has experienced that of acids absorbed by paper only a fraction can be recovered. Earlier we found at best a 50 % recovery rate [7], later we have found - as explained in chapter 5.1.1 - that this is due to acids reacting chemically with the cellulose via esterification processes, leaving only a fraction of the acids as free to contribute to the acid catalyzed hydrolytic ageing.

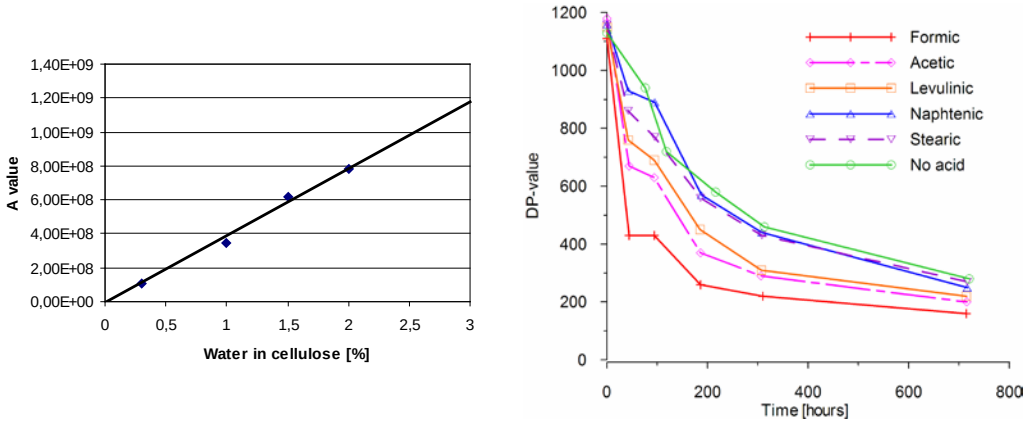

Figure 7: (Left) A value dependence on water in paper for activation energy 111 kJ/mol.(A-values only relevant for this activation energy) – (Right) Acid influence on DP-reduction from hydrolysis [7].

Still there are no valid formulae for including acidity into the A-value. An experiment where acids were added to oil and allowed to be absorbed into paper before ageing experiments were started gives some hints. It looks as if the synergetic effect of water and acids can be seen as largely multiplicative and depending on the molecular weight of the acids, being worse the smaller they are. When comparing the effects the three acids have over the range 70-130ºC one gets factors as shown in Table 4. In this case the estimated concentrations of acids in paper was in the range of 6mg KOH/g paper, which is quite high - but not extremely high - compared to what is expected for older aged transformers. The acidity of paper was estimated based on the measured reduction of the acidity in the oil. From Table 4 we can see that by increasing water content from 0.75% to 2.5% the ageing rate increased by a factor of two, while a factor of three would have been expected from Figure 7a.

Table 4: Acceleration factor A for low molecular weight acids compared to conditions without acids [7].

Acid type	Formic	Acetic	Laevulinic
Dry cond. (0.75%)	5.6	2.6	1.6
Wet cond. (2.5%)	11.6	4.4	3.0

5.1.1 Esterification of carboxylic acids in cellulose

As low molecular weight acids in paper/pressboard contribute to the degradation of cellulose, establishing a parameter which links the susceptibility of cellulose to hydrolysis to Low Molecular weight carboxylic Acids (LMA) concentration would be highly advantageous. However, establishing such a parameter requires detailed knowledge of the reactions and reaction conditions between cellulose and LMA. Here, we have studied the interaction between acidic LMA-containing oils and Kraft paper, and the subsequent effect on the molecular structure of cellulose. We show that chemical reactions between LMA and cellulose lead to loss of mass balance in simple acid extraction procedures [8].

In this study it has been demonstrated that LMA dissolved in mineral oil will interact with cellulose and form esters. In addition to available acid concentration and time of conditioning, the degree of esterification is governed by the temperature the oil/acid/paper-system has been exposed to. Specifically, higher temperatures lead to a shift towards ester formation compared to lower temperatures. The esterification process can be reversed by water extraction at elevated temperatures. However, the importance of reversing the process in order to target all acid groups present in the cellulose (both free and bounded) is questionable with regard to characterization of threatening hydrolyzing degradation of the cellulose, as only free acids

with a carboxyl group available for reaction will take part in such chain breakage of the cellulose polymer. It is therefore more appropriate to extract with cold water in order to quantify the amount of free acids dissolved in the paper/pressboard. In more detail; water extraction at 70 °C leads to an almost complete reversal of the esterification. However, extraction using cold water (4 °C) does not shift the equilibrium appreciably during the relevant extraction time interval due to slower kinetics and a relatively higher reaction barrier, mostly targeting free acids. Thus, extraction using cold water is more efficient at targeting free acids, cause negligible shifts in the cellulose composition, and comprises a more informative extraction protocol with regard to acids available for hydrolytic degradation of cellulose. It is important to keep in mind that reversal of the esterification requires large excess of water; *hence acids converted to esters will not be "released" while the paper is submerged in oil.*

Numerous cold water extractions followed by titration of the extract has demonstrated that exact determination of free acids in cellulose that has seen realistic conditions is demanding. The challenges are mainly seen as a consequence of the low concentration of free acids in paper and hence in the extract; approaching the detection limit of the titration procedure.

5.2 OXIDATION AND INFLUENCE OF OXYGEN CONTENT

Oxidation is another ageing mechanism for paper. It requires presence of oxygen. The ultimate end products of oxidation are much the same as for combustion, i.e. water and carbon dioxide. However, the mechanism of low temperature oxidation is quite different from that of combustion with a large variety of formed substances. The oxygen concentration is one important parameter in determining the rate of oxidation. However, the rate is not linearly dependent on oxygen concentration as we will see below. Oxidation is suggested to be catalyzed by hydroxyl radicals (HO^*), which are produced by decomposition of hydrogen peroxide (H_2O_2) and of organic hydro peroxides (ROOH). Oxygen is needed to form peroxides, being the rate controlling substance for this. Hydrogen peroxide can for example be formed from oxygen and water though a reaction catalyzed by transition metal ions (such as $Cu^+/Cu^{2+}/Fe^{2+}/Fe^{3+}$).

In laboratory experiments, the overall degradation rate including oxidation has been approximately twice as high as when oxygen is totally excluded. In general oxidation will show lower activation energy than hydrolysis. Values in the range of 80 – 90 kJ/mol can be calculated from early experiments performed with and without oxygen [Table 2]. In later experiments where copper dust has been added to facilitate radical formation more easily, values around 75 kJ/mol were found [5]. As the activation energy is low, then the ageing rate does not fall so quickly with reduced temperatures and at low temperatures oxidation may therefore become dominating. Oxidation is promoted in an alkaline environment, and as this process also produces carboxylic acids, it will attenuate with time. The details of the oxidation process are less understood than for the hydrolysis.

Figure 8 shows how oxidation depends on the temperature and partial pressure of oxygen. The experiments performed on Munksjø Termo 70 (a non-upgraded paper quality) in Nytro 10X mineral oil shows that a fit to a first order ageing process is acceptable. The activation energy found for the initial ageing fits with what is suggested in Table 1. We also see clearly that the reaction rate does not fall proportional to the partial oxygen pressure: one has to reduce oxygen concentration to $1/4^{th}$ of what it would be in equilibrium with air, to reduce ageing rate to 50%.

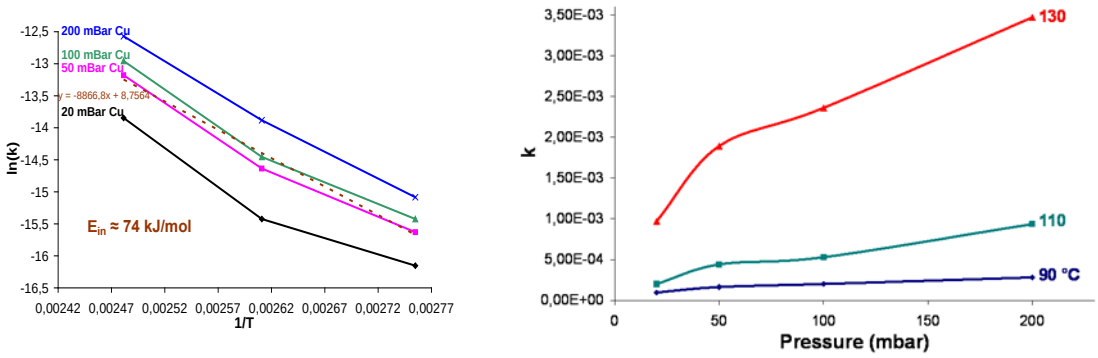

Figure 8: Arrhenius plot of initial oxidation of cellulose at different partial pressures (left) and pressure dependence of reaction rates (right) [5].

Norwegian experience on dissolved gas analysis (DGA) is that for an open breathing transformer the oxygen content is about 24 000 µl/l when measured using the headspace technique. (Using a Toepler pump it was found to be about 33 000 µl/l). For a transformer equipped with a rubber cushion the oxygen level is found to vary within 4000 – 10000 µl/l using the headspace. Assuming that these values correlate proportional to the partial pressure, you should get below the tipping point (50 mbar) to get a significant effect of reduced oxygen content, corresponding to an oxygen concentration below 6000 µl/l.

5.3 INFLUENCE OF UPGRADING OF CELLULOSE

A wide range of thermal upgrading systems are available, and the most significant difference between them is the amount of nitrogen used. Because the thermal upgrading chemicals are in most cases not present in kraft pulp, the degree of chemical modification is often determined by testing the amount of nitrogen present in the treated paper. Typical values for nitrogen content of thermally upgraded papers are between 0.5 and 4 percent.

Our results from Table 2 and Table 3 are plotted in Figure 9 to allow for an easy comparison between Insuldur upgraded paper and Munskjö Termo 70 paper, which both are frequently used in Norwegian transformers.

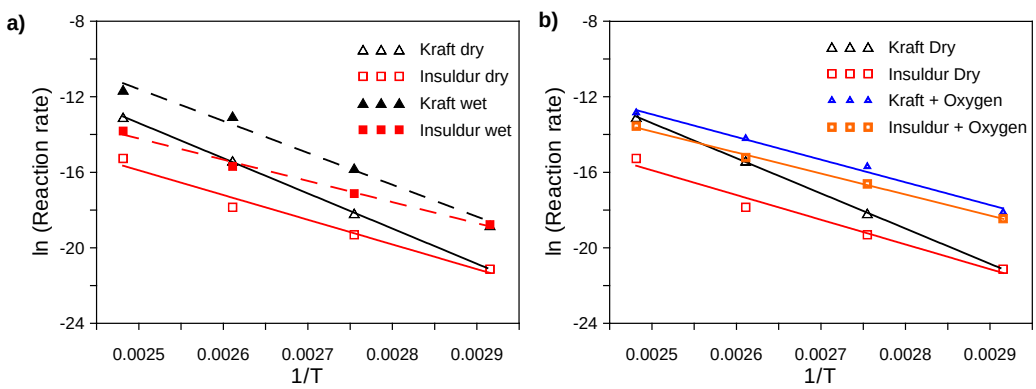

Figure 9: Comparison between effects of hydrolysis (a) and oxidation (b) in kraft paper and in upgraded paper.

5.4 AGEING OF SERVICE AGED PAPER

An ageing experiment was performed on paper and oil sampled in 2013 from a service aged GSU transformer from 1965 [9]. Crepe paper was sampled from the low voltage connections. The paper had a DP of 440 and a water content of 1.8 %. Oil had an acid number of 0.1 mg KOH/g. This value is too low to attempt extraction of low molecular weight acids from oil. Ageing was done at 90 °C and 110 °C at three different conditions (closed under nitrogen, closed under oxygen and open breathing).

Results on the closed systems with and without oxygen showed activation energies of 113 and 112 kJ/mole respectively. The presence of oxygen accelerated ageing a factor of 2,5. The water content remained around 2 %. (For the breathing system water content was unstable.)

Ageing for the oxygen free system was roughly in agreement with estimations based on values from Table **2**, fitting the A-value to 1,8 % water content. The main lesson learnt is that the activation energy for service aged systems seems to lie in the range 111 kJ/mole. Our estimates of activation energy from Table **2** for pure hydrolysis seem too high and for oxidation too low.

5.5 INVESTIGATION OF PERFORMANCE OF DIFFERENT UPGRADED PAPER TYPES

The ageing behaviour of several oil impregnated, commercially available thermally upgraded and non-upgraded paper types was investigated under different contamination conditions at 90, 110 and 130 °C. The parameters measured were: DP-value, nitrogen concentration in paper, acidity of paper and oil, and water in oil content. Experiments are described in [10]. Figure **10** illustrates the variations in performance that was experienced. The following was found:

- *The level of nitrogen* in the papers is crucial for achieving an improved ageing performance from the upgrading process. One of the paper types, which had low nitrogen content (also below the specified value) showed little or no improvement compared to the non-upgraded papers. Furthermore, nitrogen content dropped below the detection level during the experiments. The Insuldur process, having the highest nitrogen content and applying several nitrogen containing compounds, showed the best performance.
- *Water production* increases with temperature and presence of oxygen for all the paper types. More water measured in the oil for non-upgraded papers than upgraded papers at high temperatures. This can either be because less water is produced by the upgraded paper or that it binds more water.
- *The measured acid in oil* content increases with time and increased temperature, but differences are small between the 100 and 130 °C ageing conditions.
- *The thermal upgrading* of paper have the following effect:
  - Positive effect on ageing under wet conditions (3% water content), when oxygen was removed (Argon atmosphere).
  - Ageing of dry samples (< 0.2% water content) under oxygen-poor conditions is reduced. It is uncertain if ageing under these conditions is hydrolysis or oxidation.
  - In the start of the experiments presence of oxygen made no difference between upgraded and non-upgraded paper types. However when ageing had progressed the upgrading improved performance. This is explained by a shift in the ageing process from oxidation to hydrolysis as water and acids are produced.
- For normal kraft paper the activation energy (or temperature dependence) is lower for oxidation than for hydrolysis.
- For upgraded paper types there is less difference between ageing rates for oxidation and hydrolysis, and the activation energy for hydrolysis is lower than what was found for normal kraft papers. Altogether this indicates that the upgrading substances suppress hydrolysis while being less efficient for reduction of oxidation.

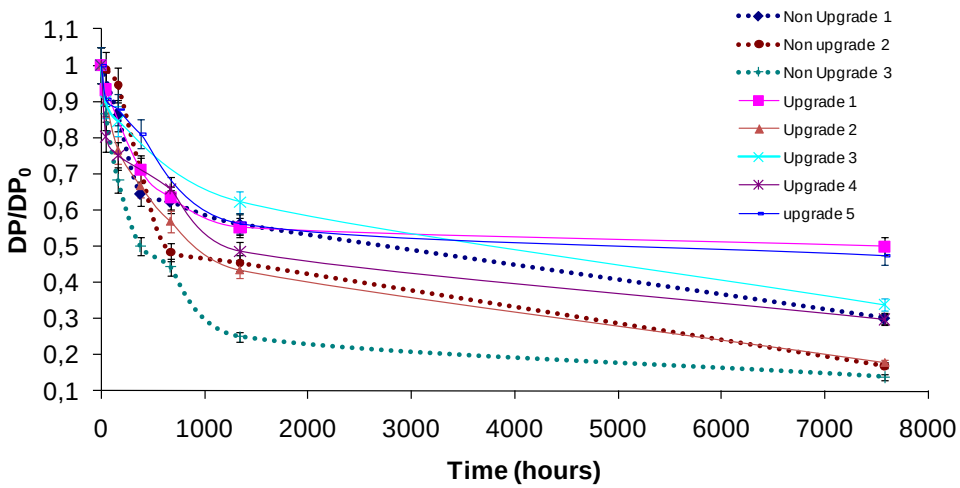

Figure 10: Ageing of different paper types under wet condition and argon atmosphere, normalized DP.

5.6 AN ATTEMPT TO CONTROL CELLULOSE AGEING BY ADDING INHIBITORS VIA THE OIL

It was suggested to add agents to the oil that would be absorbed by the cellulose and reduce its ageing rate: Amines for reducing hydrolysis and alcohols for reducing oxidation.

The results show that indeed the hydrolytic ageing was reduced by adding amines to the oil. The alcohols had no significant effect on cellulose ageing. However, in the presence of oxygen the amines showed a detrimental effect on the oil, resulting in a very fast oil oxidation [11].

5.7 MICROCALORIMETRIC STUDIES IN CELLULOSE AGEING

Because of the long experimental times and amount of labour with more traditional ageing experiments there is a wish to find faster methods to investigate the ageing rate and compatibility between materials at various conditions. It has earlier been proposed to use a micro-calorimeter to study ageing of electrical insulation materials [5, 12, 13] assuming that the heat produced from the ageing sample in steady state (after 10-15 hours) is proportional to the reaction rate. At steady state we expect most of the physical processes contributing to the initial transient heat flow (e.g. evaporation, partitioning, diffusion, swelling) to be over and assume the ageing rate to be proportional to the heat flow. At the same time it is important to recognise that the total heat production in steady state may be a sum of several processes occurring simultaneously. Figure 11 gives an example of a typical heat flow signal from two paper types: P1 is a normal kraft paper, while P2 is a refined paper where hemicelluloses and lignin content is significantly reduced.

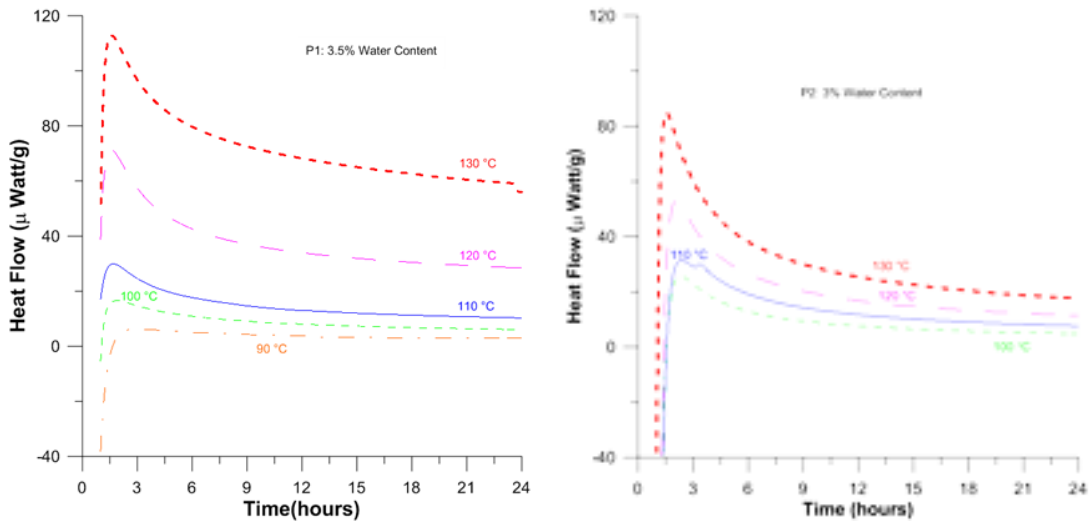

Figure 11: Heat production versus time: Hydrolysis of oil impregnated P1 and P2 papers at 90, 100, 110, 120 and 130 °C in N_2, (average values). No measurements at 90°C for P2 were performed.

Table 5: Activation energy estimation from heat flow and DP measurement for the P1 and P2 paper under different conditions.

Paper type	Water content	Gas	E_A [kJ/mol]			
			From heat flow		From DP	
			(10 hours)	(24 Hours)	Vials	Bottle
P1	0.2 %	N_2	67	**69**	**75 ***	110
P1	1.5 %	N_2	84	**87**	**105**	111
P1	3.5 %	N_2	87	**92**	**113**	111
P2	3 %	N_2	49	**54**	**80**	
P1	0.2 %	Air	48	**54**	**51**	75
P2	0.2 %	Air	20	**29**	**21**	

* For the low water content P1 hydrolysis we estimated DP after 1 week of ageing because of low accuracy in the reaction rate estimation after 24 hours.

The activation energy for hydrolysis is found to be higher compared to oxidation both when using heat flow as input in the estimation and when using more traditional methods based on DP development. In general the short duration calorimeter measurements seem to give lower activation energies than those derived from more traditional bottle experiments (Table **5**). The temperature dependence of the P1 and the P2 material are different: The P1 materials produce more heat. This is probably caused by the different material composition containing more hemicelluloses and lignin, allowing for other exothermic processes than polymer chain cleavage of cellulose. An experiment comparing heat production in a virgin and a heavily aged sample showed that heat production falls with time. The calorimeter seems to be a tool for quick ageing investigations [14].

6 CONDITION MONITORING

6.1 OVERVIEW OF MARKERS FOR FAILURE AND AGEING DIAGNOSIS

As stated above, we distinguish between diagnostic methods and condition assessment techniques for:

- Early warnings of imminent faults.
- Condition of winding due to normal ageing.

Condition assessment will almost exclusively – at least until suspicion of severe malfunction has been verified – be based on gas in oil (DGA) and oil analysis. For the windings the topics of interest are the condition of oil, the condition of cellulose and the mechanical condition of the winding.

Typical faults will be arcing and discharges in the insulation, hotspots (i.e. > 200 ºC) due to magnetic short circuits or poor soldering, and reduced clamping pressure and winding displacement. The first two are readily revealed by gas in oil analyses, which can be either periodic using glass made sampling equipment or using continuous gas monitors as e.g. fuels cells to detect combustible gasses like hydrogen and acetylene.

Ageing will relate to deterioration of the insulating liquid – here only mineral oils are considered – and to the cellulose based solid insulation in form of wire insulating paper and spacers and board. Temperature is always a driver. Diagnostics will mainly be based on oil sampling, where one infers relations to the cellulose in more or less adequate ways. Cellulose samples may also be taken directly, but with considerable more complications and effort. We can split the diagnostic parameters into two groups:

- Detection of substances that relates to ageing rate acceleration to be used for condition assessment and *modelling using ageing kinetic formulas* (A and E values for cellulose ageing).
- Detection of substances produced during ageing that can be used for *statistical correlation to the degree of deterioration*.

The oil ages primarily via various oxidation processes [15]; presence of oxygen (air) and dissolved metals will accelerate ageing, and oxidation inhibitors which can either be naturally available substances as e.g. some sulphuric compounds or declared additives, hinder ageing. Presently no general Arrhenius type ageing kinetic formulae are available for estimating oil ageing.

When ageing takes place aldehydes, ketones and finally acids are produced. Sludge which may precipitate in cooling ducts may also be produced in the late ageing state. The acids are either large naphthenic or paraffinic based acids or smaller water soluble carboxylic acids. Oxidation inhibitors will hinder oxidation of oil. When they are consumed – after the so-called induction time – oil ageing will be quickly accelerated. Surface tension will drop when an oil ages. Today mainly total acid number (TAN), surface tension and - in the case of inhibited oils –inhibitor level is used to monitor ageing progress.

The cellulose ages as described in chapter 5. To assess present and future condition one can use formulas for cellulose ageing and try to derive the pre-exponential A-factor from content of water and water soluble acids, and oxygen. One can derive water content in the cellulose from water content in an oil sample. This requires equilibrium curves (like Fabre-Pichon or Oommen curves), and knowledge of the temperatures when the oil was sampled. Equilibrium curves only exist for water distribution in new insulation systems. Such curves are not validated for an aged system. For other substances than water such curves do not exist.

Another way of assessing the ageing condition is to detect the concentration of ageing markers produced during the ageing of the cellulose. Here the most promising are furanic compounds, methanol, water, carbon monoxide and carbon dioxide. We will describe the relations a bit more in detail below. One should be aware that these markers will be produced at different rates depending on local temperatures – more at the hotter region at the top of the winding, while the oil sample represents the average. We believe that one should

build databases including all these substances and also operating temperatures and use for future analysis of transformer populations. One should not forget that also these markers will show a partitioning between cellulose and oil. This partitioning needs to be documented and concentrations should be referred to a reference temperature (e.g. 20 °C) using correction factors.

Table 6: Markers and parameters measured in oil used for assessing ageing of oil and cellulose.

Marker substance	Oil		Cellulose	
	Modelling	Statistical	Modelling	Statistical
Temperature	x	x	x	x
Total acid number		x		
Surface tension		x		
Dielectric losses		x		
Sludge		x		x
Breakdown voltage		x		
Passivator	x	x		
Inhbitor content	x			
Content of metals (Cu, Fe)	x			
Oxygen	x		x	
Carbon Monoxide		x		x
Carbon Dioxide		x		x
Furanic compounds				x
Methanol				x
Ethanol				x
Water content			x	x

Measurements on paper samples taken from the transformer will yield results with less uncertainty than indirect interpretation via oil samples. This can either be samples from intake leads, tip of barriers or from insulating materials put into “baskets” placed in the top oil for later sampling. Sampling procedure however is complicated. If one wants to measure contamination in the sample (water and water soluble acids) one has to be quick with putting the paper sample into the sample vial to avoid exchange with surrounding atmosphere. The hotter the transformer the more important this becomes as diffusion and evaporation increases with temperature. Chances to get a good sample is better when the transformer is cooled down. The vial (bottle) also has to be filled up quite well with cellulose to avoid losing contaminants to the air or oil in the vial.

From a cellulose sample one can decide DP-value, and water content. One should be very aware that when using this for evaluation of a transformer results has to be transposed to what it would be at the most critical location – namely the hotspot region. At high loads the hot spot temperature rise over top oil could easily be some 25 º C. As a first estimation one can assume that the contamination at the hot spot will be the same as at the place where the paper was sampled when worst conditions are estimated. This is conservative because when the cellulose gets warmer it will be drier and less contaminated.

6.2 MARKERS AND RELATION TO DEGREE OF POLYMERIZATION OF PAPER

As stated one has to consider that most markers will have a temperature governed partitioning between oil and paper. Furthermore, the marker production will vary with local condition and not the average bulk condition. Production and content of makers will also be different in normal kraft cellulose and upgraded cellulose.

Furanic compounds have since they were first discovered varied in popularity. They will be produced during ageing and also change with time due to chemical reaction after being produced. They are measured by HPLC liquid chromatography according to IEC 61198. Figure 12 shows how the content of 2FAL increases with chain cleavages and reduced DP for kraft paper. For upgraded paper the tendency is very unclear: either production is lower or the upgrading nitrogen compound reacts with 2FAL and breaks it down. In the start there was optimism concerning possibilities to measure 2FAL in oil and directly estimate DP from that. Later it has been clearly shown how uncertain this is. Figure 13 shows on one hand that there is a time dependent furan production in singular units and that there on the other hand is a large spread when correlated with years in service. Broadly speaking we can say that furan is not a parameter, but more an indicator of ageing.

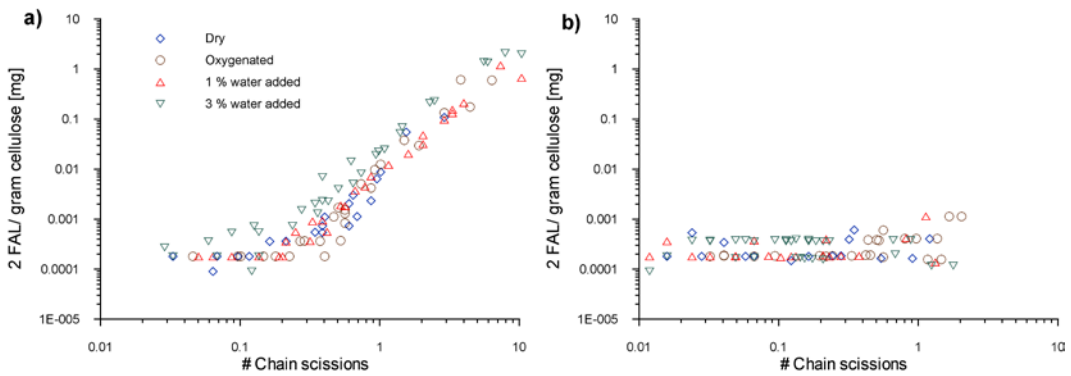

Figure 12: Production of furanic 2FAL in normal and Insuldur upgraded kraft cellulose.

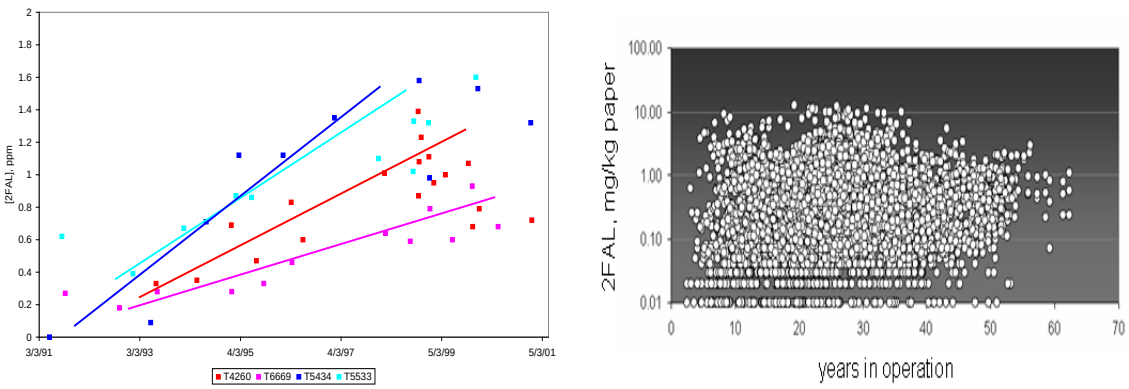

Figure 13: Furanic compounds in (a) four specific transformers over a 10 year period, and (b) 2FAL concentration with time in transformers from 30 countries [16].

Water soluble acids are produced by both kraft and upgraded paper during degradation as shown in Figure 14. These acids will comprise formic acid, acetic acid, levulinic acid and others in an unknown mix. They may also be formed from oil ageing. Concentration in paper is measured by water extraction and titration on the extract.

When measuring the acidity (TAN) of oil the acids will be a mix of larger oil soluble acids coming from oil ageing and smaller water soluble acids expected to stem from both oil and cellulose ageing. Water soluble acids in oil can be measured by measuring acidity of an oil sample before and after mixing and stirring with water to move the water soluble acids to the water and letting the mix settle to separate the oil and water phases and then calculating the difference as illustrated in Figure **15**. One can also measure acidity of the water that is separated from the oil. TAN is determined according to IEC 60296. There is still no clear procedure for measuring low molecular acids but an initial study on how such a protocol can be established has been investigated at SINTEF [17]. In this investigation samples from 43 transformers with a TAN ranging from 0,008 to 0,385 mg KOH/g oil was measured. 19 oils with a TAN> 0.099 mg KOH/g was tested for water soluble acids and the content of low molecular acids varied from 4 % to 28% with an average of 16 %.

We know that the greater part of the water soluble acids will stay in the cellulose where a fraction undergoes chemical reactions with cellulose and a fraction will distribute between cellulose and oil. We expect that one should differentiate between transformers with kraft and transformers with upgraded paper. As oil oxidation also may produce such acids one should consider whether the transformer is sealed or not. One can – even if sensitivity is limited - also analyse for water soluble acids. If water soluble acids are found in the oil, it clearly indicates that the insulation will age quickly in the future. However, the opposite is not true: the absence of water soluble acids from the oil does not mean that the insulation will not age quickly

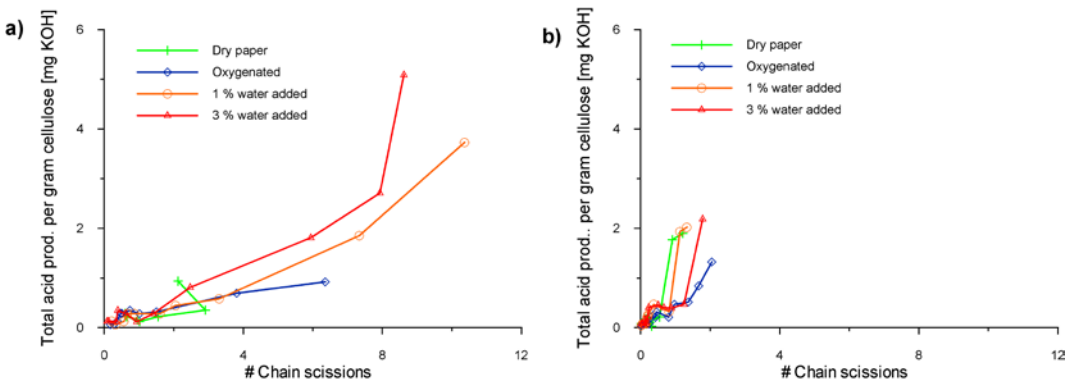

Figure 14: Acidity increase from paper ageing in (a) kraft paper and (b) Insuldur paper.

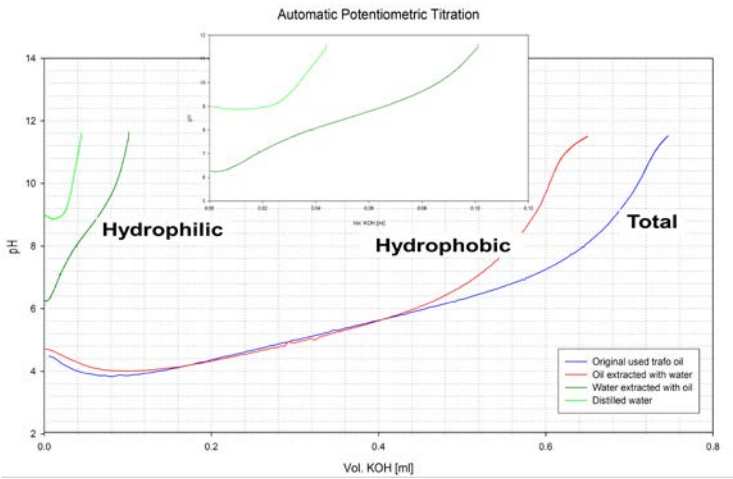

Figure 15: Changing of pH during titration for an oil sample before (Total) and after water rinsing (Hydrophobic) and on the rinsing water (Hydrophilic).

Water is produced by ageing of cellulose and therefore has the potential to be a diagnostic marker. This is problematic in several ways because it also may come from other sources; factory drying has through time varied and water may also come from the atmosphere in case of nonfunctional water traps and leakages in tubes between the expansion tank and the water trap. Figure 16 shows that water production apparently is different in normal and in upgraded kraft paper.

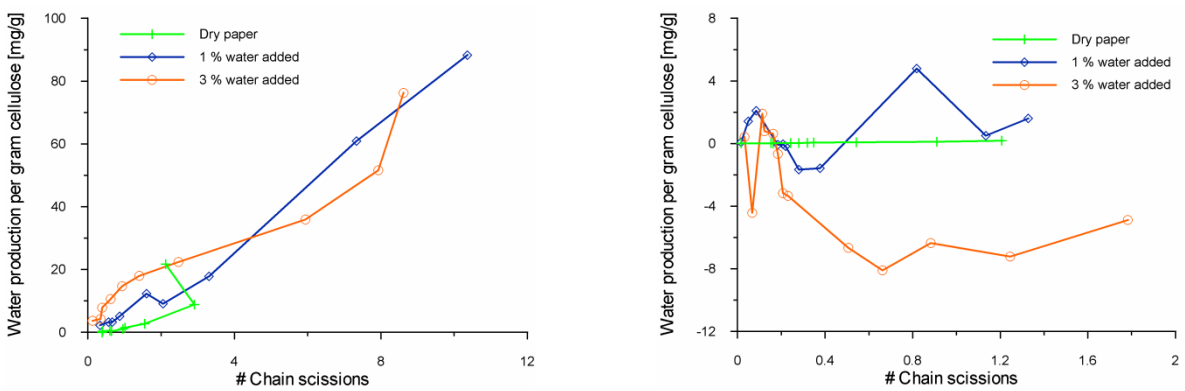

Figure 16: Water production during ageing for (a) kraft paper and (b) Insuldur upgraded paper.

Methanol formation from cellulose ageing has recently been studied by Hydro Quebec and several studies have been published. This marker seems quite promising as shown in Figure 17. One advantage claimed is that methanol is an end product from the ageing. The study is very thorough and supported by further work [18, 19]. We would recommend to test these markers.

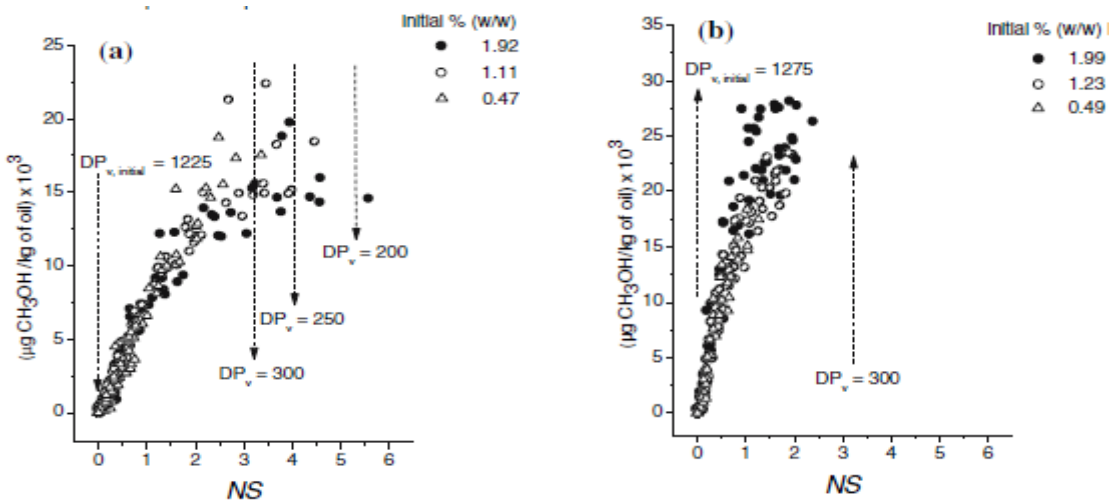

Figure 17: Production of methanol in (a) Clupak HD 75 – low nitrogen content and (b) Manning 220 Manniterm D versus chain ruptures. Water content is given in each figure. Figures from [20].

Carbon monoxide and carbon dioxide is associated with ageing of both cellulose and oil. Over the last 30 years, the analysis of dissolved gases in oil (DGA) has been recommended as a good practice for detecting and characterizing incipient faults in the paper-oil insulation. It has been shown that the amount of dissolved carbon monoxide and carbon dioxide in oil could be correlated with the degree of polymerization and the tensile strength of the paper. However, it should be noted that carbon monoxide and carbon dioxide are also – normally in lesser quantities - produced by the thermal degradation of the oil, layers of paint, varnish and phenolic resins, which are used as transformer components. Carbon dioxide could also result from

atmospheric contamination especially for open, free-breathing transformers. The IEC standard IEC 60599 suggests CO_2/CO ratios above a value of 3 for normal ageing. Otherwise a fault involving excessive paper degradation can be suspected. A low concentration of oxygen (as compared to atmospheric O_2/N_2-ratio) can also be an indication of ageing. However, this type of diagnosis has been disputed [21].

6.3 EQUILIBRIUM CURVES

Most substances in the transformer insulation partition between the liquid and solid insulation. Examples are water, , furans, methanol, to some extent acids, etc. Water partitioning, which is described below, is the most well documented case. Similar, but not yet documented mechanisms will occur for all the other diagnostic markers, and need to be established if full benefit should be drawn from oil measurements.

It is well known that in a transformer most of the water will reside in the cellulose and only a small fraction in the oil. The distribution between oil and cellulose is governed by the solubility of water in the two phases. If left undisturbed at a stable temperature the partitioning will end up in equilibrium where the relative humidity is the same. Then the water vapor pressure is equal in both materials. Since water dissolves well in cellulose and not so well in oil, most of the water will end up in the cellulose. Figure 18 shows how the absolute moisture in cellulose and in oil will end up at different relative humidities and temperatures. For example at 40% relative moisture at 40 ºC there will be 5% by weight (or 50 mg/g) water in the cellulose and 50 ppm (or µg/g) water in the oil. Had the temperature in the cellulose been 100 ºC the water content would have been 3 % by weight (or 30 mg/g).

In a transformer the hotter parts are drier than the colder parts. Much of the water will stay stable in the colder thicker parts of the insulation, while the fraction that resides in the thinner structures (windings barriers and spacers) will change dynamically with temperature and go into the oil at increased temperatures and back again when temperatures drops.

Figure 18shows that water content in oil will change linearly with relative moisture, while for the cellulose the relation is complicated. Particularly at low relative moistures it becomes difficult to measure, and accuracies are low.

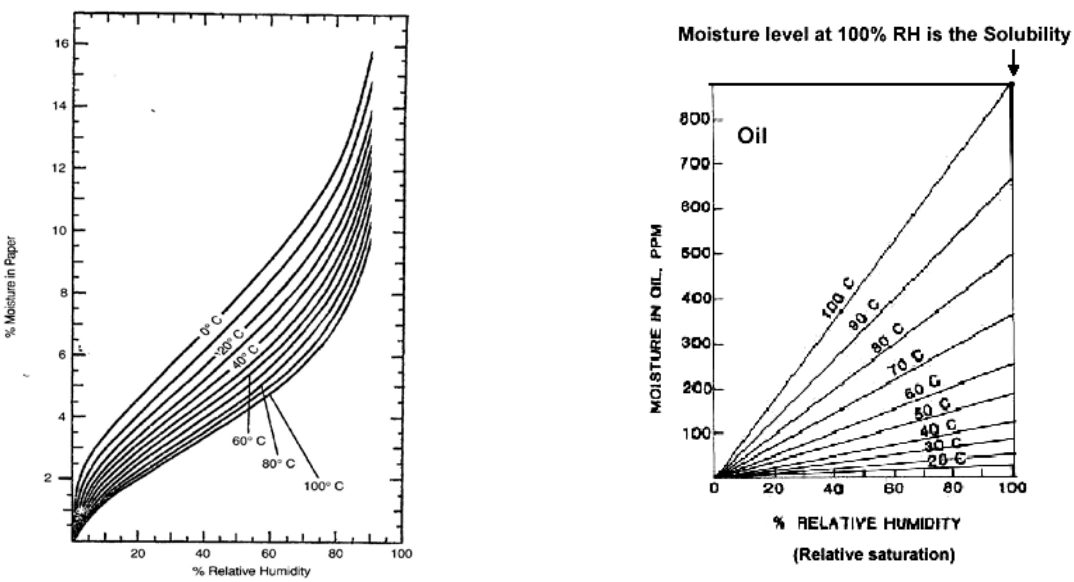

Figure 18: Total water content vs. relative moisture in a) paper and b) oil.

When combining the curves from Figure 18 one can establish equilibrium curves for water in an impregnated system like those shown in Figure 19. These are the curves normally used for transformer insulation assessment: One measures the concentration of water in oil by using Karl Fisher titration, and calculates the concentration in the cellulose. To do this one needs the transformer temperature at the time of the sampling. In practice one uses the average of top and bottom oil temperature and assumes that all cellulose is at this temperature. In reality all the oil will have the same water concentration while in the cellulose the water content will be temperature and therefore location dependent.

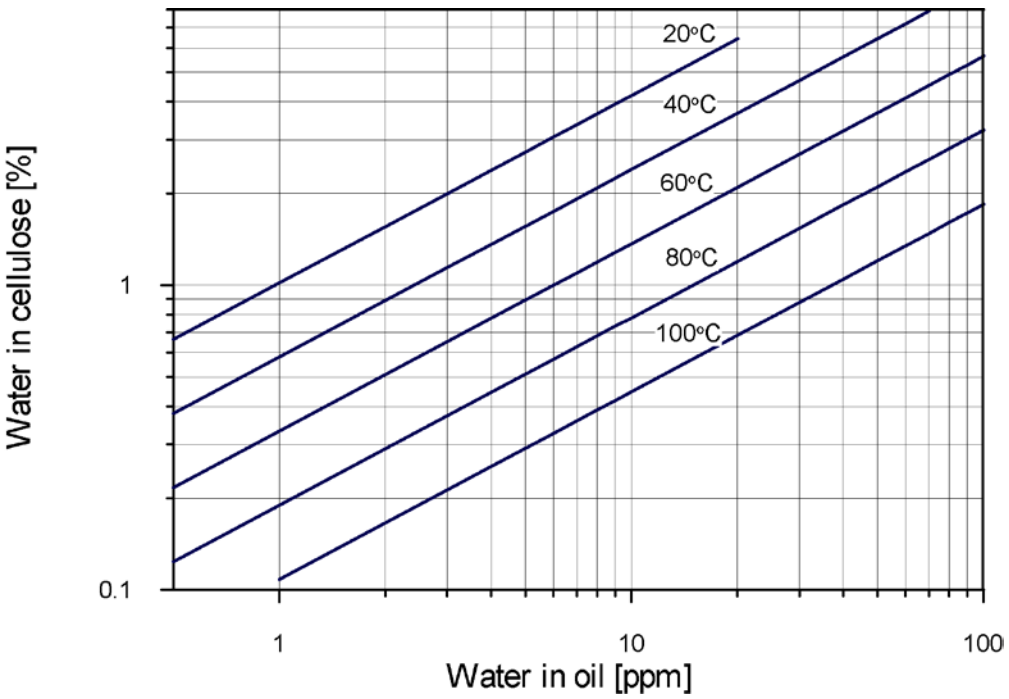

Figure 19: Equilibrium curves for water in a new impregnated insulation with Nytro 10X and Munksjø paper.

A complicating factor is that the water solubility in oil is not universally constant. In particular, when an oil ages and more polar and acidic components are produced it will dissolve more water. Figure 20 shows how the water solubility – being the maximum water concentration the oil can dissolve at a given temperature - will increase with temperature. Often one can use the formulae $K_W = Ae^{-E/T}$ to describe how water solubility changes with temperature. Her K_W is water solubility, A and E are constants and T is the absolute temperature. When the oil ages and the acidity increase the oil can dissolve more water. This seems to be governed by the content of water soluble acids TAN_{LMA}.

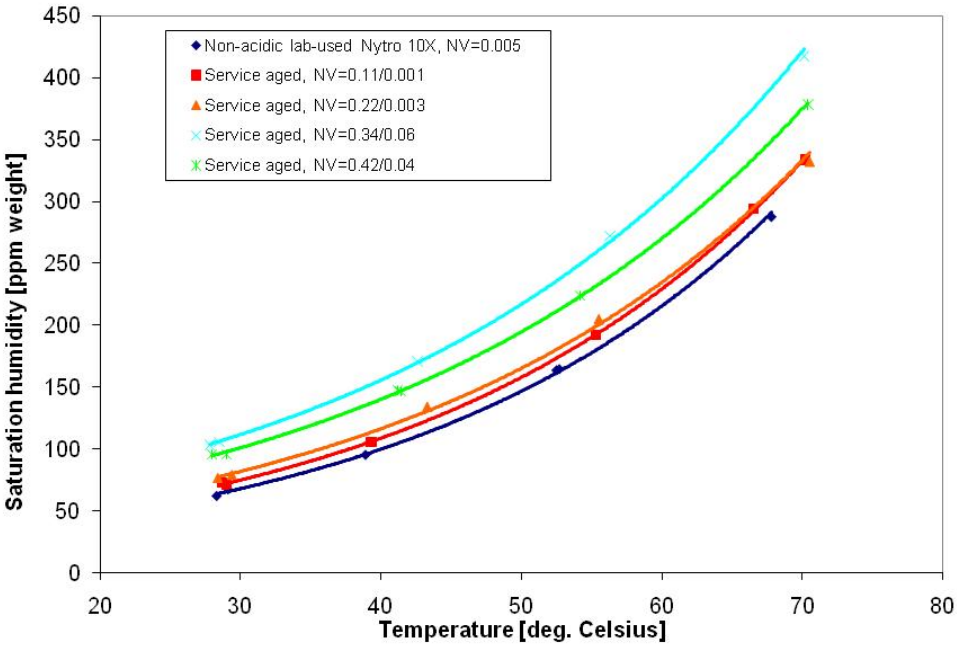

Figure 20: Moisture saturation limit vs. temperature for oil with varying content of acid number. In legend is given total acid number and acid number reduction due to water rinsing: TAN_{TOTAL}/TAN_{LMA}.

Increasing water solubility of the oil can potentially change the equilibrium curves. This is because the oil will carry more water at a certain relative humidity than expected.

In principle one can measure relative moisture to avoid this difficulty. Relative moisture sensors exist in the market. There is still some discussion about their sensitivity, accuracy and stability. These sensors are based on water ingress into a substrate causing changes in its capacitance. This is feasible because water has a very high permittivity (around 80 at room temperature) compared to relevant detector materials having a permittivity around 3. In such sensors there is always built in a temperature sensor for reference purpose. Oil temperatures will vary in the transformer while the moisture concentration will be the same. From Figure **18**b one will see that at a given absolute water content the relative moisture will depend on the temperature.

When relative moisture sensors are used one has to know the solubility of water in the specific oil to calculate the water content at the relevant temperature and then – knowing how the solubility changes with temperature –finding the relative moisture content at the winding temperature. Water in cellulose can then be calculated by using known relations for cellulose like shown in Figure 18a.

6.4 TWO-TEMPERATURE RIG FOR PARTITIONING STUDIES

A rig has been constructed for the investigation of temperature-dependent equilibrium distribution of moisture and other contaminants, see Figure 21 [22]. Basically, it circulates oil between two cellulose-containing chambers which can be kept at independently set temperatures. The chambers are denoted chamber 1 and chamber 2 and their respective temperatures T1 and T2. The cellulose comes in the form of Kraft paper or pressboard. When equilibrium has been reached, the contaminant concentration is the same everywhere in the circulating oil. There is an arrangement for easy extraction of oil from the rig for contaminant measurement, and there are three solid state sensors (Vaisala) measuring temperature and "water activity" a_w (believed to be equivalent to relative humidity) in addition to the two temperature sensors used by the temperature controllers.

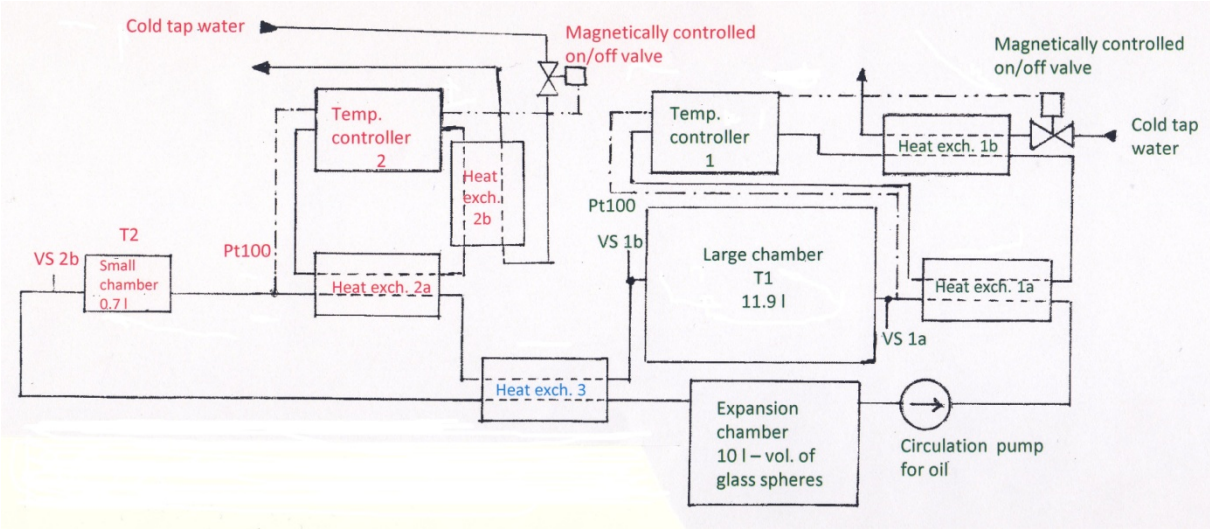

Figure 21: Two-temperature rig.

The rig is built with one large, dominant chamber 1 used to set (by means of temperature) the circulating contamination level in the oil and a small chamber 2 set at an independent temperature T2 above or below T1, holding the cellulose for the equilibrium measurements. Due to a cellulose weight ratio of at least 20 between the two chambers, the amount of contamination taken up in the chamber 2 has only a very small influence on the circulating contaminant level and the contaminant level in the cellulose in chamber 1, so the cellulose in chamber 1 acts to a reasonable extent as an “infinite” buffer of contaminants. In normal operation, it should therefore be sufficient to measure the contamination content in the material in chamber 1 only once for each filling of that chamber. With pressboard in the large house, the oil: cellulose weight ratio in the system is in the range 0.3 – 0.9, depending on pressboard density and shape of the pressboard pieces, so very little of the total contamination should be found in the oil (at least for moisture).

Two different experiments were done in the rig:

- One experiment using low density precut new pressboard (Munksjø) and a mineral oil (Nytro 10X) that was spiked with formic and acetic acids to a neutralization value of 0,912 mg KOH/g
- One experiment with service aged low density (LD) pressboard, crepe paper and mineral oil sampled from a scrapped transformer from a GSU installed in 1965.

6.4.1 Water absorption for mineral oils

As the rig is a closed system and both absolute and relative moisture can be measured, it can also be used for finding water saturation curves at elevated temperatures, also in the presence of other contaminants provided the “water activity” a_w of the Vaisala sensors can be considered sufficiently equal to the relative humidity. An example is shown in Figure 22 where the obtained curve in 2010 fits reasonably well with a curve from an old experiment (at lower temperature), with the same content of low-molecular weight acids (LMA), but the figure also shows the 2012 results and 2014 results (the last with unmeasurably low LMA concentration) that do not fit with the old experiment. However, for when establishing the 2012-14 curves the relative humidity was measured to be in the 2-10% range, using Vaisala sensors. For these a systematic error of ±2 % could occur resulting in and uncertainty of ±20 %. The curves was however based on averaging results from two Vaisala sensors, that gave very similar results.

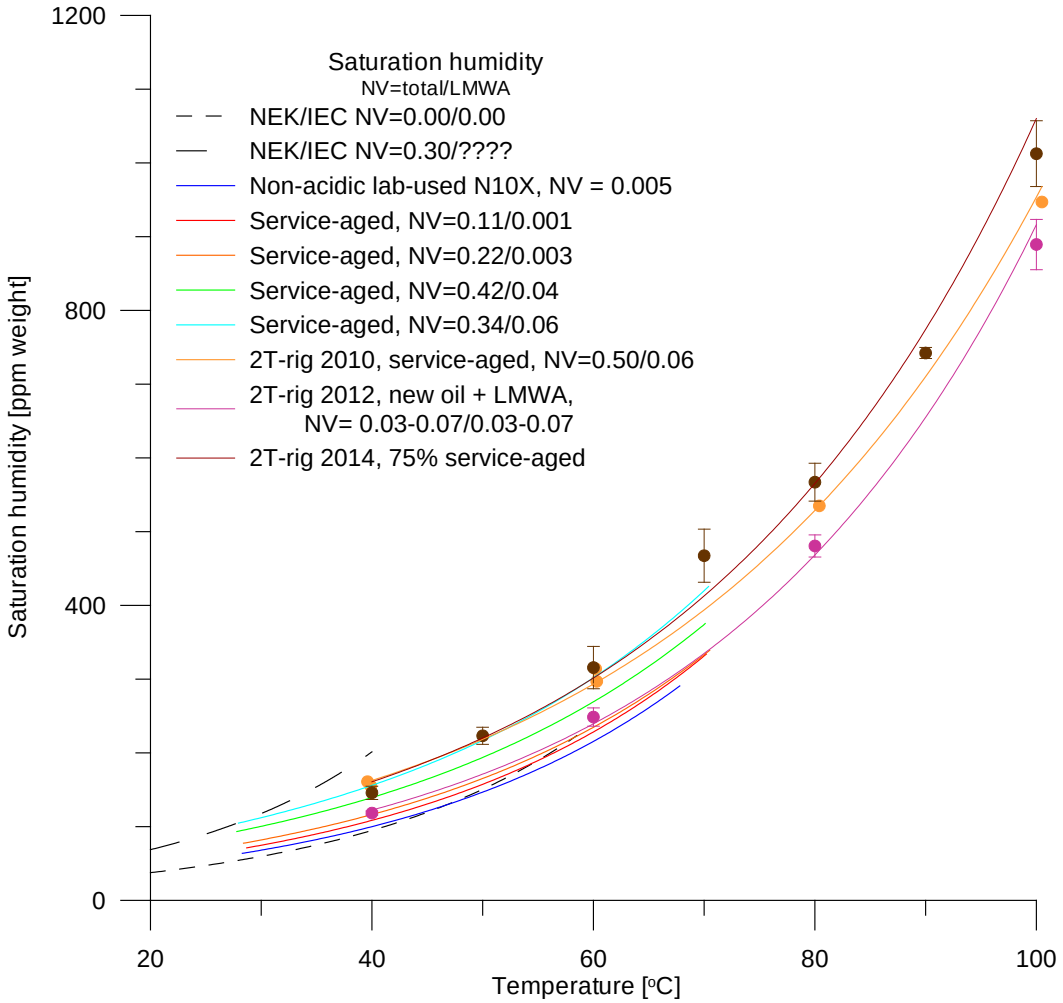

Figure 22: Moisture saturation measured to 100 °C for laboratory conditioned and service aged mineral oils.

6.4.2 Water partitioning in model system and service aged materials

One experiment was designed as a kind of calibration for the equilibrium in an acidic system, with precisely known acid content.

1 mm thick new pressboard cut into pieces were filled into both chambers at the start of the experiment, and would not be refilled later. Moisture was 4.3 ± 0.3 %. In the small chamber, there were also some new strips of Munksjö Thermo 70 Kraft paper, but this was insufficient for the entire experiment series and had to be replenished from time to time, causing the thermal history of the material to become variable. The rig was filled with new Nytro 10 XN with an LMA mix causing a total neutralisation value of 0.912 mg KOH/g. The mix of acids consisted of formic and acetic acids contributing equally to the neutralisation value. The rig was then run for two months at 40 °C before starting the experiment. Most of the acids were taken up by the cellulose, so the neutralisation value of the oil was reduced to 0.032 mg KOH/g, giving a calculated acidity of cellulose of 7.79 mg KOH/g cellulose.

The temperature matrix had 8 combinations: Both T1 and T2 had the values 60, 80 and 100 °C, but the combination 80/80 was not used.

It was expected that the acidity would cause the moisture equilibrium to be very different from a clean, new system. Earlier experiments at SINTEF Energy Research [4], using a wide variety of acids with new paper and oil, in bottles at various temperatures, clearly found this to be the case. Therefore, it was unexpected – and unexplained - when the results showed moisture equilibrium very similar to a new, clean system (Figure **23**). The figure includes a broken line indicating expected values at small chamber temperature 80 °C based on the previous work at SINTEF Energy Research.

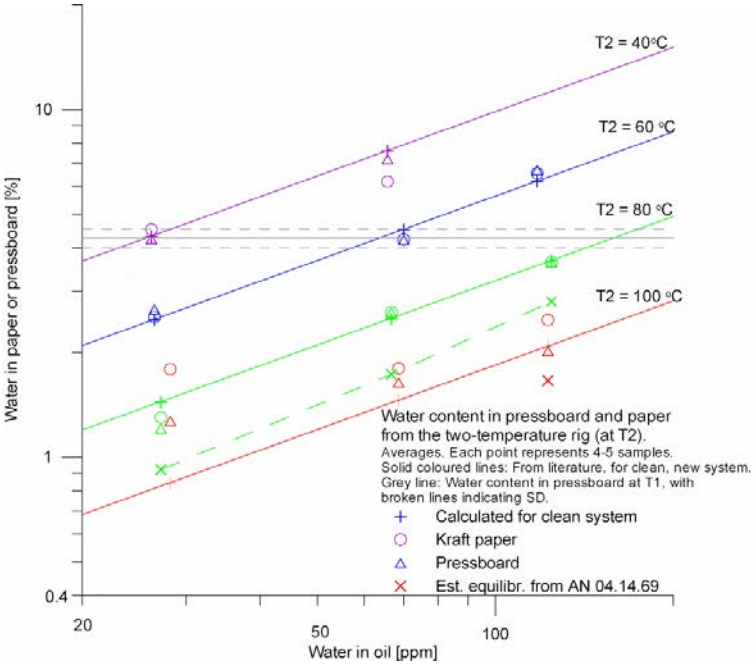

Figure 23: Water partitioning in model system. In the legend it is the shape of the symbol that identifies the materials.

In a second experiment, the material and oil was service aged came from a transformer in Suldal.

The large chamber was filled with 4.85 kg (impregnated weight) low density pressboard from the transformer's outer barriers. In the small chamber, there was service aged pressboard, service aged crepe paper and new Munksjö Thermo 70 Kraft paper strips, approx. 5.5 g of each. Before start of the experiment, samples suited for the various measurements to be done were made as described below and stored in packages, all stored in oil at 40 °C. For each new combination of temperatures T1 and T2, the material from one package was loaded into the small house, ensuring that the material did not have any compound thermal history in the rig.

The samples of pressboard were made in sizes suited to the various measurements before being loaded into the small chamber. These were usually disc shaped and were punched out in sizes which usually had dry weights of about 60, 170 and 330 mg, for moisture measurement and acids measurement, respectively. Two of the 330 mg discs were used for each acids sample. Based on a sample of washed, dried creped paper, the area for the intended weights was found, and two sizes of samples were made: intended weight 65 mg and intended weight 150 mg. Four of the latter were used for each acid measurement. Because of varying shape and overlap of bits of this material taken from the transformer, it was difficult to cut pieces to the intended weight by apparent area alone, and the samples varied considerably in weight. For acidity samples the variation is in the range 500 – 100 mg.

Because of a shortage of oil, new Nynas Nytro 10XN was mixed into the old oil with a ratio 1:4. The acidity of the mix is 0.07 mg KOH/g.

There were 16 temperature combinations with cellulose: Both T1 and T2 had the values 40, 60, 80 and 100 °C. In addition, oil was also sampled at the intermediate T1 temperatures of 50, 70 and 90 °C.

Normally, the rig was run for a 1 – 1.5 weeks for each temperature combination, but the first two combinations involving low temperatures were run for 3 weeks, and similar times have occasionally occurred later, too. Eventually, it was observed that 1 – 1.5 weeks was too short to obtain equilibrium for low T2's (40 and to some extent 60 °C). Therefore also a late combination involving low T2 was run for 3 weeks, and another was redone.

In Figure **24**, the moisture in cellulose are log-log plotted together with the lines for clean new, material; Figure **19**.Water content for the three different materials are plotted for each different T2 temperature with varying water content in the circulating oil from varying T1. Most of the points for new material lie above the clean, new system lines, while most of the points for service aged crepe paper lie below. It is more variable for service aged pressboard.,

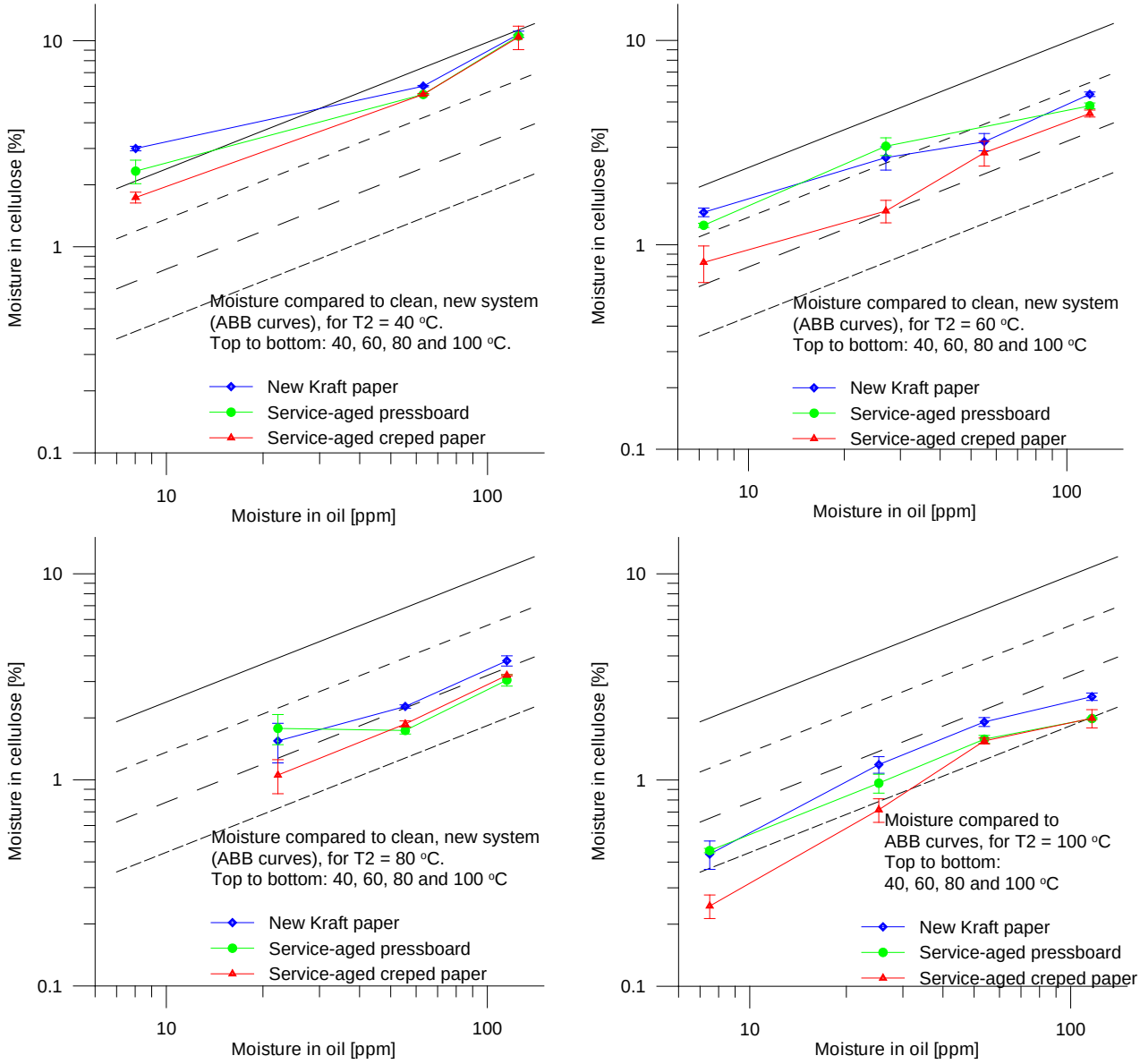

Figure 24: Water partitioning for aged system.

On one side the results give no conclusion supporting the hypothesis that one need to develop specific partitioning curves for old material. On the other side it shows that the accuracy expected when deriving water in cellulose from equilibrium charts and values of water in oil is not better than approximately 0,5 %.

6.4.3 Acid partitioning

The acids present in the two systems are quite different. In the model system the acids are a mix of formic and acetic, while in the service aged it will be a mix of fatty acids and water soluble acids. It is earlier shown that little of the fatty acids are dissolved in paper. The increase seen with temperature will be partitioning.

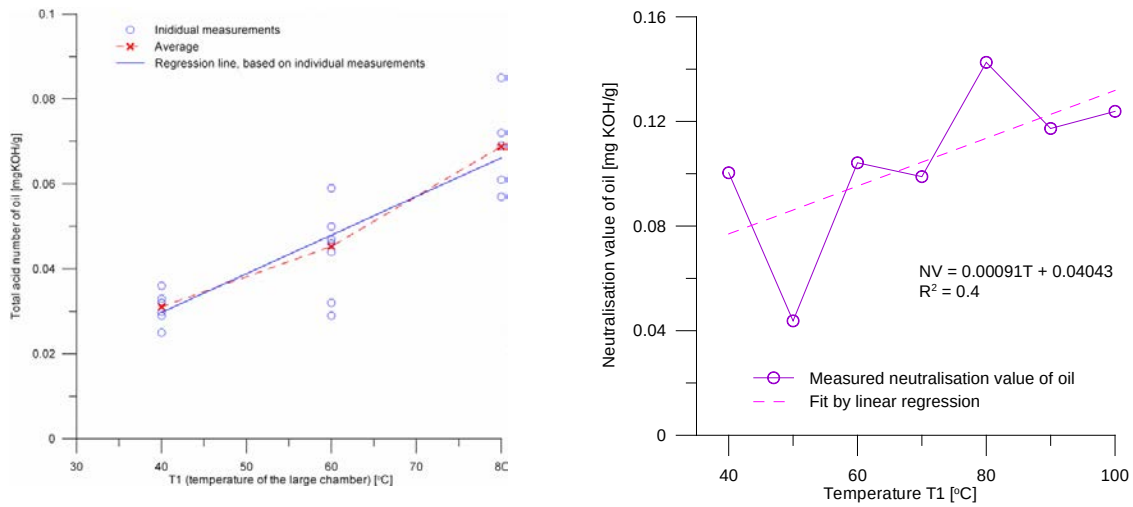

Figure 25: Variation of acidity with temperature for model system (left) and service aged system (Right).

Attempts to measure acids in the paper gave no correlation with temperature. For the model system, measured cellulose acidity was roughly 2-4 mg KOH/g paper and 1-2 mg KOH/g pressboard, which was low compared to the "theoretical" content of 7.79 mg KOH/g cellulose. For the aged system content of water extracted acids measured in the cellulose was in the range 1 – 1.7 mg KOH/g.

6.4.4 Partitioning of furans and alcohol

It is expected that water, furans and alcohols all have a temperature dependent equilibrium between cellulose and oil. There exist both well established and standardized methods for measuring furanic compounds in mineral oils.

Figure **26** show the content of these substances in our partitioning experiment on service aged materials. As expected the concentration in the oil increases with temperature.

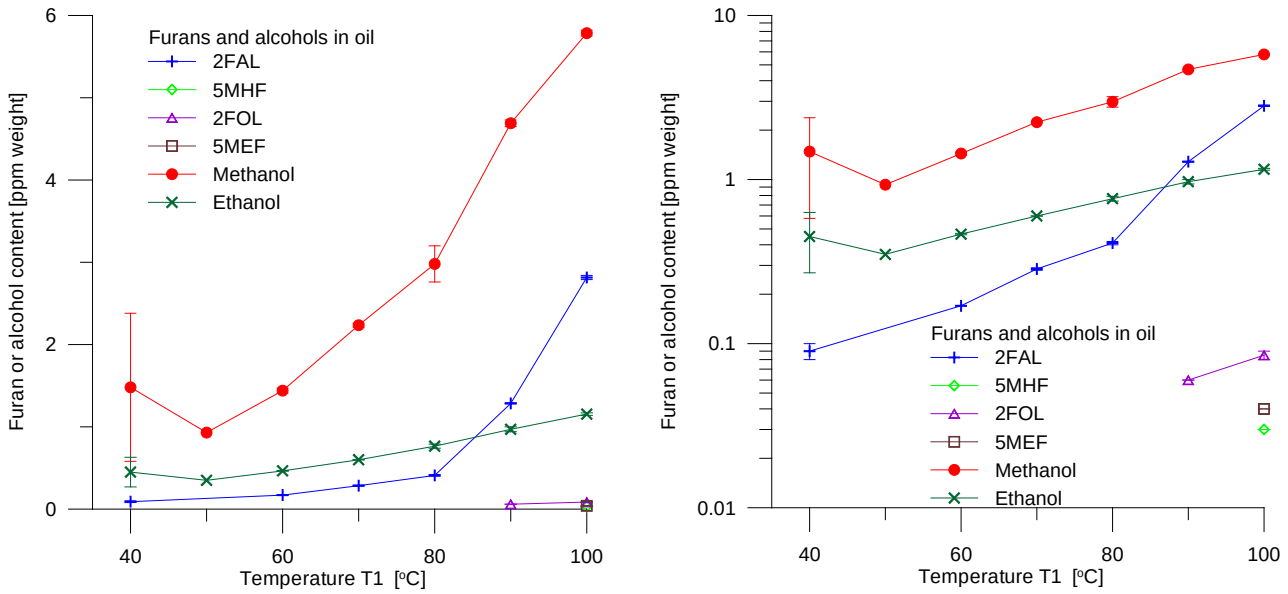

Figure 26: Furans and alcohols in oil vs. large chamber temperature. Linear plot (left) and lin-log (right).

Based on these curves correction factors are calculated for referring a sample back to what could be expected at 20 °C. The factors are calculated by fitting the measured concentrations to an exponential correlation to temperatures. In the table we also included the correction factors for water as suggested in IEC 60422. It must be stressed that different from water, the correction factors suggested for alcohols and 2FAL should be validated in control tests.

Table 7: Correction factors for water and ageing markers to 20 °C.

	20 °C	30 °C	40 °C	50°C	60°C	70 °C	80 °C	90 °C	100 °C
Water	1,00	0,64	0,41	0,24	0,17	0,13	0,10	0,08	0,07
Furanes	1,00	0,57	0,32	0,18	0,10	0,06	0,03	0,02	0,01
Methanol	1,00	0,68	0,46	0,31	0,21	0,14	0,10	0,07	0,04
Etanol	1,00	0,78	0,61	0,47	0,37	0,29	0,22	0,17	0,14

6.5 WATER ABSORPTION IN NYTRO 10XN, MIDEL, FR3, EXXSOL AND SILICONE OIL

An experiment was done to check the moisture absorption in other insulating liquids in the temperature range from 20 to 80 ºC. This was done by putting small trays with oil in a sealed box with controlled temperature, and a saturated salt solution producing a relative humidity of 70 %. A fan was used to give an even temperature and moisture distribution. From the measured water content the concentration at 100% was calculated and plotted (Figure 27). New ester liquids dissolve much more water than a mineral oil (Nytro 10XN).

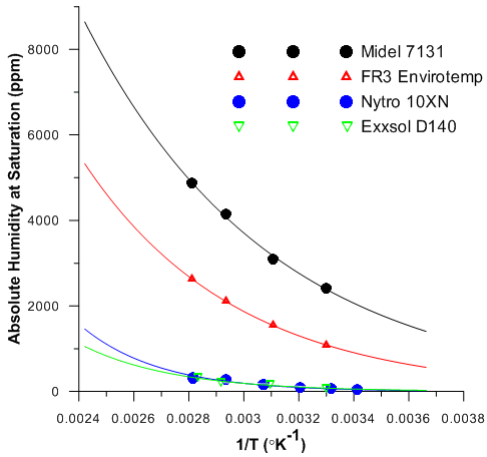

Figure 27: Absolute humidity at saturation for different oils.

6.6 WATER CONCENTRATION PROFILE THROUGH CONDUCTOR INSULATION (THREE-TEMPERATURE RIG)

As described, temperature differences between different parts of a transformer lead to different concentrations of contaminants (and in particular water) residing in the insulation at those parts. But what about one randomly selected place on a winding? There is a radial temperature distribution through the winding insulation. Is there a temperature-dependent radial distribution of contaminants also? Another modification of the rig described in chapter 6.4 can be used for experiments around this problem, and it has been used for two small experiments with moisture but otherwise clean, new cellulose and oil.

Chamber 2 is switched for a set of concentric tubes, with the oil flowing between them. Paper representing winding insulation is wrapped on the outside of the inner tube. 9 layers and 31 layers (0,54 and 1,86 mm radial thickness) were used in the two experiments. The inner tube is heated by an electric heater in the space along the axis of the setup, representing the heating from the winding conductor. A thermocouple is located between the inner tube and the wrapped paper. The temperature of oil flowing in is strictly controlled, and the temperature of the oil flowing out is measured. With a suitable (laminar) oil flow the temperature rise of the oil from inlet to outlet is about 1K for a heater power setting a temperature gradient of about 1K per paper layer (temperature difference between inner tube and oil, but surface temperature of the paper against the oil should be expected to be a little higher than the temperature of the oil).

Sampling of the paper for moisture measurement requires the moisture to be frozen in place. The heater is removed and the central tube with the paper on is quickly removed and dipped in liquid nitrogen for a time sufficient to cool most of the paper to room temperature. Thus the outermost layer and often also the next layer will be contaminated by moisture from the surrounding air condensing on the paper. Samples are then cut out of the paper. The resulting radial distribution for the rest of the layers in an experiment with 31 layers of paper, 58 ppm water in the oil, oil temperature 74 °C and "conductor" temperature 95 °C is shown in Figure **28**. A strange result is that the moisture is considerably lower than it ought to be, as equilibrium curves for clean material indicate that the outer layers should have had about 2,5 – 2,8 % moisture and the innermost layer 1,6 %.

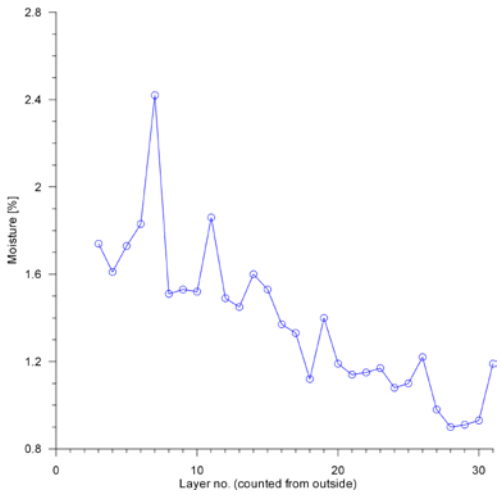

Figure 28 : Measured radial moisture distribution in one experiment.

6.7 EXTRACTING CONTAMINANTS AND WATER FROM PAPER IN EQUILIBRIUM WITH OIL IN TRANSFORMER (PAPER SAMPLER RIG)

Traditionally, the pre-exponent value and activation energy are obtained for different temperature, moisture, and oxygen levels from accelerated ageing of oil-paper systems in laboratory experiments. However, each operated transformer may experience somewhat different insulation contamination levels and temperature distributions. Also the oil data represent average values. In turn, this will affect accuracy of the transformer life estimation. Therefore, one of the objectives of this research task was to minimise the uncertainties by obtaining the genuine pre-exponent and activation energy values by introducing a nonintrusive, online device that could be used for imaging the hot-spot conditions. The results, obtained so far, are summarized below.

6.7.1 Paper Filter Concept and Design Upgrade

In this device, shown in Figure 29 and Figure 30, oil is taken from the transformer and passed through a container with paper samples before being returned to the transformer. The container can be set to a specified temperature representative to specific location as e.g. the hot-spot. The contamination of the sample paper will then equilibrate to the same level as in a specific location in the transformer [23]. Thereafter contamination of the paper sample is easily analysed in the laboratory, to allow for an improved estimation of the A value. Combined with knowledge of the transformer temperature [4, 24], an improved life assessment should be facilitated. The initial design of the paper filter rig, Figure 29 [23], has been upgraded by installing a relative humidity sensor in the loop after the filter cell, Figure 30. A safety power supply cut-off relay has also been added to prevent possible overheating, Figure 30.

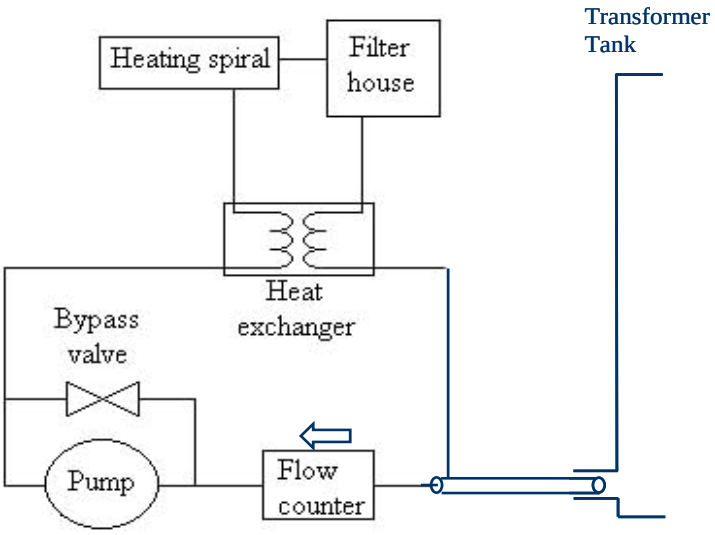

Figure 29: Initial paper filter rig design.

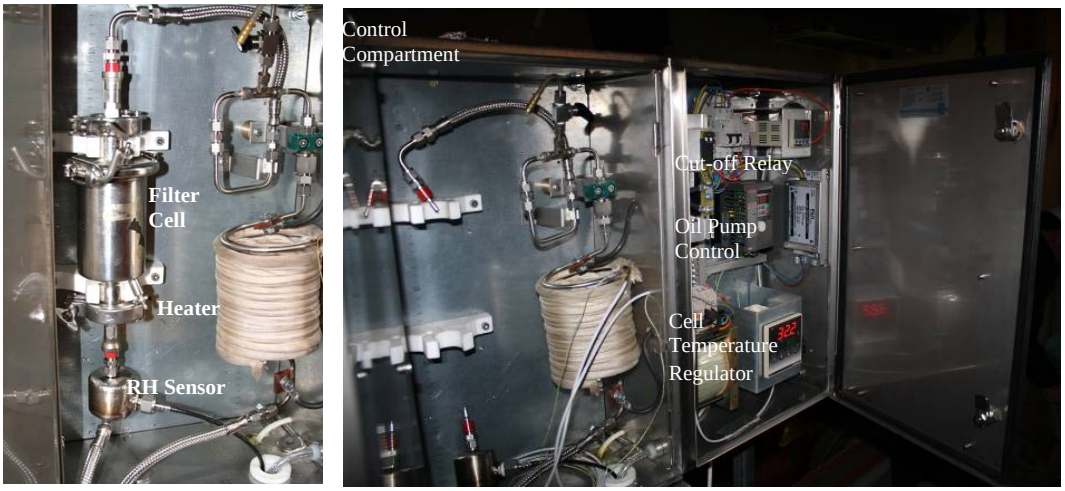

Figure 30: Paper sampler and control compartment.

6.7.2 Field Experience

The rig has been tested on three transformer units so far. All units were in service for a long time prior installing the monitoring system. They were scheduled either for refurbishing or scrapping. The intention was to take a representative sample from the transformer insulation just after the transformer was de-energized and compare the conditions in in the sample from the paper filter. However, this was not always possible due to some technical obstacles, (i.e. specific transformer design prevented access to the hot-spot location or de-energizing activity could not always be coordinated with the following sampling procedures).

The paper filter was connected to the transformers through the flange at the bottom of the transformer tank, Figure 31, and by using the connecting adapter, Figure 31 and
Figure **32**.

Figure 31: Connection Flange (Left) and connecting adapter (Right).

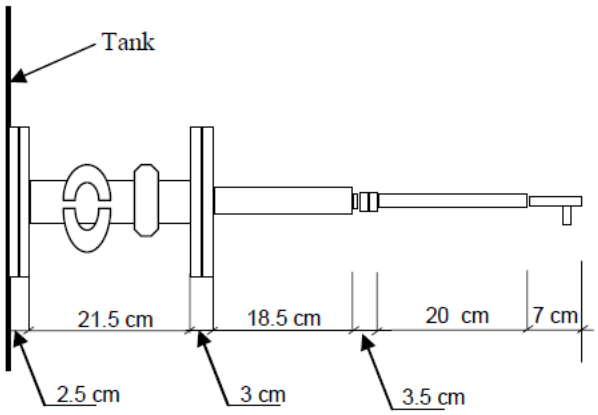

Figure 32: Connection design.

The oil sample moisture measurements were based on the Karl Fisher coulomb-metric titration with the preheated syringe. We measured 14 ppm humidity in the oil for the whole measurement period (two measurements performed at different times). Based on these measurements and standard equilibrium curves [25], the water in paper content was estimated for the cell temperature. The cell temperature was set at 39 °C (similar to the top oil temperature) for the first period and at 67 °C (similar to estimated hot spot temperature) for the second period. From the equilibrium curves in Figure 19 we calculated the equivalent paper humidity using the cell temperature equal to the oil temperature giving about 1.4 % paper humidity in the paper at 67 °C and 2.8 % at 39 °C. We measured also directly the paper humidity in the cell for these two temperatures giving 1.4 and 2.7 % respectively at 67 and 39 °C corresponding very well to the estimation via the equilibrium curves. During the measurements the relative humidity was monitored to 2.1% at 67 °C corresponding to a oil saturation of 667 ppm which is significantly higher than the highest saturation at 67 °C (360 ppm) in Figure 20. However we know that the accuracy of relative humidity sensors in general is poor at low relative humidity (± 2 % relative humidity error) since they are calibrated for the full 0-100 % relative humidity range meaning that our measurement are quite good and not way off.

6.8 CONTINUOUS MONITORING OF GASSES

Dissolved gas analysis (DGA) has gained worldwide acceptance as a diagnostic method for the detection of incipient faults [26]. Fault gases are produced by degradation of the transformer oil and solid insulating materials such as paper, pressboard and transformer-board, which are all made of cellulose. The rate of cellulose and oil degradation is significantly increased in the presence of a fault inside the transformer.

Although a DGA sample will generate information necessary to make an accurate determination about the present health of a power transformer, over the years, inputs from operating utilities indicate that reliance solely on routine DGA sampling is not the complete answer. A DGA sample represents a five minute information window or snapshot in time reflecting only the present condition of the power transformer. By the nature of the test, it is unreasonable to expect the DGA event to provide any guarantee of satisfactory performance until the next DGA sample takes place, i.e. in 6 to 12 months sampling period. However, the periodic DGA is good diagnostic technique for the most typical failures, which develop slowly. One of devices used to bridge this DGA bottleneck is the multi gas on-line monitor Transfix from Kelman [27].

The Transfix system was connected to a Jensen degasser installed to a 150 MVA, ONAF-cooled free breathing transformer as one of the project activities. The transformer rated voltages are 275±10x1.5%/47.25 kV, Figure 33. The on-site setup is in close agreement with the Transfix and Jensen pre-installation and installation guides [27] and [28]. A recommended Transfix installation is also given on Figure 33, indicating oil sampling points at the top and the bottom of transformer as the system has to be supplied with a sample representing the well mixed transformer oil, (i.e. bulk oil), from the active cooling loop.

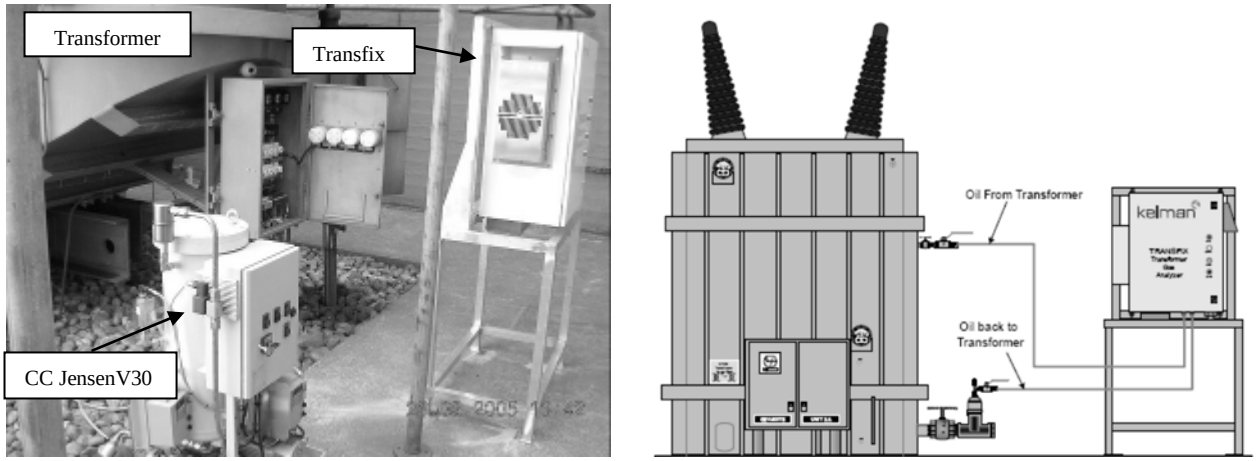

Figure 33: Typical Transfix Installation, [x].

6.8.1 Monitoring Gasses

The transformer was continuously monitored on the Transfix from the 23rd of June 2005 to the 29th April 2008. The Jensen degasser was added to the site on the 11th of January 2006, and its operating mode had been alternatively changed over the time as follows:

- ON, 11/01/2006
- OFF, 08/09/2006
- ON, 11/02/2008
- OFF, 21/04/2008

The times to get a stable gas content when connecting/disconnecting a degasser was estimated and they were in the order of 15 to 18 months with the degasser turned “off” and 3 to 5 months with the degasser turned “on”. Consequently, it appears that the usual sampling period between 6 and 12 months for the general DGA test could be enough assuming that all other transformer key parameters are under limits. Similarly, the gas ratios are calculated and their dependency on the degasser operation mode are observed. Finally, the transformer condition assessment, which is based on the typical concentration values given in IEC 60599, indicates a healthy unit. Consequently, the further fault diagnostic by considering the gas ratios was not considered as necessary. The use of the on-line monitor is recommended as a diagnostic tool for the detection of the incipient faults. However, the application of the degasser should be carefully considered on the case-by-case basis as inappropriate application could easily “mask” the valuable early fault indicators.

6.9 CONTINUOUS MONITORING OF TEMPERATURES, COMBUSTIBLE GASSES AND CONDUCTIVITY

The system was a custom made version of ABB’s transformer monitoring equipment T-monitor with standard input for transformer temperatures, load and one Hydran solid-state gas sensor. It was extended to allow for recording of oil conductivity by using an Irlab sensor. The T-monitor software was unable to accept input from another sensor, therefore data from an installed Vaisala sensor was not included in the data set to be downloaded in an Excel file from the T-Monitor.

During the project a revision of our T-Monitor special system setup was performed and it was redesigned and rebuilt to avoid erroneous readings of HYDRAN humidity sensor by directing the oil flow into the humidity sensor location. In addition, Vaisala moisture sensor was added in the IRLAB-HYDRAN oil circulation loop to verify HYDRAN moisture readings. This revealed a “fault” in the calibration of the HYDRAN humidity sensor which was set to focus on the 0-100% relative humidity. With the used set-point one will get 0% relative humidity for low humidities (< 3% relative moisture), giving a wrong indication that the sensor is faulty. It was suggested that the relative humidity sensor in the Hydran should be recalibrated for more accurate readings for low humidity.

The system connectivity and mobility was improved by adding self-stand foundation and flexible cable connectors.

The on-line IRLAB-HYDRAN monitoring has three tasks:

- Use the relative humidity sensor in HYDRAN monitor to observe moisture changes with load and oil temperature to better understand moisture transients and to understand the quality if a moisture assessment based on a sampling of a one liter oil volume as used in all oil diagnostic procedures
- The IRLAB cell was added to the system to measure the oil conductance and its dependence on the oil temperature
- HYDRAN monitor is used to estimate amount of the total gases.

As an outcome the correlation between moisture, conductivity and oil temperature is established from the IRLAB and the Vaisala-Hydran relative humidity and temperature sensors (Figure 34). Note that the when the conductance varies that is due to varying temperature, which of course also influence relative humidity. The performance of the HYDRAN Monitor is evaluated and the system is absolutely able to accomplish its primary task, to detect faulty gases. It can detect early signs of faults in the power transformers.

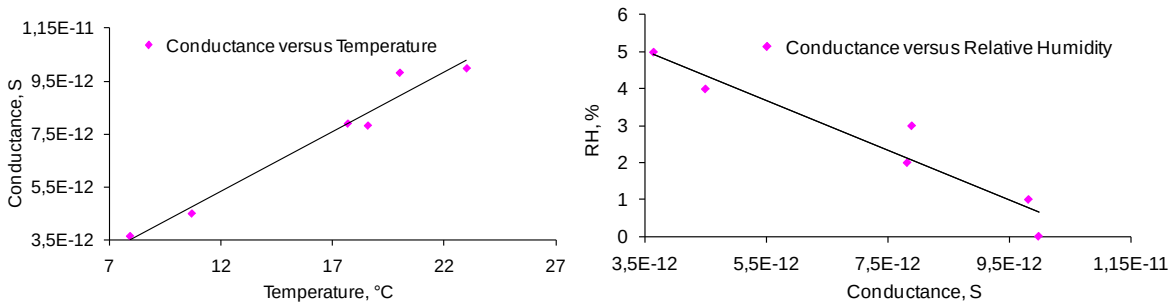

Figure 34: Conductance versus temperature (left) and relative humidity versus conductance (right).

7 THERMAL MODELLING

Ageing rates are always depending on temperature. As it has already been discussed in this report, the degree of polymerisation (DP) has commonly been used as the primary indicator of the condition of insulation paper in power transformers. The paper deteriorates with age, leaving the insulation vulnerable to stresses generated by thermal, mechanical and electrical transients. Temperature, water, low molecular weight acids and oxygen all contribute to acceleration of the degradation process, reducing the DP of the paper and with it, the mechanical strength. The paper (initial DP-1000, after drying) is expected to last the lifetime of the transformer (25-40 years), but at a DP of 200 the mechanical strength of the paper can be reduced to 20% of its initial value. This state is often regarded as the end-of-life criterion for transformer insulation. Degradation is a chemical reaction and as such behaves largely according to the Arrhenius theory of reaction kinetics. The ageing model based on this theory is used as a tool for forecasting ageing development and for analysis of the impact from changes in operational conditions as given in the equation below:

$$Expected\ life = \frac{\frac{1}{DP_{end}} - \frac{1}{DP_{start}}}{A \times 24 \times 365} \times e^{\frac{E_A}{R(\theta + 273)}} \tag{5}$$

where DP_{end} is the end of life criteria, and DP_{start} is the start value at the accessible winding location. R is the molar gas constant (8,314 J/mole/K) and E_A is the activation energy in kilojoules per mole. The pre-exponent value A is a constant depending on the chemical environment and contamination. θ is corresponding winding temperature, (ºC), which is obtained according procedures given in sections 4, 8.1 and [1]. Also, the more accurate thermal model is suggested in section 7.1 and [37]. The pre-exponent A-factor can be estimated based on oil data, but without knowing the temperatures all attempts to model ageing are in vain.

7.1 MODELLING TRANSFORMER TEMPERATURE WITH VARIATION OF OIL VISCOSITY

When the load is increased it takes some time before the corresponding oil circulation adapts its speed [29], due to lower temperature and higher oil viscosity at the preceding loads. Consequently, the hot-spot temperature rises rapidly during the first 10-20 minutes with a time constant equivalent approximately to the winding time constant [30]. Nevertheless, this time period is different for each transformer and it is very dependent on the transformer design. Conveniently, it has been further observed that 50% of the temperature change occurs during the rapid rise. When the temperature threshold level is reached the oil circulation is established at a rate, which is defined as critical, preventing further rapid temperature rise. Therefore, the hot spot temperature will continue to rise slower with a time constant equivalent to the top-oil time constant.

On the other hand, at the transformer cold start 75% of the temperature change occurs during the rapid rise period due to more harsh initial oil conditions, i.e. initial oil speed is zero.

In contrast, the initial oil circulation prior to a load decrease is faster than it will be under the load considered. Therefore, the temperature will now decrease rapidly with a time constant equivalent approximately to the winding time constant. Once the 50% of the final temperature drop is reached the oil velocity will be much lower than initially. As a result, the temperature starts decreasing slowly with a time constant equivalent to the top-oil time constant.

This work presents a simpler but still accurate temperature calculation method taking into account the findings mentioned above. By alternate switching between two different time constants, (the short one equal to the winding time constant and the long one equal to the top-oil time constant), the model is based only on the hot-spot to ambient air gradient.

The thermal model is based on heat transfer theory, [31,32,33,34] numerous transformer thermal tests and reports [29, 30, 35, 36] application of the lumped capacitance method, the thermal-electrical analogy, and the concept of thermal resistance between winding insulation surface and ambient, i.e. air.

The model presented in this paper takes into account oil viscosity changes and loss variation with temperature. The changes in transformer time constants due to changes in the oil viscosity are also accounted for. The model requires an iterative calculation procedure.

The measured temperature results, which are recorded for the 250 MVA transformer (230±8 x 1.5%/118/21 kV) during different varying load tests, Table 8, are compared to the new calculation method presented in [37] and the IEEE Annex G method.

Table 8: Load Steps for 250 MVA Transformer.

Time period, min.	Load Factor, p.u.
0.0 -187.4	1.0
187.4 -364.9	0.6
364.9-503.4	1.5
503.4-710.0	0.3
710.0-735.0	2.1
735.0-750.0	0.0

The measured hot-spot temperature results of the hottest winding and sensor, recorded during the varying load current test, are compared with results obtained from the thermal models in Figure 35.

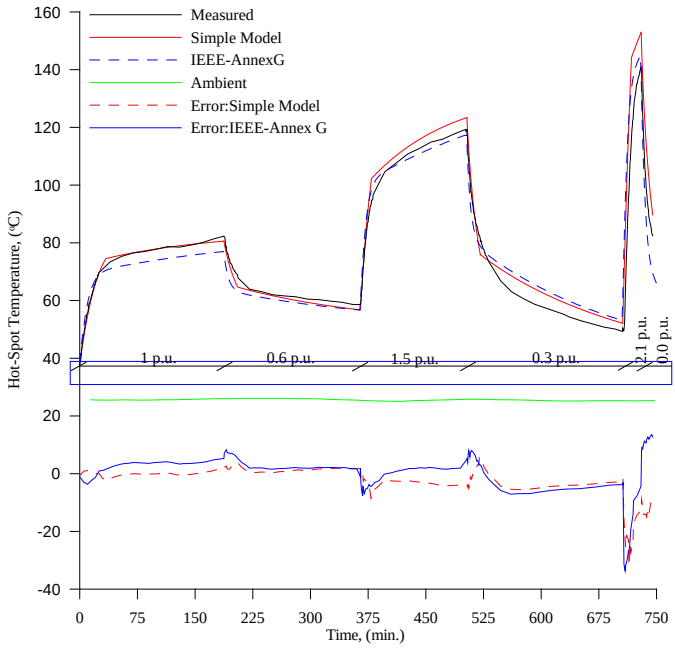

Figure 35: Hot-spot temperature of the 118-kV winding in the 250 MVA ONAF-cooled transformer.

7.2 VISCOSITY OF NYTRO 10XN, MIDEL AND FR3

As a part of the project activity regarding thermal modeling, the dynamic viscosity levels of the three different oils were obtained by a rheometer for the temperature range from -20 °C to 120 °C. The measured values are plotted in Figure 36 below.

The fact that the viscosity of the esters are much higher than the mineral oil shows that care should be taken when applying these for low temperatures. Also the pour point for the esters does not go down to the low temperatures that a mineral oil does. Transformers where the esters are applied should have a thermal design specific for these liquids.

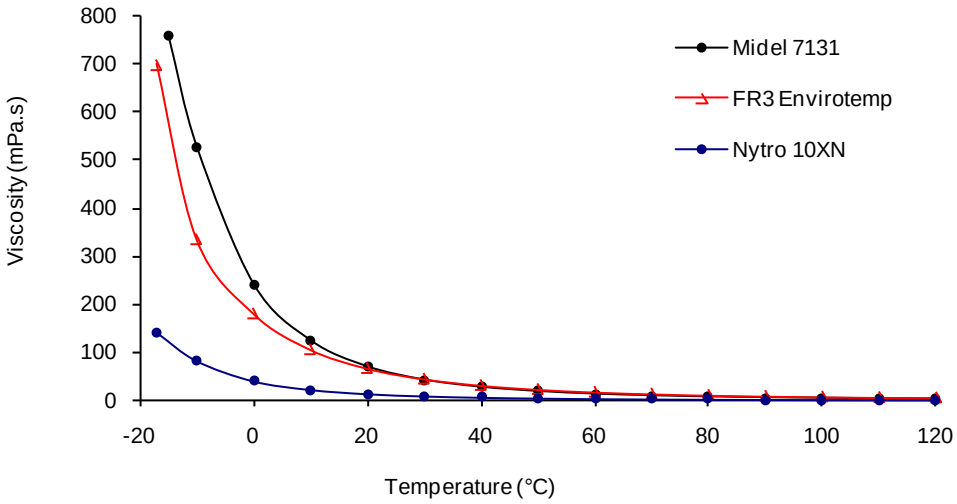

Figure 36: Viscosity for liquids versus temperature.

8 EVALUATION OF CONDITION OF INSULATION: PRESENT AND FUTURE

As stated earlier, for evaluation of the winding insulation there are two possible roads:

- *Diagnostic indicators* as described in Table 6. This requires long time series and well maintained databases. One cannot expect that singular parameters will give correct estimations: To that, the stories telling that transformers with a high content of e.g. furans or methanol in reality were in good condition are too many. However, using multivariate analysis on groups of parameters is expected to be a better way of doing it. To correlate condition markers with a failure the failure statistics are necessary to gain experience and benefit. Here one can expect that collaboration between users will increase.
  Water, methanol, ethanol and furan content measured at various temperatures should be normalized (e.g. to 20 °C): For water IEC 60422, Annex A suggests correction factors. For furans and methanol suggested correction factors can be found in chapter 6.4.4 .
- *Estimation of ageing* based on ageing kinetic formulas as suggested in Chapter 5. The challenge is to find which parameters should be used for the chemical condition, the realistic temperatures and the type of cellulose used. This approach can be used both to estimate present state of ageing and to estimate time to end of life.

The final objective should be to avoid accidents and failures of units by removing and scrapping those with a high failure probability. We believe both methods should be used as health indicators to single out suspicious individuals. For both approaches there will be uncertainties that can be reduced by improving the input data. We believe that one can start with a simple approach, accepting uncertain estimates for the gross majority, and then spend more resources on more thorough investigations for the units where the condition seems to be worst and risk highest to improve the condition assessment accuracy for these units.

For a simple population study based on ageing kinetics we suggest to establish an Excel sheet where one for each transformer determines the input for the kinetic calculations and then estimates expected condition based on average values.

The data one needs to establish this are:

- *Insulation type*: upgraded or not upgraded paper, which each have different ageing and sensitivity to contamination.
- *Age*: How many years has the transformer been in service?
- *Contamination level*: We are concerned about water in cellulose, water soluble acids in cellulose, and oxygen content. This will have developed over the transformer life, and a linearization can be used to estimate an average.
- *Average, weighed hot-spot temperature*: which either may be found from models using ambient temperature and load as input, or from measurements using winding temperature indicators. In any case the hot-spot factor is needed. For older units hot-spot factors will anyway be incertain

In the future automatic systems for recording average top-oil temperatures and transformer loads should be integrated into monitoring and SCADA systems.

8.1 ESTIMATION OF PRESENT STAGE OF AGEING BASED ON LABORATORY EXPERIENCE

While waiting for return of experience from service aged transformers data from our laboratory experiments (Table **2** and Table **3**) can be used for modelling.

The present ageing state is then estimated according to the following formulae:

$$DP_{Present} = \frac{DP_{new}}{\eta_{Tot} + 1} \tag{6}$$

Here $DP_{Present}$ is the degree of polymerization at the time of the analysis, DP_{new} the value when the transformer was put in service (e.g. 1000) and total chain scissions η_{Tot} is calculated according to:

$$\eta_{Tot} = DP_{new}\left(A_{Oxi}\, e^{\frac{-E_{Oxi}}{R \cdot T}} + A_{Hyd}\, e^{\frac{-E_{Hyd}}{R \cdot T}} \right) \cdot t \cdot 365 \cdot 24 \tag{7}$$

where the activation energy - describing temperature sensitivity of the ageing process - is E_{Oxi} and E_{Hyd} for respectively oxidative and hydrolytic material ageing, *A*-values describes corresponding contamination in paper, *R* is the molar gas constant, *T* operating temperature in Kelvin and *t* the time in service.

The E and A parameters for respectively oxidation and hydrolysis can be found from Table 2 for normal kraft paper and Table 3 for transformers with thermally upgraded paper. We here disregard the term for pyrolytic ageing included in equation 3. *E*-values are just lifted from Table 2 and Table 3, depending on whether the insulation was normal kraft or upgraded kraft. (One must be aware that the E and A-values relates to time in hours.) For transformers supplied from National Industry in Drammen all transformers delivered in the period 1967-1978 were supplied with Insuldur upgraded paper. Modern kraft paper may contain too low concentrations of nitrogen to achieve the functionality expected of an upgraded insulation as indicated in chapter 5.3.

A-values have to be established based on the contamination in the cellulose. For *oxidation* we suggest a binary approach: if oxygen content is below e.g. 5 000 ppm the oxidation term is disregarded. Otherwise use the A-values found in the tables for the whole life of the transformer. For *hydrolysis* we suggest to use a linear relationship with water for the A-values suggested in Table 2 and Table 3. Content of water soluble acids is very uncertain and until we know more is suggested to be disregarded. Most likely the information on historical data is sparse. We suggest making a qualified guess of the starting condition (e.g. 1 % water in cellulose for the new transformer) and then interpolate towards present values over the life of the transformer. 1 % is on the high side of what is expected in a new transformer today: after vapor phase drying was introduced 0,5 % is a more likely starting value.

Finding the average, weighed transformer temperature is maybe the most difficult part. In principle one could use three approaches:

- Use the winding temperature indicator. This however is depending on good calibration and qualified setting, and can be questioned.
- Measuring top oil temperature and add hot-spot to top-oil temperature rise according to load and hotspot factors.
- Measure ambient temperature and calculate hotspot according to load using Equation 2.

One has to consider historical loading values; again linearization between starting values and present values is a possible path. Some information on the starting values can be found from the original investment analysis. When calculating the hot-spot temperature the correct cooling mode, and setting of fan and pump starting temperatures has to be considered. Uncertainties on the hot-spot factor must also be considered, and values on the conservative side should be chosen. One can use values suggested in the loading guide, but these values are not necessarily correct. To improve accuracy there is a need to establishing guidelines for calculation and estimation of yearly average temperatures for typical cases.

8.2 ESTIMATING END-OF-LIFE FOR TRANSFORMER INSULATION

Estimation of end of life is quite equivalent to the procedure described above. One difference is that one has to decide on and end-of –life criterion. A DP_{End} value of 200 is often used. In principle one should choose values adapted to the importance of the transformer and the stresses it will be subjected to. End of life is calculated according to:

$$\boldsymbol{t} = \frac{\frac{\mathbf{DP_{Start}}}{\mathbf{DP_{End}}} - \mathbf{1}}{\mathbf{365 \cdot 24}} \cdot \left(A_{Oxi}\, e^{\frac{-E_{Oxi}}{R \cdot T}} + A_{Hyd}\, e^{\frac{-E_{Hyd}}{R \cdot T}} \right)^{-\mathbf{1}} \qquad \textbf{(8)}$$

This estimation may be done with either installation or present condition as DP_{Start}-value. Of course uncertainties are reduced if one can get a better impression of the present DP value. Sampling paper from leads and recalculate to hot spot condition with a higher service temperature is one viable path.

Again A and E values are chosen as described above. Here one can assume a condition development (stable, continued increase or a sudden reduction in case of drying or degassing) when estimating the A values.

Again temperature can be estimated as described above. For future temperature one could base the future on a measured last year average considering the cooling modes used in the different periods.

8.3 EXAMPLE ON LIFE ESTIMATION

Assuming that we want to estimate the life of a transformer that was bought in 1980 and being equipped with normal kraft paper and with open breathing system. We can then use the equation (8) above and the data from Table 2 and Figure 7, assuming that oxidation and hydrolysis are independent

We will assume an average yearly temperature of 50 degrees and 40 % load and ONAF operation. The hot spot to top oil temperature rise is as calculated according to the last term in equation (2): $H \cdot g_r \cdot K^y$

- Here the hotspot factor (H) for a large transformer can be 1.3
- The rated average winding to oil temperature rise g_r can be 20 degrees
- The load K is 0,4
- The winding exponent y is assumed to be 1,6

The top oil to hot spot temperature rise then becomes 6 K and the hot spot temperature becomes 56 K.

The average water in cellulose was in 2010 estimated to be 2,5 %. We can assume a water content of 0,5 when the transformer was new and an average water content of 1,5 over the life of the transformer. The A_{Hyd}-value is then read from Figure 7 (left) being $1{,}5 \cdot 10^{11}$ [h^{-1}]. A_{Oxi} is taken from Table 2 for high oxygen content being $4{,}6 \cdot 10^{5}$ [h^{-1}].

When entering the data for hydrolysis and oxidation from Table 2 one has to recall that the E_A values (E_{Oxi} and E_{Hyd}) – which in the table is given as kJ/mole - has to be in joule as the gas constant is 8,314 Joule/mole/Kelvin, and the temperature T is the temperature in Kelvin (add 273).

We will assume that the DP_{start} value was 1000 and use DP_{End} of 200 as the end-of life criterion.

Based on the assumption that oxidation and hydrolysis are additive and independent processes we can assume a time to end of life of 117 years. Assuming only hydrolysis to be active life expectancy becomes the 693 years, and assuming only oxidation we get 140 years.

8.4 POSSIBLE SIMPLIFIED SCHEME FOR EVALUATION OF AGEING

Our continued and accelerated ageing of materials sampled from service aged transformers [9] indicate that even if oxygen was present the activation energy (~111 kJ/mole) was in line with what could be expected for hydrolysis. Also it is lower than what we have found for initial hydrolysis (128 kJ/mole), but in line with what is suggested in other studies [3, 38]. A moderate uncertainty in activation energy will lead to large variations in A-values as these strongly depend on the E-value.

The effect of oxygen on ageing of service conditioned materials gave no change in activation energy, but accelerated the ageing a factor 2.5.

For kraft paper it seems that the simplest approach is to use an activation energy of 111 kJ/mole and A values depending on water content according to Figure 7, and then include effects of oxygen by multiplying with 2,5 for open breathers, and a lower number in case of closed conservators.

For up-graded systems there are no tests on service aged materials, and the parameters suggested in Table 3 are still the best we have.

Again it is stressed that all these values are based on early ageing and will yield conservative estimates on more progressed ageing (i.e. DP-values <500).

9 IMPROVING AGEING MODELS BY SCRAPPING INVESTIGATION

In all condition assessments there are many sources of uncertainty: Ageing kinetic models are based on laboratory experiments, thermal models for old equipment have uncertain hotspot factors and finally the diagnostic methods and interpretations are uncertain. To get confidence in the proposed schemes one has to test estimated condition versus real conditions by performing scrapping analysis. We can list a number of interesting questions:

1. Is water content in solid insulation as expected from oil samples and equilibrium?
2. Does ageing of cellulose at outer barriers vary as expected from top to bottom oil temperature difference?
3. Is paper ageing at top of winding as expected from measured/estimated top oil temperature and water content?
4. Does the difference in paper ageing seen at hot spot and winding leads fit with expected hot spot to top oil gradient?
5. Does paper ageing distribution fit with thermal models?
6.

9.1 SIRA KVINA TRANSFORMER

An investigation of cellulose ageing was done on a step-up transformer that was scrapped due to a gassing fault [39]. The transformer had been in service from 1971 to 2007, and it had Insuldur upgraded paper in the windings and normal kraft in spacers and pressboard. It was water cooled and normally when operated run at 90% load corresponding to best point of the turbine. More than 70 paper samples along and around the windings were analyzed.

We found during the investigation that:

- It was difficult to establish a thermal model for the transformer
- Water content of cellulose was uncertain as preinvestigations prior to opening was not done, and after opening the cellulose was exposed to ambient conditions for too long.
- Records on thermal history were sparse.
- The fact that both normal and upgraded paper was used facilitated estimation of temperature for neighboring locations where conditions and ageing time had been similar.

The main lessons learnt were that:

- The windings were in good condition due to low operating temperatures, fairly dry insulation and the use of thermally upgrade paper.
- The lowest measured DP value was 650
- Operated under same conditions in the future it would take another 130 years to reach a DP value of 200.
- The DP values varied more than expected, so the identification of hot spot conditions became uncertain.
- The ageing estimation using thermal and condition approximations seems to fit with the measured DP values.

Figure 37 shows the DP-values estimated from the ageing of both kraft and Insuldur paper. We can see that the hot-spot region expected to be the 2nd upper disk is not very pronounced.

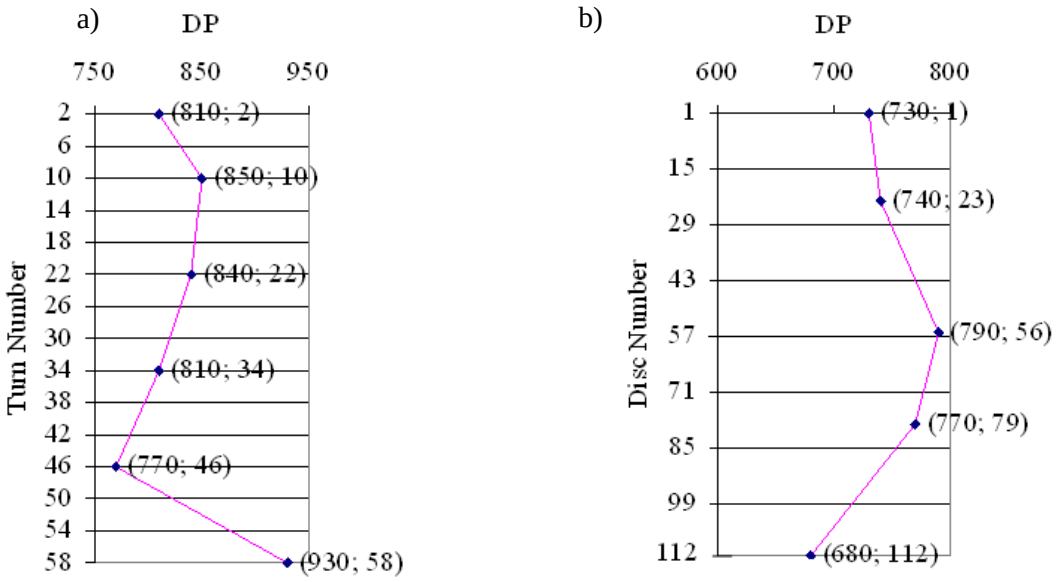

Figure 37: Paper condition (DP value) at phase C: a) low voltage winding and b) high voltage winding.

9.2 NEA TRANSFORMER

The paper filter rig was connected to a single phase generator step up unit. The transformer power was 36.67 MVA and cooling mode was OFWF. The winding connection was Yz with the voltage and current ratings of 244/sqrt(3)/10/10 kV/kV/kV and 260/2x1834 A/A respectively. The transformer was built 1960 and was scheduled for replacement. As in the previous case the transformer loading, ambient and top-oil temperature histories were unknown. Again, no appropriate thermal analysis has been performed.

The paper cell was kept at two different temperatures, i.e. at 62.6ºC and 45.9 ºC respectively. The high temperature setting simulates the winding hot location, while the lower temperature setting refers to the top-oil temperature condition. The time period for each temperature settings was 15 days. After the first 15 days at 62.6 ºC a paper sample was taken from the paper cell and replaced with the new one, and then the temperature is decreased to 45.9 ºC for the following 15 days. The transformer and the paper cell were disconnected simultaneously, and the *pressboard sample*, (1mm thickness), was taken from the top yoke 20 minutes later. Due to specific design this was the only accessible location in the transformer at the time. The results of the paper and oil quality analyses are given in Table 9.

Table 9: Conditions measured at Nea transformer.

Water in Oil-Bottle Sample, ppm	12.2
Water in Paper,(Equilibrium Curves at 62.6°C),%	1.3
Water in Paper, KF, (Paper from Cell at 62.6°C),%	1.9
Water in Paper, KF, (Paper sampled at 53.5°C),%	1.3
Water in Paper,(Equilibrium Curves at 45.9°C),%	2.3
Water in Paper, KF,(Paper from Cell at 45.9°C),%	2.6
Acidity in Oil (TOTAL), NV, mg KOH/g (TAN)	0.0496
Acidity in Washed Oil, distilled water, NV, mg KOH/g	0.0358
Low Molecule Acids(LMA), NV, mg KOH/g	0.01
NV(LMA)/NV(TOT), %	20
Paper Acidity, NV(paper filter at 62.6°C),mgKOH/g	0.274
Paper Acidity, NV(paper filter at 45.9°C),mgKOH/g	0.375
Paper Acidity, NV(paper filter at 45.9+62.6),mgKOH/g	0.457
Paper Acidity,NV(paper sampled at 53.5°C),mgKOH/g	0.364
DP Value	310
Average Temperature, paper cell, °C	62.6/45.9

The measured water content of the paper in the filter for both temperature settings was higher than the values estimated from the equilibrium curves. At the assumed transformer sample temperature the equilibrium curve estimation is 1.8% water content. Accidentally, this number is approximately equal to average moisture level between the filter and transformer sample measurements at the same temperature. It should be noted that the transformer sample temperature was chosen arbitrarily as arithmetic mean between the measured top-oil and assumed transformer top-winding temperature. Clearly, the temperature estimation uncertainty is very high as the sample location temperature could easily be 20 ºC higher, and difference between the rig and transformer samples would be much lower. On the other hand, the paper acidity results indicated that the transformer sample location temperature could be between two rig temperature settings as suggested already or even lower.

9.3 HOFF TRANSFORMER

A power transformer located in one of Oslo's district heating plants was scheduled for the refurbishment due to weak paper insulation, (DP value was 250 for the sample taken from the low voltage leads) and very bad oil quality. Also, the transformer production year, 1966, suggested that the insulation was approaching possible end-of-life. The transformer was a 40 MVA OFAF-cooled unit with three windings per limb. The voltage and current ratings of the primary and secondary windings were 50 kV/10,3 kV±9x1.5% and 407A-462-534A/2240A respectively. The tertiary-stabilizing winding was with 4 MVA power rating and the voltage was 6 kV. The transformer connection was Yy0 and the total and oil weight were 57000 kg and 13375 kg respectively. The transformer was heat-run tested at the maximum tapping, i.e. 43.25 kV /10.3 kV. Upon the rig connection the oil was circulated through the paper filter system for five days, from the 2nd to the 6th of June, 2008. During this period the filter temperature was held at approximately 60 ºC, which was 25 K higher than the top-oil temperature. The filter temperature was increased to simulate a possible winding hot-spot location, and to establish the moisture equilibrium condition on the paper-oil interface rapidly as a higher temperature provides faster absorption of contaminants from oil into paper.

At the end of the test the paper from the filter and the transformer oil were tested for the contamination and the results are summarized in Table 10. The obtained oil ppm value was further used to estimate the water content in the transformer paper insulation by using the standard equilibrium curves at the assumed hot-spot temperature of 60°C. In such way determined moisture content is equal to 1.8% and it is in relatively good agreement with the water content of the paper sample taken from the filter, 2.1%.

Table 10: Paper sample contamination results.

Water in Oil-Bottle Sample, ppm	18.7
Water in Paper, (Equilibrium Curves at 60°C9),%	1.8
Water in Paper, KF, (Paper from Cell at 60°C),%	2.1
Acidity in Oil (TOTAL), NV, mg KOH/g (TAN)	0.589
Acidity in Oil after water washing, mg KOH/g	0.484
Low Molecule Acids(LMA), NV, mg KOH/g	0.105
NV(LMA)/NV(TOT),%	17.9
Acidity in Paper, NV (paper sample), mg KOH/g	0.82
Average Temperature, paper cell, °C	60

9.4 VERDAL TRANSFORMER

A thorough scrapping investigation was done for the Verdal transformer. The transformer was manufactured in 1965 by Per Kure with plain kraft paper. In 2007 it was moved from Blåfalli to Verdal.The transformer was a 107 MVA OFAF-cooled unit with three windings per limb. The voltage and current ratings of the primary and secondary winding were 305 kV/66,5 kV and 202A/929A respectively. The tertiary-stabilizing winding had 50 MVA power rating and the voltage was 17,05kV. The transformer connection was YNyn0 and the total and oil weight were 156000 kg and 40000 kg respectively. The transformer was heat-run tested at the maximum tapping.

The water content in cellulose was in 2012 estimated to 2,7 %. Oil acidity was 0,11mg KOH/g, with 7 % of this coming from water soluble acids. Weighted average of transformer hot-spot temperature for 2010-2011 was estimated to 40 °C based on temperature and load monitoring data.

Figure **38** and Figure 39 show the DP values from external accessible cellulose and from winding paper. The data from the windings clearly shows that paper should be sampled from more than one channel to give get a representative value of the hot-spot region.

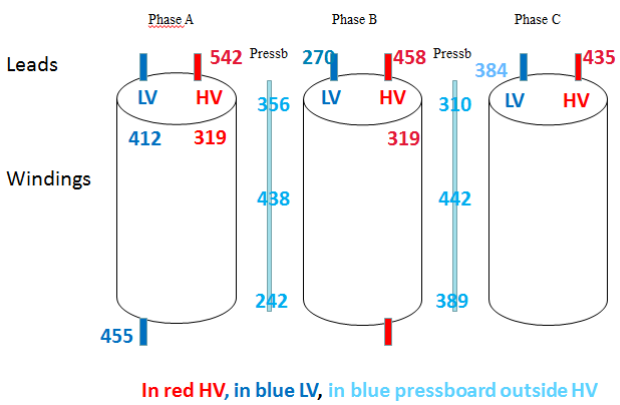

Figure 38: DP-values from results from leads and barriers in Verdal transformer.

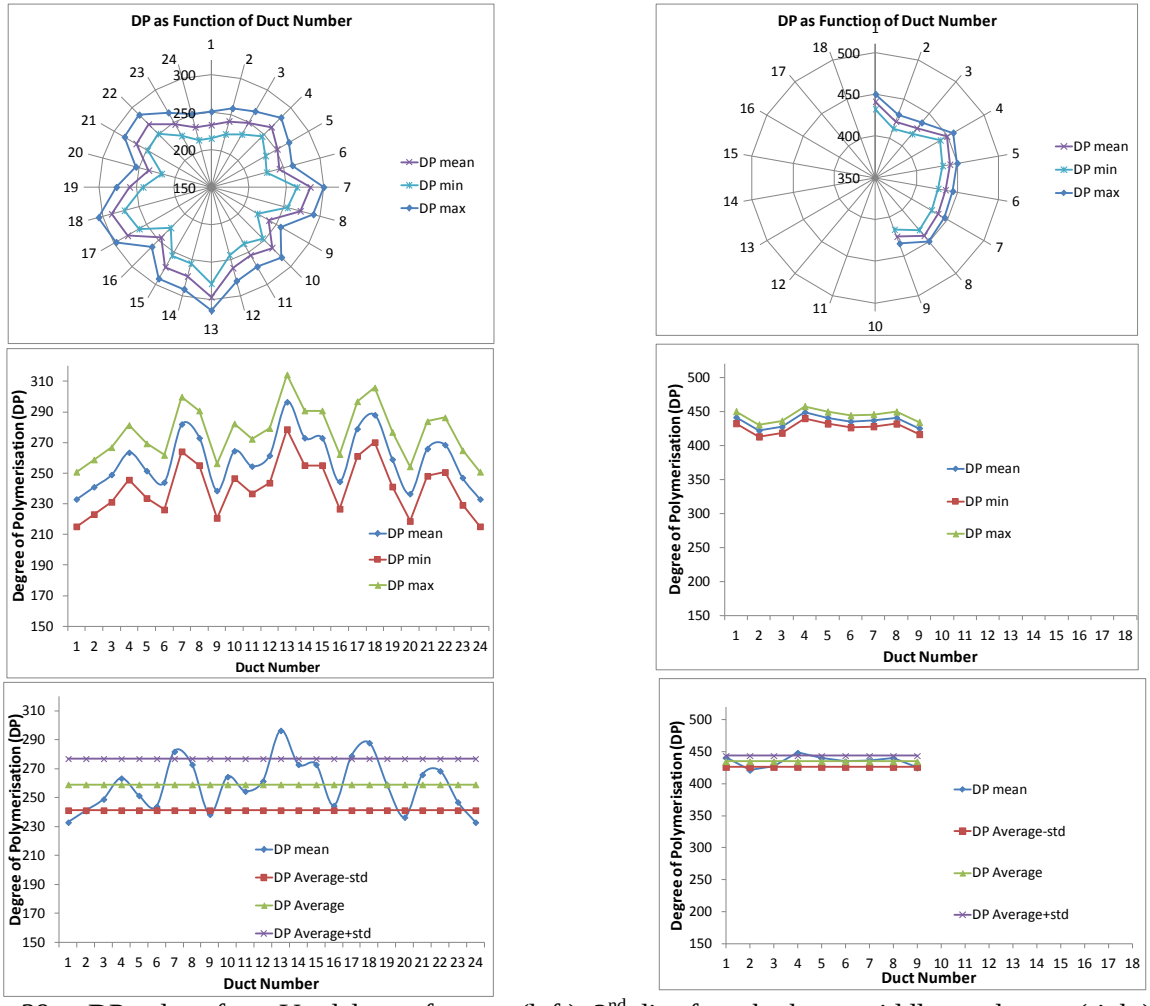

Figure 39: DP values from Verdal transformer: (left): 2nd disc from b phase, middle conductor. (right): 2nd disc from b phase, middle conductor

Assuming an average water content of 2 % of the cellulose during its life time and using ageing DP values from Figure 39 and ageing parameters from Table 2 for hydrolysis, indicated temperatures respectively 71°C for the HV-winding and 65°C for the LV winding. Using the oxidation parameters, 63 °C for the HV-winding and 56 °C for the LV-winding is found.

The simplified approach for synergy suggested in chapter 8.4 with and activation energy of 111 kJ/mole, and A-value of $8 \cdot 10^{8}$ hour^{-1} for hydrolysis with 2% water in cellulose and multiplied with 2,5 due to access to oxygen yields 59 °C and 53 °C for the HV-winding and the LV-winding respectively. This brings the estimated temperatures down towards what was estimated from load logs, but it is still high. However no certain conclusions can be drawn as also the temperatures logged can be wrongly calibrated.

The average DP-value of the samples from the HV-leads shown in Figure 38 at the winding top is 478 which corresponds to 52 °C. Comparing to the hot-spot temperature of 59 °C calculated according to the simplified method, this suggests a top-oil to hot-spot temperature rise of 7 °C.

10 MAINTENANCE AND AGEING CONTROL

One can reduce ageing of transformer windings by influencing parameters and conditions that govern the ageing rates.

- Reinhibiting of oil will reduce risks of forming water soluble acids from oil oxidation and also of forming sludge that will sediment in cooling channels and increase temperatures in the paper. Inhibitor content of the oil is usually 0.3 % and the level should not fall below 0.1 %. Practice is now usually to reinhibit without reclaiming the oil, provided the acidity and interfacial tension is well away from action levels. Otherwise oil reclaiming should be performed to get a stable result. In case of high copper content, which can be measured by atomic absorption, one should consider oil exchange.
- Temperature reduction will reduce ageing. This can be achieved by starting fans at lower temperatures. For a transformer that already operates at low temperatures benefit may be marginal, but reduction in copper losses may give a payoff even if the fans and pumps require energy.
- Oil can be reclaimed and cellulose dried; a reclaiming has a positive but marginal effect on the cellulose. For drying of a transformer one can either – for a small unit – transport it to factory for vapour phase treatment, or use low frequency heating combined with hot-oil spray for on-site treatment of larger units. Then oil is removed from the tank and usually reclaimed. A drying process will be efficient for ageing reduction provided water and water soluble acids are removed from the cellulose in sufficient quantities. For water one will roughly get a doubling of the life for every percent of water one reduces the water-in-cellulose concentration with. For water soluble acids no quantitative rules can be given. Because all reclaiming and drying processes are most efficient when the contamination concentration is high and pumps remove a large quantity of contaminant per pass, the cost benefit of running a process falls with time. There is a need for good criteria for quality verification of drying projects.
- Retrofitting expansion tanks with rubber bags or diaphragms can reduce oxygen content and reduce ageing.
- Degassing transformers with rubber bags should be considered if oxygen level gets higher than 6000 µl/l (measured with head-space).
- Continuous degassing pumps can reduce oxygen concentration –more efficient in case of sealed units – and reduce oxidation. Such pumps usually have too low capacity for efficient removal of water. However, if one manages to reduce the water-in-oil concentration then the water-in-paper concentration of the thin winding insulation - which is well coupled to the oil – is expected to fall proportionally.

All such actions should be considered on the background of the achievable life extension it can bring: a life doubling of a transformer expected to live 30 years may be a good project, while doubling the expected life from 150 years is less beneficial.

11 RECOMMENDATION FOR SPECIFICATIONS FOR NEW DESIGN

These studies accentuate properties, measures and designs that should be considered when purchasing transformers:

- Upgraded paper reduces hydrolytic ageing. The functionality of the upgraded paper requires high nitrogen content in the paper.
- Upgraded paper is still subjected to oxidation; sealing of transformers to reduce oxygen concentration will further reduce cellulose ageing and also reduce oil oxidation.
- Quality of the rubber diaphragm will influence oxygen level in oil.
- Care should be taken when specifying upgraded paper.
- Much uncertainty in thermal modeling stem from lack of specific data. Hot spot factors should be requested for each main winding. Good heat run tests are required to verify designs and hot-spot factors for the windings.
- To get paper samples from the transformer in service is complicated. To place a string basket with paper at a convenient place in the top oil volume is a good idea. If one knows the thermal design one can – by compensating for temperature differences – estimate the hot spot condition from the condition of paper in the basket.
- Solid state sensors are not exposed to the same problems as conventional water in cellulose estimation. However their use will require knowledge of water solubility of cellulose and temperature dependence of water in oil solubility.
- Fitting of solid-state sensors for measuring relative humidity and connection of hoses for paper sample filter (chapter 6.7) is complicated without flanges and ball valves. To have a ball valve at mid tank for the filter connection or for any other similar equipment is recommended. Another suitable location is close to or in the intake to the coolers. The oil going into the cooler is well connected to the oil flow out of the winding.
- Fibre-optic temperature sensors will improve knowledge of thermal design and models, and can be used for safe operation of transformers during overload.

12 POSSIBILITIES FOR CONTINUOUS MONITORING

Monitoring serves two purposes: early failure warning and estimation of slowly developing ageing.

DGA is mainly related to the early failure warning, but shorter sampling intervals than once per year are hardly practical. The fuel cell based detection of combustible gasses as used in e.g. Hydran sensors was developed to give better control in-between the sampling periods. Most insulation faults will develop some combustible gasses that can be detected, but not identified by such equipment. If a failure situation is identified or if one for other reasons wants better control there is a selection of continuous gas in oil monitors based on head-space sampling and either on conventional gas chromatography or acousto-optic principles [40].

For ageing monitoring the sampling intervals can be longer. It is mainly ageing markers and drivers that are of interest (see chapter 6.2), together with temperature. There exist continuous monitors for moisture in oil and conductivity, otherwise one are restricted to the use of periodic oil sampling. For oil temperature and winding temperature monitors are in widespread use. These are often just connected to over-temperature indicators/relays. Temperature monitors are often built into stand alone monitors, which have a microprocessor that will detect cooling modes etc. and can calculate e.g. temperatures according to IEC 60076-7. With modern SCADA systems such intelligence can also be built into the control room software. *To monitor life consumption it is essential to monitor and store yearly averages of oil and winding temperature*. The hot spot temperature can either be estimated using the IEC loading guide, provided the real hotspot factor is known, or one can use fiber optic detectors if such has been installed when the transformer was purchased.

A.1 SCRAPPING AND POST MORTEM PROTOCOL FOR TRANSFORMERS

When a transformer fails or when it is decided to scrap an old unit one gets an opportunity to learn about its condition. This knowledge can be used for assessing expected life of units in service for e.g. reinvestments.

The investigation of scrapped transformers is a valuable tool for gaining understanding of the degradation kinetics of materials and for calibration of the end-of-life estimation techniques. We will here briefly describe steps in making *medium* or *minor* scrapping investigations to build databases over paper ageing conditions of service aged units. We will here disregard extensive sampling to analyse chemical conditions of the insulation, winding clamping, etc. as described in [41]

The post mortem procedure can be divided in three steps. The first addresses work planning. The second addresses data collection relevant for design and service, and the last addresses the procedures for sampling paper. The second step defines procedures to obtain the paper samples for DP analysis and for calibration of the kinetic model.

A.1.1 Step I: Work planning.

The location of the scrapping must be identified; is there access to cranes and local help. Experience shows that scheduling of jobs often is uncertain and in a scrapyard paper sampling is an unrecognized and non-prioritized task. It is therefore recommended to prequalify scrapyards for such tasks, and establish clear protocols and contracts to be prepared. Direct contact with personnel performing the physical on-site scrapping would in addition be very valuable and is mandatory. Agreeing on penalties in case protocols are not followed can reduce risks of jeopardizing an investigation.

A.1.2 Step II: Pre-investigation and Insulation Sampling for Contamination Measurement

Here just list information that is valuable for assessing ageing:

1. Design.: Design data, Test data, Heat Run Test Data, Nameplate Data, Drying procedure, Material types, Breather types: open or closed.
2. Operating Condition: Maintenance history. Load history Oil temperature history, Ambient temperature history, Operational Cooling Mode (ONAN, ONAF, OFAF or combination of these ones)
3. Diagnostic Data: DGA and oil analyses both historical and at shutdown. Water content in cellulose, Moisture, furans, alcohols.

A.1.3 Step III: DP Sampling

It is recommended to use personnel who are trained/qualified for taking samples. This personnel must as mentioned earlier (A.3.1) have direct contact with the people performing the actual scrapping to be able to sample at the wanted locations, otherwise one risks impossible work conditions (destroyed windings and impossible to locate the planned sample positions).

One need to decide on how many locations one needs to sample: Which phases, which windings (HV/LV/Tertiary), from intake leads, from low density pressboard at top-oil region, and how many samples one wish from hot spot region to calculate averages with a low uncertainty. Ageing will usually be highest in the middle leg, adjacent to the outer phases.

One needs to decide if one will measure each paper layer or mix all. The last is probably cheapest and easiest in the long run. Normally one needs 0.5 gram paper pr. sample. When cutting pieces of paper wrapped copper conductors one has to have a sufficient length if one wants to measure DP of each paper layer. In case measuring average DP from all layers length can be shorter. One needs to mark all samples. Often it is easy to cut out whole sections of discs and strap them together before sending to the lab.

A toolbox must be carried along containing:

- Wedges, crowbars and levers for prying windings apart
- Metal saw (electric crocodile type) for cutting out sections of windings
- Metal cutters.
- Knives, cutters, scissors, wire cutter?
- Bottles and plastic bags for samples
- Map of windings for identifying sampling locations
- Containers and boxes for shipping back samples
- Plastic strips
- Premade labels
- String for fixing labels
- µ-Scale to check sample weights
- Camera
- Notebook

Health, environment and safety needs to be analyzed and secure job analysis made.

The laboratory that will do the DP analysis needs to be identified and samples shipped.

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