

# Moisture equilibrium in transformer insulation systems: Mirage or reality? Part 1

## ABSTRACT

In the operating transformer water is always in transition, either moving within cellulose insulation or migrating from paper to oil and versa visa. This article introduces a methodology where we use an equilibrium chart for an assessment of a dynamic process which may not reach an equilibrium and still give us a good sense of moisture state in the oil/paper system.

## Introduction

After a short introduction of key water parameters in the previous issue [1] we continue to answer your most burning questions on water in transformers. In this issue we are going to cover only one topic and that is moisture equilibrium.

One of the most cited research publications on transformer diagnostics has been a paper by Du, et al. "Moisture equilibrium in transformer paper-

oil systems" [2]. According to Google scholar, it was cited by more than 400 times at the time of writing. This is by far exceeding any research work in area of diagnostic of power transformers, except for Duval's work related to DGA.

The very first CIGRE Technical Brochure (2008) [3] exploring phenomenon of moisture in transformers was titled: "Moisture equilibrium and moisture migration within transformer insulation systems" [3]. The first article of inaugural issue of CIGRE SCIENCE &

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their development. A curious reader can find many sources and names associated with research on the subject.

In that paper the authors clearly state that “when the transformer is in equilibrium operation, this [moisture partitioning curves] provides a quick way of examining the moisture content in paper to predict future failure by measuring the moisture in oil”. However, as it was mentioned above, a transformer in operation does not experience a truly thermodynamic equilibrium, a situation where water exchange between various insulating components ceases to occur. The definition of thermodynamic equilibrium was given in previous issue of Transformer Magazine [1], but could also be found elsewhere. Are we all misusing and misinterpreting the theory? Is there any practical implication of these curves? By now you may already have guessed that there is a positive answer to our quest, otherwise we would not have bothered by keeping you engaged in reading this article. It is a desire to look at this important and controversial subject of transformer diagnostics from different perspective motivates us to embark on this journey.

### The beginning

Following the steps of Du et al [2] we could find out that the first moisture equilibrium chart as applied to electrical apparatus was published by John Piper [7]. The problem raised was a possible condensation of water in gas space and drop-outs on active parts leading to increased risk of failure. The objectives were: a) to use dew point instrument to predict condensation temperature and b) to develop equilibrium charts for practical use.

The author gave a few examples of the use of the chart and in particular:

a) in predicting the equilibrium moisture content that fibrous materials will acquire when exposed to atmospheres of various relative humidity and temperatures

b) in predicting the dew points of the gas in enclosed electric apparatus, and  
c) in employing dew point measurements as a non-destructive analytical tool for determining the moisture content of fibrous materials in electric equipment.

The paper covers moisture behaviour in gas insulated electrical equipment. A special attention was given to gas insulated HV cables where temperature of the gas is relatively constant and equilibrium state could be assumed. Although the paper does not refer to moisture paper/oil system, it lays a foundation and suggests an approach of how to develop such graphical tools to relate water content in the gas space to water content of solid insulation.

In theory, the amount of moisture organic materials (such as cellulose insulation) contain is primarily determined by the relative humidity of the surrounding gas, or by relative saturation when immersed in the insulating liquid. Dew point is not such a parameter - relative water vapor pressure is. It follows from the fact that in the case of constant temperature chemical potential of water is determined by relative water vapor pressure. Thus, any correlation of dew point and moisture content is prone to error. Therefore, the practical use of Piper's diagram is very limited, to say the least.

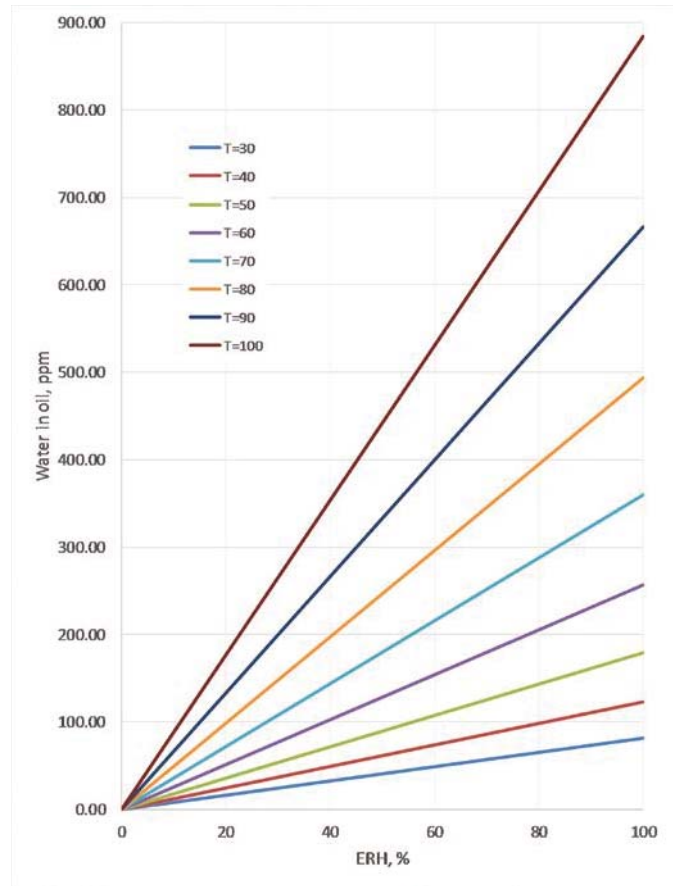
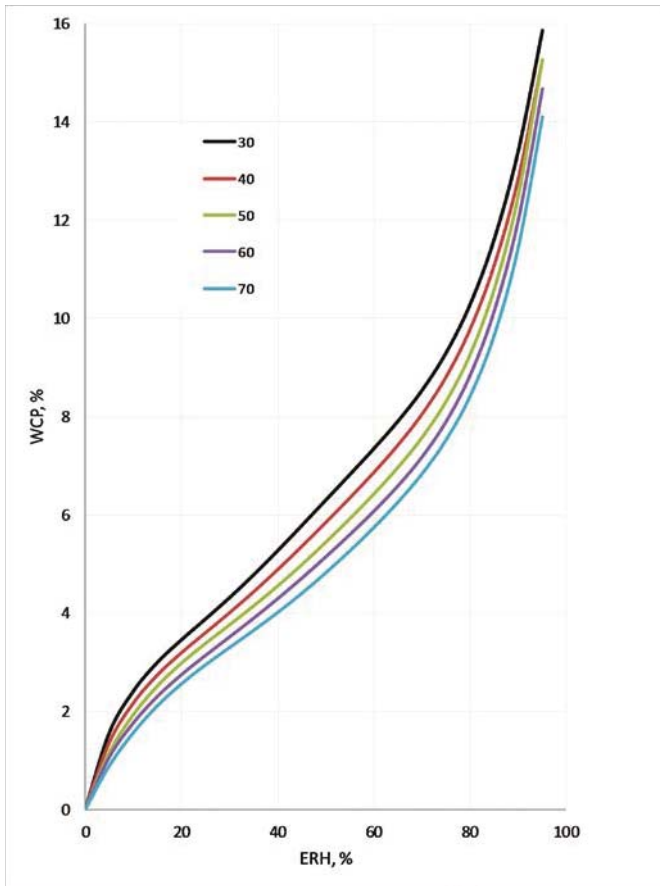
The phenomenal success of Du's review can be explained by the desire of engineers to find a quick and easy way to make an approximate assessment of moisture state in solid cellulose insulation. The amount of water in oil could be more than 100 times less than it is in the paper, and therefore WCO appears to be insignificant and not necessarily harmful. Further historical background on development of equilibrium charts and their refinement could be found in Du's work. We would only like to draw your attention to two distinct methods of generating these charts.

ENGINEERING Journal was a paper by C. Perrier et al, fully dedicated to establishing new moisture equilibrium curves for transformer cellulose insulation immersed in ester liquids [4].

Yours truly Transformer Magazine have not missed the boat, publishing extensively on this topic too [5, 6].

On the other hand, we all (experts and users alike) know that moisture equilibrium does not exist in operating transformer. That's right, in the operating transformer water is always in transition, either moving within cellulose insulation or migrating from paper to oil and versa visa. Then it raises the question, “what is the value of all the knowledge and experience behind it?”. Is the water equilibrium in transformer oil/paper insulation just an illusion as the title suggests?

To answer that question a very good place to start is a research work by Du et al [2] where the author and her co-authors provide a historical background on moisture equilibrium curves and



a) Figure 1. Sorption isotherms for a) Kraft paper and b) oil

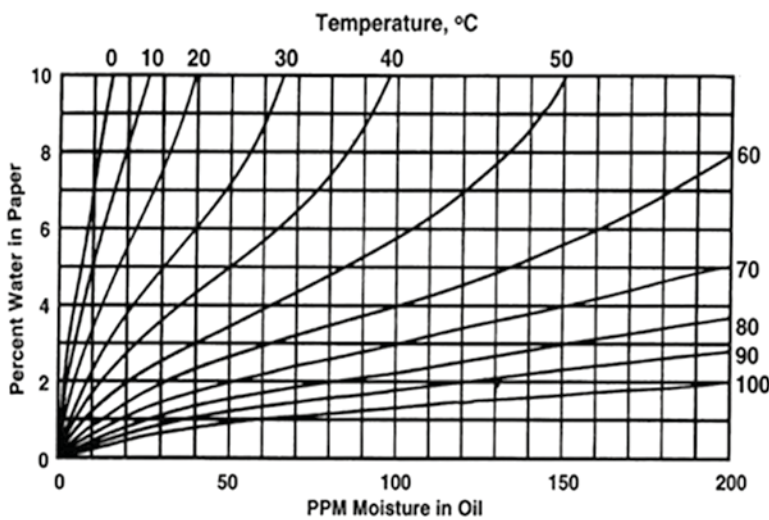


Figure 2. Moisture equilibrium isotherms per Oommen 2003 [12]

1. Experimental

It is not exactly known how the equilibrium curves were developed prior to Oommen's work, but most likely these were developed as a result of physical experiment. No mathematical formulas were given and only hand drawn diagrams were published [8].

2. Analytical

Based on known data and knowledge of

natural laws of physics this method was used by Oommen [9] and Du [2], which presents pure mathematical exercise of combining two sets of sorption isotherms to arrive at another set of isotherms which is known as Oommen's curves. As described in [9], Oommen was not able to find a mathematical equation to fit mentioned in [9] Jeffrie's sorption isotherms (Figure 1a) and therefore did not provide us with the mathematical

formula of his hand drawn diagram. However, Roizman [10] managed to fit experimentally obtained data for 1 mm pressboard at 80°C by Guggenheim, Anderson and De Boer model (GAB) using the following formulation [10]:

$$WCP_a = \frac{WCP_0 \cdot C \cdot K \cdot Awp}{(1 - K \cdot Awp)(1 - K \cdot Awp + C \cdot K \cdot Awp)} \quad (1)$$

where *Awp* is the water in paper activity determined under equilibrium conditions or inferred from online moisture monitoring. This is NOT a RS/100!

*WCP<sub>a</sub>* is equilibrium water content in paper corresponding to *Awp* as determined above.

*WCP<sub>0</sub>* – is water content of monolayer.  
*C* and *K* – energy constants.

The set of sorption isotherms constructed with GAB model is presented in Figure 1a.

Sorption isotherms for water in oil are shown in Figure 1b. These are created following a linear equation of the form:

$$WCO = (RH/100) \cdot e^{A-B/T} \quad (2)$$

At *RH* = 100%, *WCO* is at its maximum

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value and is called water in oil solubility (definition is introduced in the previous issue of TM [1]).

It is clear that when A and B are constants at a given temperature, function  $WCO = f(RH)$  is a linear one. However, non-linear  $WCO = f(RH)$  can also be observed for the oil heavily contaminated with polar compounds caused by high aromatic content and/or high acidity [11].

Water in oil solubility ( $WCO^*$ ) is a function of temperature. And for transformer operating temperatures could be approximated by integrated form of van't Hoff equation [13], which relates equilibrium constant (in this case  $WCO^*$ ) at a given thermodynamic temperature to the change in enthalpy.

$$\ln(WCO^*) = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \quad (3)$$

where  $\Delta H$  (J/mol) is the change in standard enthalpy of water in oil solution,  $\Delta S$  is the change in standard entropy of the same chemical reaction, and R is the universal gas constant  $8.3144598 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ .

Assuming that  $\Delta H$  and  $\Delta S$  do not change significantly with temperature within operating transformer range, equation (3) can be written as

$$\ln(WCO^*) = A - \frac{B}{T} \quad (4)$$

where constants  $A = \frac{\Delta S}{R}$  and  $B = \frac{\Delta H}{R}$  are called solubility coefficients.

In transformer literature equation (4) is often given without any reference to its origin and has various (often erroneous) interpretations. Almost elsewhere equation (4) is mistakenly referred to Arrhenius equation describing the rate of chemical reaction. This is not

correct, as the chemical process of water dissolution in oil is a thermodynamic one while as Arrhenius rate equation is used in chemical kinetics. Confusing one term with another may lead to wrong inference and even to erroneous estimation.

Sometimes equation (4) is given in decimal logarithm form. However, for consistency and ease of comparing, it is recommended to use natural log notation. It also follows from equation (3) that natural log is originally used in van't Hoff equation.

Once the graphical and mathematical relationship between water in oil and water in paper is established the assessment is carried forward, considering the following assumptions [10]:

**Assumption 1:** Moisture equilibrium is readily attainable. Thus, water-in-paper content can be evaluated from the measurement of water-in-oil content with the help of the moisture equilibrium charts.

**Assumption 2:** Water content of oil in the transformer is uniformly distributed across the transformer tank. Thus, the top oil temperature can be used when relating the moisture-in-oil taken from the bottom drain valve to moisture in cellulose insulation.

**Assumption 3:** The water solubility characteristic of oil in the operating transformer is unique for all new mineral oils and does not change with aging. Thus, the published moisture

equilibrium charts are applicable to any mineral transformer oil.

**Assumption 4:** Value of WCP obtained from the moisture equilibrium chart corresponds to the moisture content by dry weight of the bulk cellulose insulation. Uneven distribution of water in solid insulation is neglected.

**Assumption 5:** Absorption and desorption of water from paper can be described by the same equations. Thus, hysteresis is neglected.

**Assumption 6:** The time constant to attain moisture equilibrium is equal to the time constant of the temperature equilibrium. Dynamic lag is neglected.

**Assumption 7:** The sorption isotherms – Equilibrium Relative Humidity (ERH) versus WCP, which were used to generate the WCP versus WCO curves, are universal for all kinds of cellulose material used in a transformer. Thus, 1 mm barrier insulation would have the same sorption isotherms as 30-40 mm supporting wood rings.

**Assumption 8:** The sorption isotherms – Equilibrium Relative Humidity (ERH) versus WCP are not affected by the age of cellulose material used in a transformer. Effect of chemical degradation on sorption characteristics is neglected.

**Assumption 9.** Water solubility coefficients published in literature and used as default in moisture sensors for new oil do not change with time. Thus, the equilibrium curves are not affected by the change in oil quality characteristics. Since most of the above assumptions do not hold for ever aging and diverse transformers, the moisture assessment based on the published equilibrium diagrams may not correspond to the true value of water content in the oil/paper insulation.

An error estimation was carried out by

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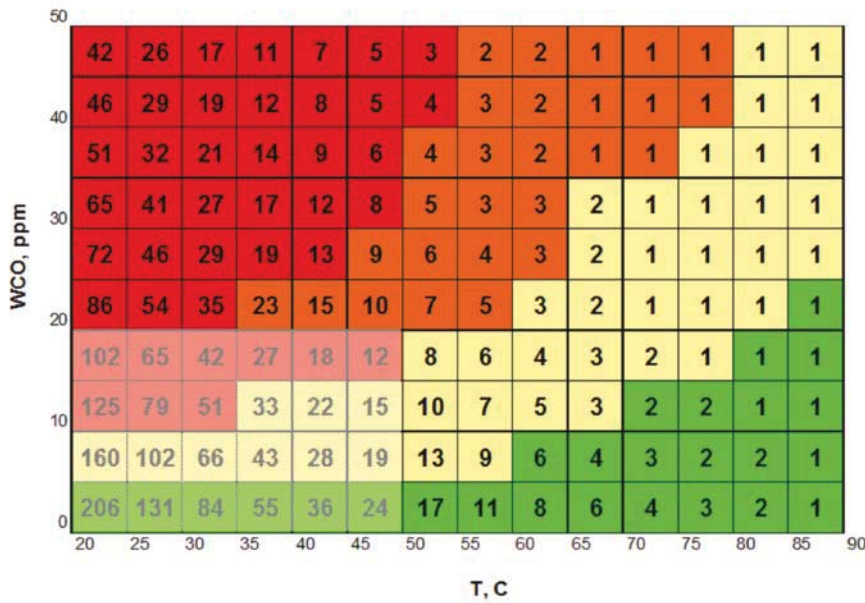


Figure 3. Moisture equilibrium diagram in WCO and T coordinates

## The major advantage of the Colour Chart, developed by Roizman and Davydov, is the avoidance of exact estimation of WCP

various researches i.e [3,10] and could reach more than 100 %.

Dr. Oommen dedicated the whole paper on use and misuse of moisture equilibrium curves [12], where he summarises many pitfalls of incorrect application of moisture equilibrium and suggests how these curves can be used in more reliable and useful way.

The error in relation to the assumption 9 may be significant, therefore the use of equilibrium curves of Figure 1a is often recommended as preferred option by some sources [3]. The issue of changing water solubility as affected by oil chemical composition can be overcome by applying the method recently introduced in [13]. Therefore, in the following section we explore some of the advantages of using WCO vs WCP equilibrium.

### WCO vs T equilibrium chart

One of the good ways to demonstrate the correct use of equilibrium charts is to examine the moisture equilibrium diagram developed by Roizman and Davydov [14].

By applying the three-color set (“red” has a few shades) and combining the diffusion data obtained for a 1 mm pressboard plate [14], the colour moisture equilibrium diagram has been created. This is shown in Figure 3.

The chart of Fig. 3 is based on equilibrium between state of water in oil and paper. It was first constructed based on infield data and experience, but it can be derived from the Oommen’s equilibrium chart (Figure 2) above, where boundaries separating the colours are lines of equal water content in paper. Green zone is limited by 1 % of moisture in paper, ‘Yellow’ zone is limited by 2 % and ‘Amber’ is limited by 3 %, and anything else is ‘RED’.

RED colour in Figure 3 means transformer is in critical condition (in terms of moisture) and requires immediate attention. If it is a top part of the transformer then AMBER is the same as RED, otherwise it should be treated as YELLOW. YELLOW - transformer is questionable, but does not require an immediate action, although further periodic monitoring is recommended. GREEN - transformer

is in good moisture condition. The numbers in the cells represent the diffusion time constant for moisture across a 1 mm pressboard plate exposed to the oil from both sides. There is a substantial difference in equalization times. Thus, the shaded cells in the lower right-hand corner are the area of high level of uncertainty with low degree of confidence in diagnostics. The above Colour Chart was developed for off-line use when new and “like-new” mineral oils were analysed in a laboratory.

To assess the moisture state, classify, and rank transformers using the Colour Chart of Figure 3, it is recommended to implement the following steps [14]:

1. Take an oil sample at the time when transformer is relatively “cold”. Measure oil sample’s temperature (T, °C) and water content (WCO) at that low temperature, i.e. when the oil temperature indicator reads a minimum value for the day (e.g. at 9 a.m.).
2. Measure water content of oil (WCO) taken from the same port at a higher temperature of the rising load cycle. Depending on the oil temperature cycle, the measurement can be taken either on the same day (e.g. at 4 p.m.) or on another day at a higher ambient temperature and/or higher load.
3. Plot results of the two consecutive measurements on the Colour Chart of Figure 3.
4. Connect the two points and observe that there is a positive slope (second ppm value is higher than the first one). The direction of a vector connecting two points is indicative of the moisture state of the studied transformer.

The major advantage of this diagram is the avoidance of exact estimation of WCP. Rather than calculating water content precisely (which in most practical cases is not possible), the diagram is used to classify an insulation into “RYG” zones which presents more realistic approach to estimation of water state in the operating transformers. With experience, it is also possible to rank a transformer fleet in terms of moisture condition. This opens a path to development of a health index, which then could be incorporated in any asset maintenance program.

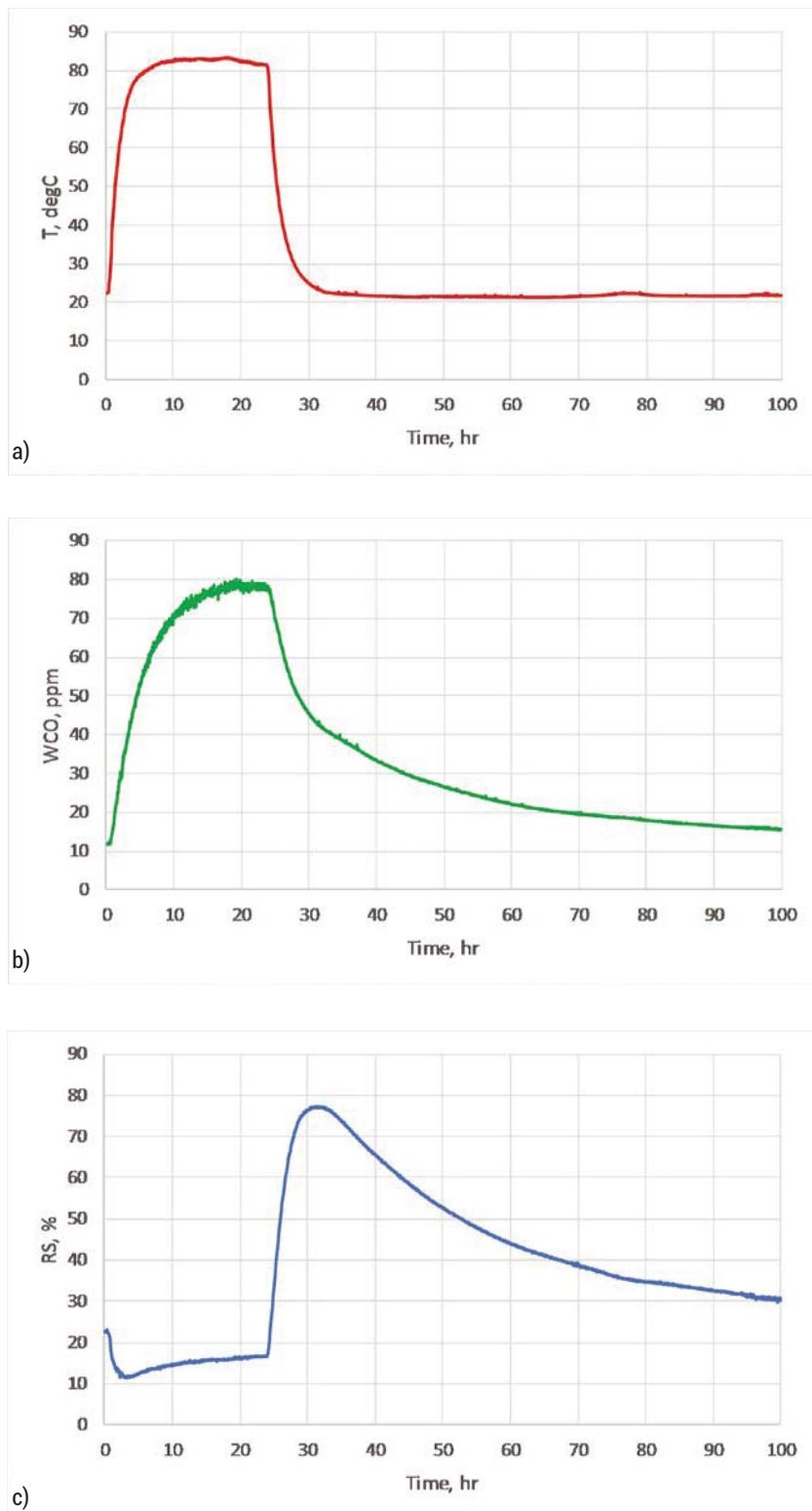
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### Dynamics of moisture in oil/paper system: Formation of moisture cloud

Let's examine an example of heating and cooling of 1 mm pressboard spacer assembly immersed in oil. The initial water content of the spacer is 2.5 % measured by gravimetric method. The system is closed, i.e. no water vapor exchange between test rig and the surroundings.

Figure 4 illustrates that during the temperature rise, initially, the pressboard would desorb (give) moisture into the oil thereby increasing oil's ppm value (Fig 4a). However, the relative water saturation remains almost constant, slightly dropping initially and increasing again soon after, reaching an equilibrium value of 18 % at about 25 hour mark since the beginning of the test. Such nonlinear, uncorrelated with temperature, behaviour of RS can be explained by its dependence on water solubility and absolute water content simultaneously in such a way that RS decreases when oil temperature rises, and it increases because of WCO increases. Which way RS goes depends on the amount of water in the system in the absolute terms.

During the shutdown of the heating process the reverse happens. The oil temperature decreases at the same rate as it was rising. However, the return of water ppm from oil to the pressboard does not occur at the same speed as it was during temperature rise, but much slower. Hence, there is a relative saturation hump of 80 %, which may be high enough to affect the dielectric strength of the oil. The cold start under those conditions could be hazardous,



a) Temperature variation profile; b) WCO response to temperature change; c) %RS response to temperature change

Figure 4. Heating and cooling of oil immersed pressboard of known water content. WCP = 2.5%

**Time constants for moisture desorption and adsorption are significantly different – this is a phenomenon known as hysteresis**

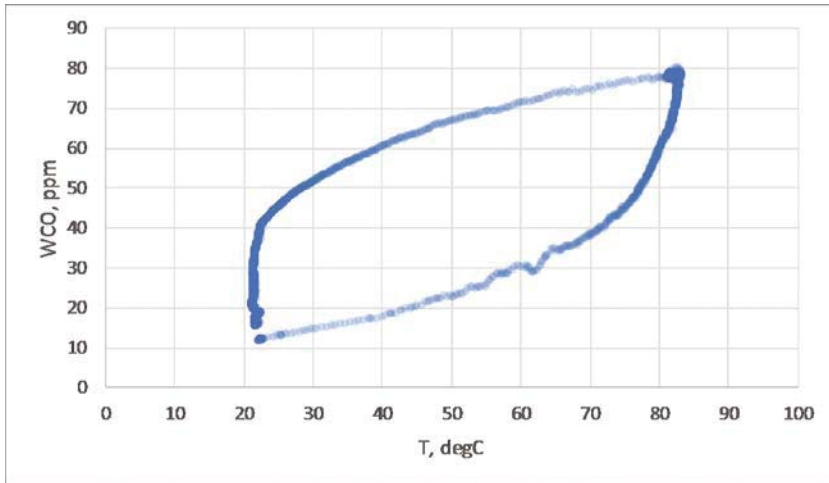


Figure 5. Moisture cloud plot of WCO vs T based on data in Figure 4a and 4b.

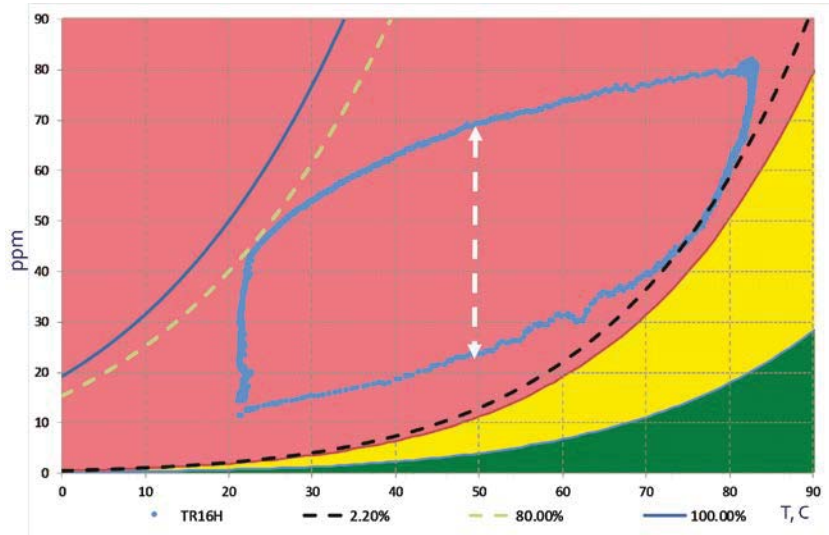


Figure 6. Superposition of moisture equilibrium chart and scatter plot of Figure 5

## Large hysteresis means more risk of dielectric breakdown due to moisture not being able to return to paper in reasonable time

as 80 % of RS decreases oil dielectric breakdown voltage by 70 %, as it was shown in Figure 1 of the previous issue of Transformer Magazine [1]. Now let's get back to an equilibrium and find it in Figure 4.

In about 24 hours at the very end of temperature rise both WCO and RS have stabilised. It is at that point we can say that our process of moisture exchange has reached thermodynamic equilibrium. Thus, the curves of Figure 1a can be used to determine the pressboard water content. That

is 2.3 % which is in a good agreement with the gravimetric method we used to determine WC in the pressboard spacer initially.

Scatter plot of WCO vs T provides an additional insight towards above mentioned hysteresis. Indeed, one can see that at 60 °C there are two values of WCO observed, these are 30 and 70 ppm. A quick estimate of the WCP using the Oommen's curves of Figure 2 results in 2.7 % and 4.8 % respectively, both are overestimates, but the second is more than two times larger. It is concluded

that moisture in oil returning back to the pressboard should be excluded from an estimation of WCP.

In addition, the following observation can be made from Figures 4 and 5:

1. WCO correlates with temperature. During the temperature increase WCO increases too, and during the temperature decrease WCO decreases. Although time constant is almost the same for temperature decrease and increase, time constants for moisture desorption and adsorption are significantly different. This phenomenon is known as hysteresis and can be seen in Figure 6. At 60 °C WCO is about 30 ppm on the temperature rising part, and 70 ppm on the temperature dropping part. As it was mentioned earlier, a large error can be introduced by ignoring this difference. This is also a good example of how misleading the use of equilibrium curves may be.

2. Relative saturation dose not correlate with temperature; thus, it is more difficult to predict its response to temperature fluctuations, meaning that scatter plot of RS and T is generally not practical. Therefore, we do not recommend plotting scatter of RS vs T.

As it will be shown in the second part of the article, repetitive cycling of load and temperature causes multiple loops of ppm in the WCP/T coordinates chart which forms a "cloud" like pattern. Figure 6 shows one such a loop and could be used to explain how scatter plot of WCO/T data can be superimposed on a classification chart, like the one shown in Figure 3.

The following observations could be made:

Every moisture cloud can be characterised by three main parameters:

1. Lower boundary (black dashed line) representing equipotential curve of WCP, touching the cloud at the bottom (In Figure 6 this is 2.2 % of WCP)
2. Upper boundary (green dashed line) representing equipotential curve of %RS, touching the cloud at the top part and,
3. Hysteresis – (white dashed double arrow line) the maximum difference

# With the moisture cloud approach, the moisture assessment becomes as simple as noting the location of the cloud with respect to equilibrium diagram

between top and bottom part of the cloud taken at the same temperature. This is 50 ppm in Figure 6.

The difference between upper boundary value and 100 % RS is the safety margin. For example, safety margin for the cloud depicted in Figure 6 is 20 % = 100 % - 80 %. From Figure 1 of [1] it follows that for a transformer with no risk of dielectric breakdown, the safety margin must be better than 80 %. The risk is increasing thereafter till 40 %, beyond which a possibility of dielectric breakdown due to moisture is at its maximum.

With the moisture cloud approach, the moisture assessment becomes as simple as noting the location of the cloud with respect to equilibrium diagram. If a bottom part of a cloud falls in the GREEN zone above 50 °C, a transformer is dry. If it falls in the RED zone – the transformer is WET, anything in between requires further attention. Large hysteresis means more risk of dielectric breakdown due to moisture not being able to return to paper in reasonable time. Large hysteresis usually is accompanied by small safety margin, as it is demonstrated in Figure 6.

In this part of an article we have introduced a methodology where we use an equilibrium chart for an assessment of a dynamic process which may not reach an equilibrium and still give us a good sense of moisture state in the oil/paper system.

In the next issue we will spend more time explaining how this approach works in practice. Number of use cases with real life operating transformers will be examined to show many benefits of the proposed methodology.

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