Moisture equilibrium in transformer insulation systems: Mirage or reality? Part 2

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 discusses the moisture cloud algorithm, which reveals the value water in oil measurement has in predicting the amount of water available for drying out, determining the safety margin of the insulation dielectric strength, assessing the residual water in new units undergoing temperature rise test, and in reliably ranking transformers across the fleet in terms of water state.

KEYWORDS

water, cellulose insulation, oil, moisture cloud algorithm

Introduction

In Part 1 of the article titled "Moisture equilibrium in transformer insulation systems: Mirage or reality? Part 1" [1] we discussed theoretical and historical background of moisture equilibrium in transformer oil/paper insulation complex. In Part 1, we reinforced that the main use case for water equilibrium had been a determination of water content of solid insulation derived from

In operating transformer, due to varying load and ambient temperature, conditions for the water equilibrium rarely exist and it is almost impossible to make an accurate assessment of water content in solid insulation based on published oil/paper sorption curves

the measurement of water parameters in the surrounding environment, such as insulation liquid or air. We pointed out that despite a very sound theoretical foundation and support from chemical thermodynamics, it is almost impossible to make an accurate assessment of water content in solid insulation due to lack of conditions for the water equilibrium to exist. An error exceeding 100 % can easily be made if we do not follow many precautions expressed in various publications on the topic.

To overcome many pitfalls of incorrect use of equilibrium theory, we introduced a method called "moisture cloud algorithm", which allows estimation of moisture in solid insulation with reasonable accuracy [1, 2]. One of the key advantages of the cloud algorithm over all other methods is an ability to predict a range of water content values as opposed to just one single estimate. In addition, this method goes beyond just an assessment of water in solid insulation, it offers a way to estimate various risks associated with presence of moisture in transformers.

In order to understand why and how the cloud algorithm can estimate a possible range of water distributed across the insulating parts, we need to explain a mechanism of moisture adsorption to cellulose surfaces in a transformer.

Water adsorption and distribution within cellulose insulation

As was previously discussed, water finds its way in a transformer through two major paths:

1. Chemical decomposition of cellulose and oil lead to formation of water as a by-product of chemical reaction which naturally takes place during insulation aging.
2. Due to difference in vapor pressure, water is 'sucked' inside oil/paper insulation from outside environment through bad sealings, outdated desiccant, or other openings.

In any event, after prolonged operation, water settles within various parts of a transformer with very uneven distribution.

A mechanism of water adsorption and its distribution within cellulose insulation can be explained with the assistance of Figure 1.

Let us assume that during steady state of transformer operation, oil with 25 ppm of water leaves the main tank and goes into a cooling system as shown in Figure 1. After passing an upper pipe and a radiator header, the oil of the same 25 ppm cools down and then returns to the transformer tank through the lower pipe of the radiator. The temperature of the top oil is 60 °C, while the temperature of the bottom oil is 40 °C. Under given conditions, there will be a difference in relative saturation (%RS) between top oil and bottom oil. The magnitude of %RS at both locations can be readily determined by using Equation 2 from [1]. It could also be validated by moisture sensors which could be installed at both locations as shown in Figure 1. By using sorption curves of Figure 1a or Equation 1 of [1], and assuming a local thermodynamic equilibrium (LTE), the water in cellulose insulation (WCP) in the upper part of the transformer and in the lower part will be about 2.1 % and 4.2 % respectively. It supports our knowledge that water content is higher at the bottom than it is in the top part of a transformer, even though water content of oil (WCO) in the loop of radiator – tank remains the same - at a level of 25 ppm. It shows that distribution of water in solid insulation is driven by water relative saturation rather than absolute water content of oil (ppm). This hypothetical situation helps us understand the driving forces behind water adsorption and distribution within oil/paper insulation complex.

In reality, being affected by the load and ambient temperature, top and bottom temperatures vary, sometimes significantly. So does the water relative saturation. Nevertheless, distribution of water in solid insulation will always be in accordance with the described mechanism, i.e. WCP is higher at the bottom and lower at the top in proportion equal to the ratio of average relative saturation (RS) of water at the bottom and RS of water at the top.

Distribution of water in solid insulation is driven by relative rather than absolute water content of oil

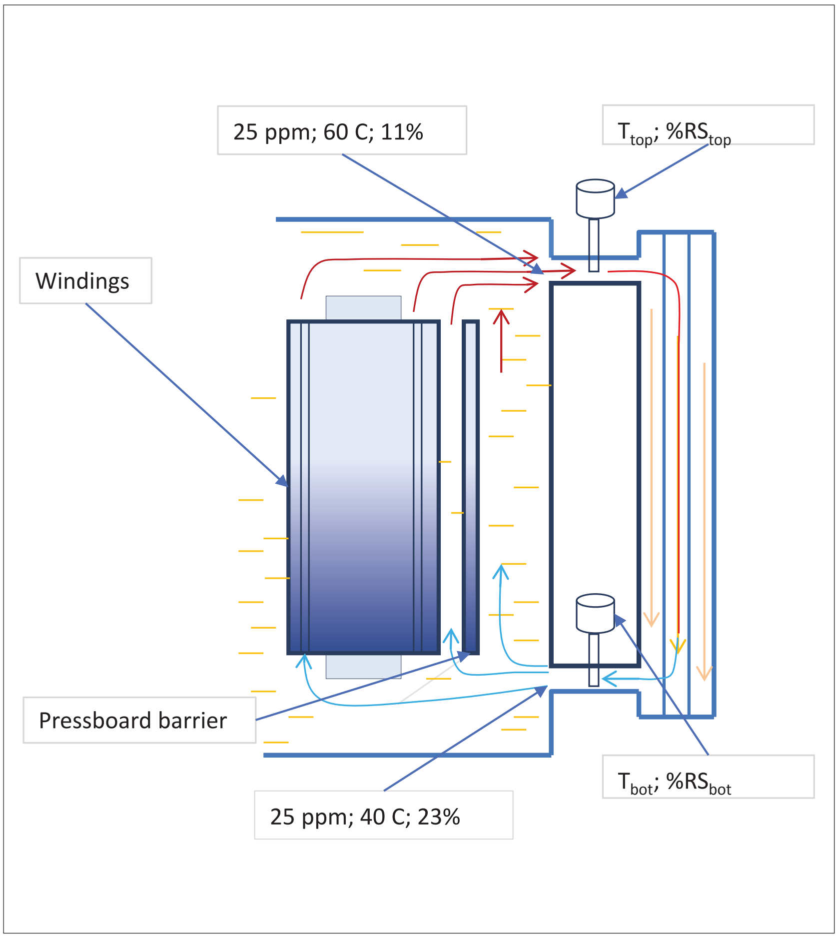


Figure 1. Mechanism of water adsorption and distribution within cellulose insulation

> **From the dielectric point of view, low values of absolute water content in oil could be just as bad as high values**

Case Study 1: Near new small distribution transformer

Now let us recall the moisture cloud theory introduced in the previous issue of TM [1] and apply it to the moisture assessment of nearly new small distribution transformer.

Similar to the setup depicted in Figure 1, the transformer is equipped with two moisture meters, one at the top and another at the bottom of radiator pipe.

For a relatively new transformer undergoing multiple steps of temperature increase and decrease during special temperature rise test the WCO and temperature profiles are shown in Figure 2a.

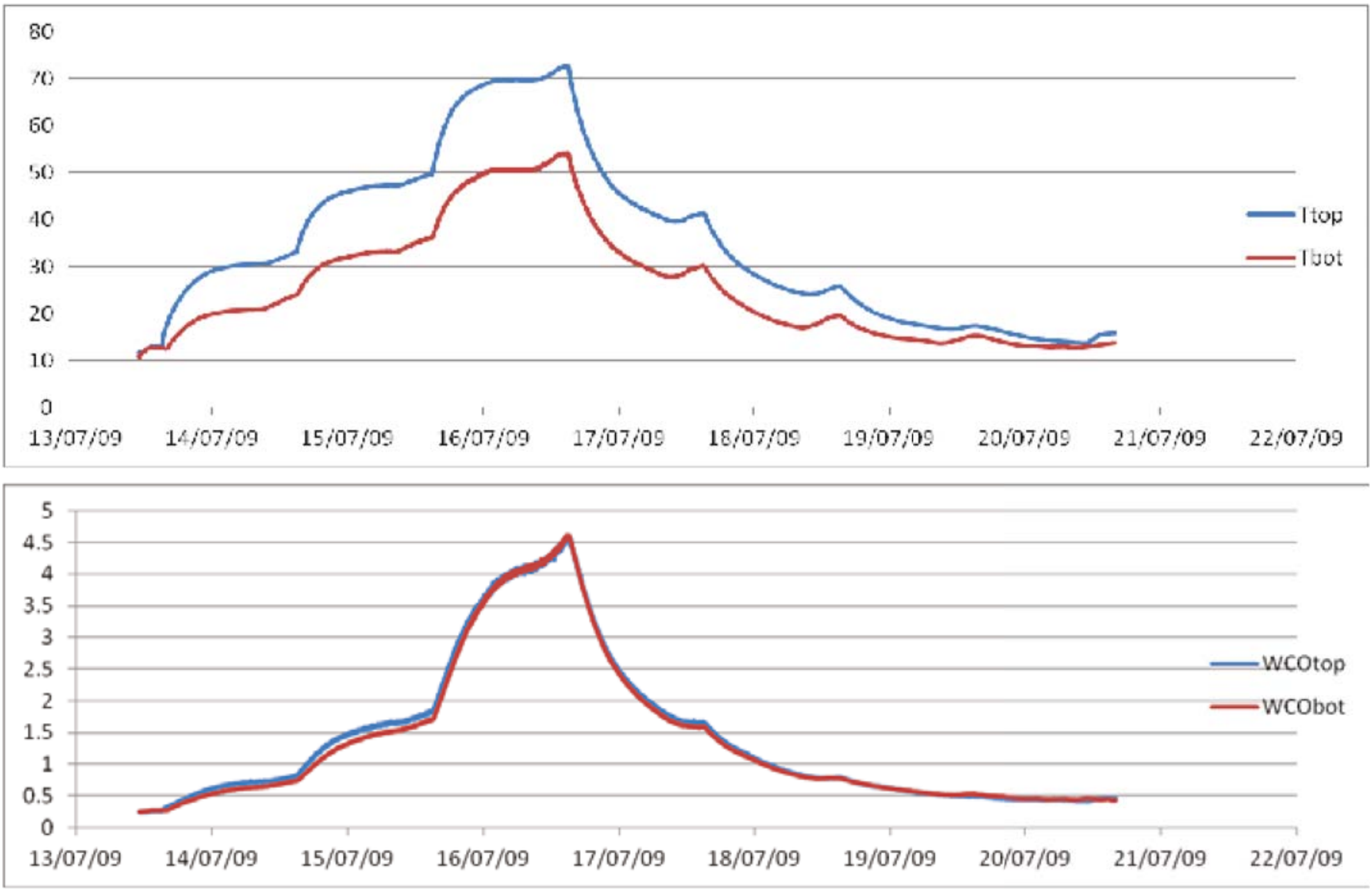


Figure 2a. Seven-days temperature/WCO profile for bottom and top oil of the transformer TR1

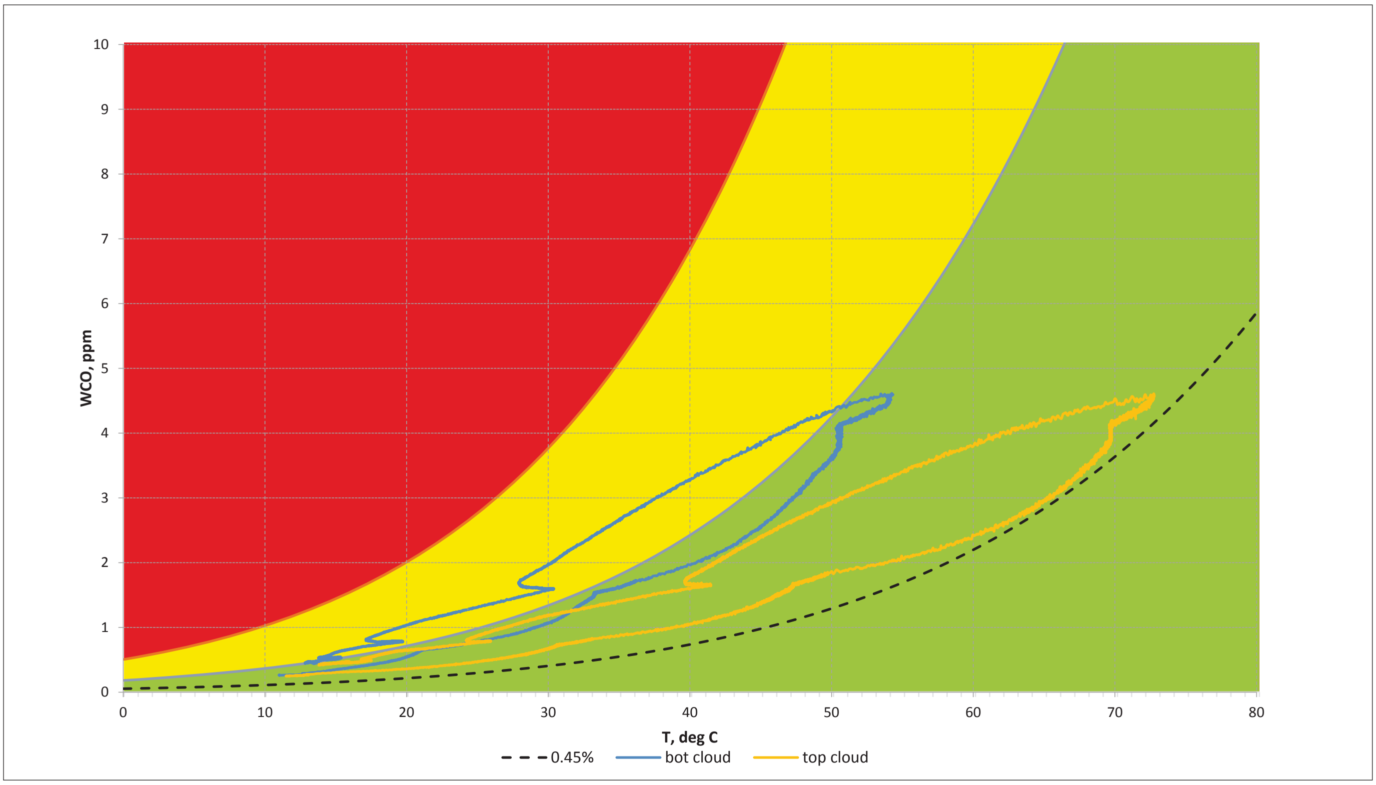


Figure 2b. Moisture clouds for top and bottom oil of the transformer TR1, WCP = 0.45 %; RS (max) = 3 %; H = 2 ppm

Utilising the procedure described in [1] we can plot two moisture clouds (for top and bottom oil) as shown in Figure 2b. Also shown is WCP equipotential line (black dashed line), touching the top cloud at about 65 °C.

It can also be observed that both top and bottom clouds indicate low cellulose moisture content and very high safety margin. Hysteresis of 2 ppm is an indication that there is very little water available for exchange between paper and oil. An estimated water content of the top part of insulation is about 0.5 % while the bottom cellulose is slightly higher but still less than 1 % by looking at the position of the bottom part of the cloud. As mentioned, this transformer has been in operation for less than one year and appears to be in 'like new' conditions. Maximum WCO is less than 5 ppm at a very high temperature, indicating that the oil water content is well under standard limit of 35 ppm for voltage class of that transformer [3, 4,]. This is an example of a perfectly dried transformer. It could also serve as an acceptance test graphical report of the residual moisture of a transformer. From Figure 2a it could be observed that, while top and bottom temperatures are sometimes approaching steady state, the WCO values are not. Due to the fact that both clouds' bottom parts are comfortably sitting in the "green" zone, we do not need to do any further analysis to conclude that this transformer is dry.

Another example considers a distribution transformer of medium size 66/22 kV which could be found at many of the zone substations across Australia and other countries worldwide.

Case Study 2: Medium size distribution power transformer

Three weeks' worth of on-line data for TR2 is shown in Figure 3. Despite this transformer being on a drying cycle, the two distinguished peaks in temperature and water-in-oil can be observed.

It could also be observed that, for the period of the first eight days, moisture content is just above 10 ppm. According to the oil guides [3, 4,], this would indicate that the transformer oil (in terms of moisture) is in "good" health.

However, a few days later, moisture level reached 60 ppm at the temperature of 60 °C, and now must be considered as having a rather high level of water in the oil, and consequently in the paper too. Unfortunately, this event occurred after hours and any opportunity to take an oil sample of that high value will be missed under these conditions.

From this example, it is clear that conventional periodic assessment of water content does not deliver reliable results. According to the above-mentioned standards, water content is an oil quality characteristic which changes rather slowly and gradually; and can't change from "Good" to "Poor" in 8 days. The moisture cloud method produces much more consistent and logical results.

Plotting temperature/moisture values on the colour chart, adjusted for correct solubility coefficients, produces the moisture cloud shown in Figure 4.

> **A method called "moisture cloud algorithm" allows estimation of moisture in solid insulation with reasonable accuracy**

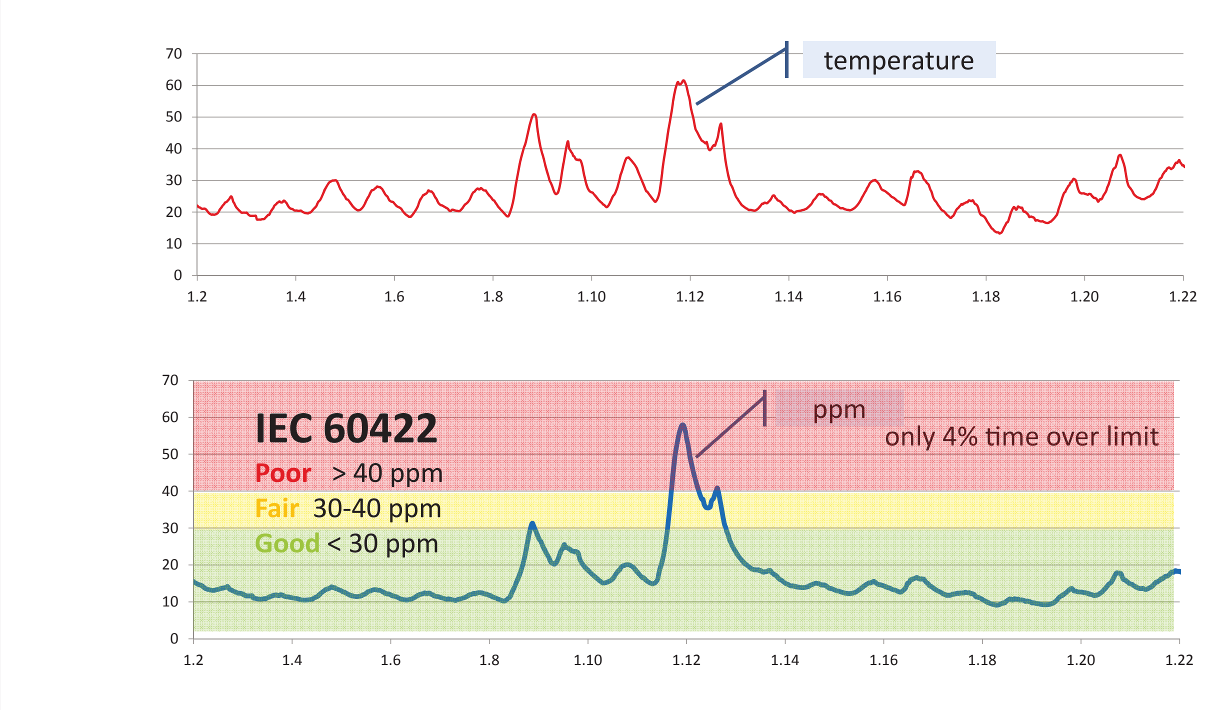


Figure 3. Temperature and water content of oil profile during 3 weeks of online monitoring

> **The cloud algorithm goes beyond just an assessment of water in solid insulation, it offers a way to estimate various risks associated with presence of moisture in transformers**

The bottom part of the "cloud" is associated with moisture in solid insulation. The points at the very bottom are formed by plotting only those ppm which lay on the increasing parts of the temperature profile. By disregarding all the data below 50°C and 20 ppm, we can observe that active water content WCPa is 3.5% which indicates rather large water content in paper.

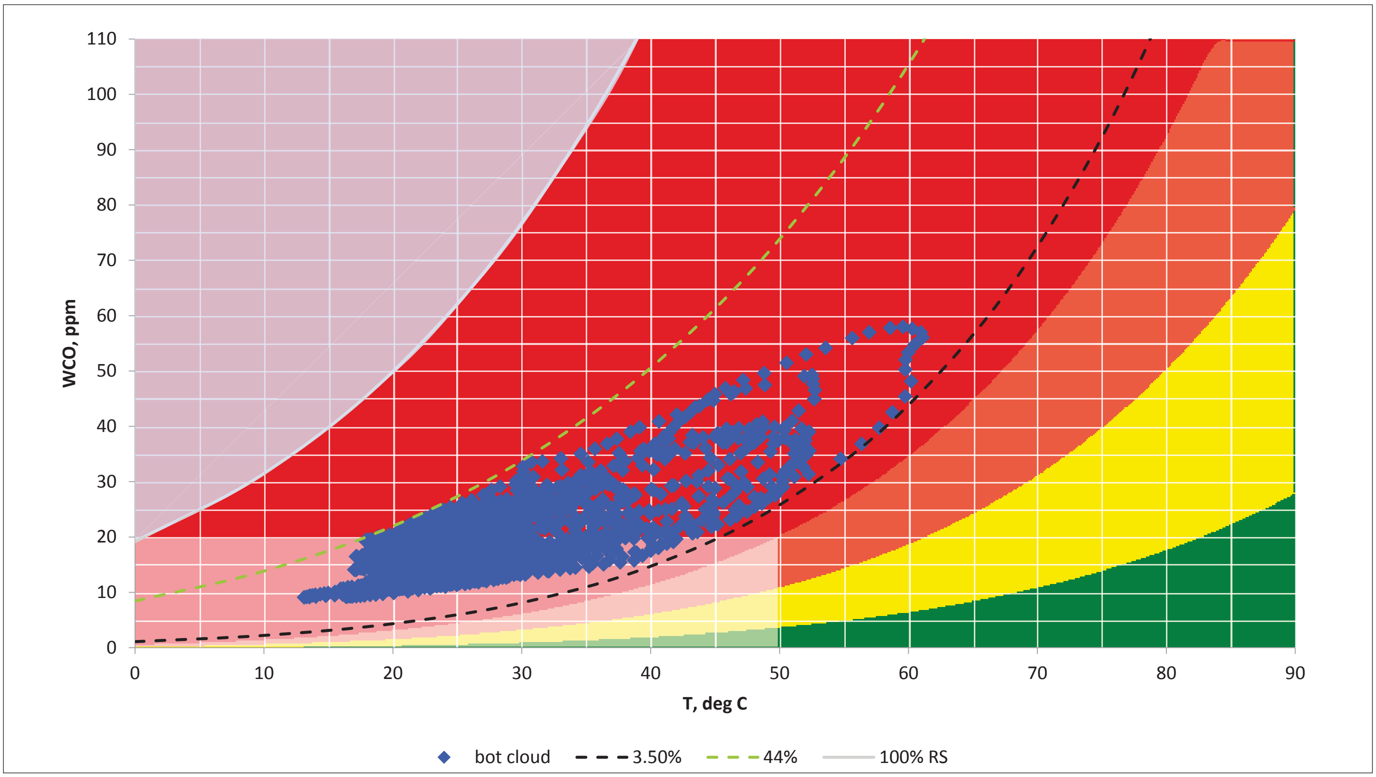


Figure 4. Moisture cloud for TR2 after one month of dryout

> **Transformer diagnosis by moisture cloud algorithms includes plotting a temperature/ppm graph on top of equilibrium chart and noting the position of the cloud on the diagram**

The top part of the cloud represents moisture in oil returning into the paper during the temperature decrease. There is a substantial hysteresis, which could be observed by comparing the data points of moisture content for the same temperature. For example, water-in-oil is 35 ppm at 55 °C on the increasing part and 55 ppm on the decreasing part of the temperature profile. This hysteresis is caused by a dynamic lag in change of water concentration in response to the increasing and decreasing temperature of the oil/paper system.

The light blue area at the top left corner of the diagram represents a 100 % saturation zone. The most dangerous situation with respect to possibility of oversaturation of oil with water occurs when moisture returns to the paper due to a decrease in temperature. As can be seen in Figure 4, there is a substantial margin between the top part of the moisture cloud and that of saturation zone, implying that the risk of oversaturation for this transformer which is undergoing dryout is rather low.

Application of the "moisture cloud" algorithm reveals that water content of the cellulose insulation at the bottom part of the transformer is no less than 3.5 %. The "hysteresis" of 20 ppm (maximum distance between bottom and top lines of the cloud at the same temperature) suggests that the transformer has a substantial amount of water for exchange between paper and oil. The highest relative saturation is 44 % which could be determined by fitting equipotential curve of RS into top part of the cloud (dashed green line). It could be observed that %RS is larger in the low WCO range, being 20-30 ppm, than it is in the range of higher WCO, i.e. 50 – 60 ppm. This fact is in disagreement with the guidance of both [3] and [4], where "good" oil is less than 30 ppm and "poor" oil is more than 40 ppm (see Figure 3).

Before drying had started, this transformer was monitored and one year of data is presented in Figure 5. This cloud is larger and higher with respect to equilibrium colour chart. Its safety margin at RS = 73 % is considerably smaller 27 % vs 56 % than safety margin for TR2 during dryout. Max WCO at 60°C is 100 ppm while for the cloud in Figure 4 is 60 ppm. Hysteresis is also considerably larger.

Active moisture in paper WCPa is more than 4.25 %.

Superposition of two dryout and pre-dryout clouds is performed and shown in Figure 6.

In addition to our observations above, we can see that the 'blue' pre-dryout cloud is pushed down and shrunk in size (green cloud) - the hysteresis is reduced by more than two times. Second, and the most important observation, is the reduction of water-in-paper activity for the dryout cloud. Detailed estimation of water-in-paper activity is beyond the scope of this article, but a rough estimation can be made by using sorption isotherms given in Figure 1 of [1], recalling that water activity is ERH/100. Reduction in

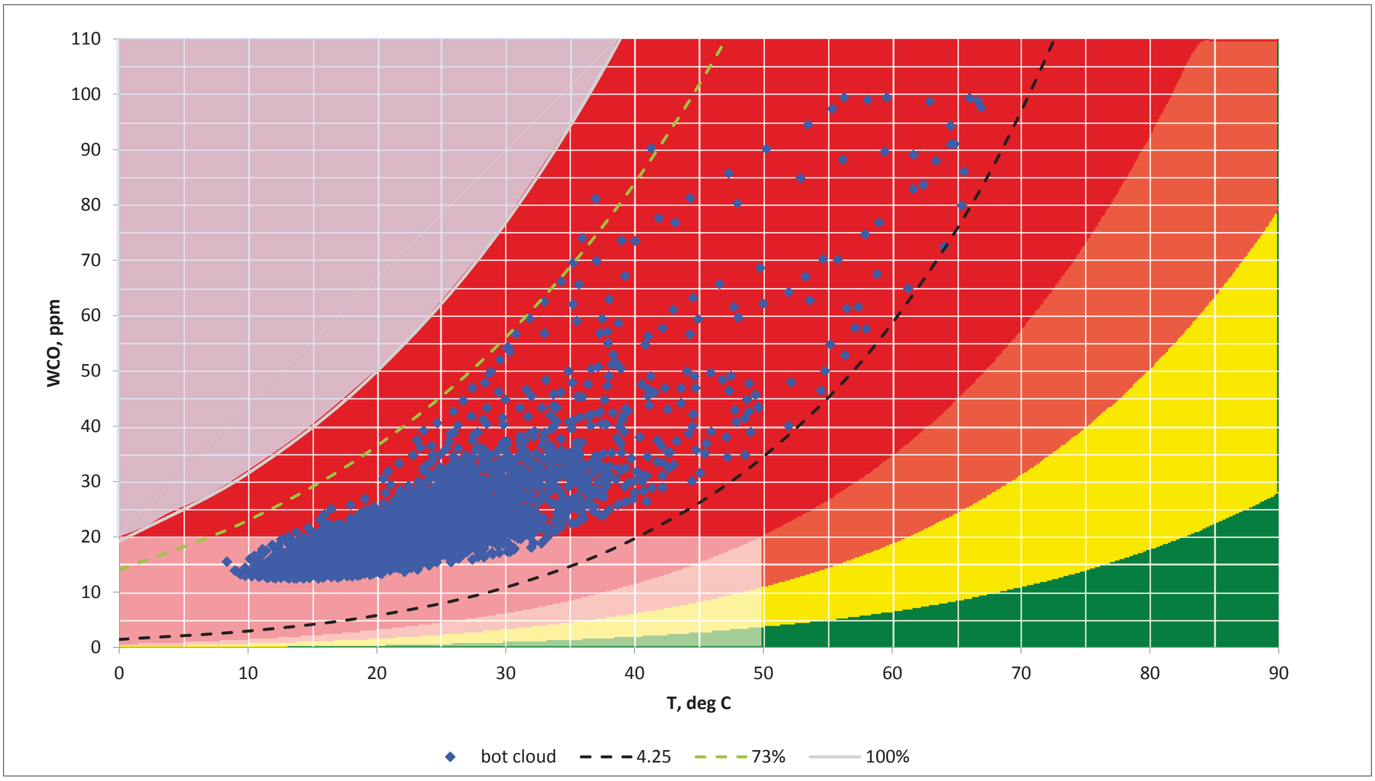


Figure 5. Moisture cloud for bottom oil of TR2 during one year of monitoring prior to dryout. WCP > 4.25 %. RS(max) = 73 %, H = 50 ppm

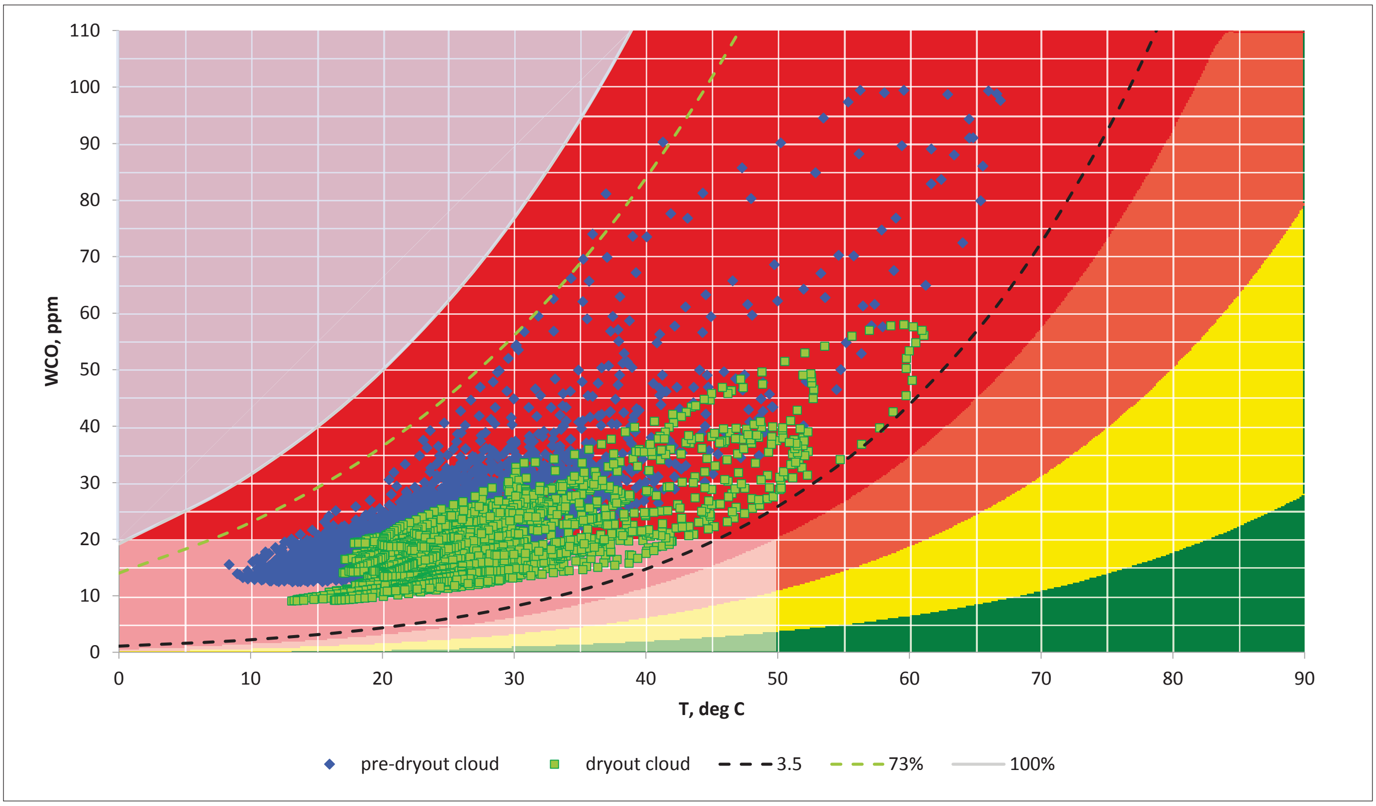


Figure 6. Comparison of a pre-dryout cloud and post-dryout bottom oil of TR2

water activity by estimated 10 % means a reduction of water available for exchange between oil and paper. Despite the total amount of water in cellulose insulation had changed insignificantly, the water-in-paper activity (Awp) was reduced to a safe level of Awp < 0.2

The data for the top part of the transformer TR2 is presented in Figure 7. The top cloud is shifted to the right and remains within nearly the same ppm range as the bottom cloud. This proves that, during a temperature fluctuation and having a temperature difference between the top and bottom parts of a transformer, the water content of oil leaving the transformer tank from the top is equal to the water content in the oil entering the transformer tank from the bottom.

When applying a similar analysis for the top part of the transformer as we did for the bottom one, it becomes evident that a hysteresis remains within 20 ppm. This implies that amount of water circulated via cooling system does not change and no water condensation has occurred.

Conclusions

In this column we have taken a deep dive into moisture equilibrium theory and its use and misuse when dealing with tasks of transformer moisture assessment. There are few things we must always remember.

In operating transformer, due to varying load and ambient temperature, a thermal equilibrium, let alone full thermodynamic equilibrium, could never be achieved. Therefore, any published moisture equilibrium diagrams cannot be applied directly without causing significant error. It is not possible to assess with any degree of certainty water content of insulating paper from a single sample of insulating oil by using Karl Fischer method in laboratory. The absolute values of WCO alone make little sense unless these are provided along with locations of its measurement and temperature dynamics.

Dew point measurement should only be made with the purpose of determining the dryness of a gas (e.g. nitrogen, air) surrounding the solid insulation. It is incorrect to use dew point as a parameter and dew point equilibrium curves for assessment of moisture in solid insulation because moisture in solid insulation is a function of relative water content and not an absolute moisture, i.e. dew point. The correct parameter to use is relative humidity along with the temperature of surrounding media.

A current use of absolute water content (ppm) in oil supervision and maintenance guides [3, 4] does not have any scientific justification for its limiting values. In this paper, we demonstrated that low values of water in oil ppm could be just as bad (if not worse) then high values from the dielectric point of view. Dielectric integrity of oil/paper insulation is dependant on water relative saturation as shown in Figure 1 of [5].

In this article, we have demonstrated how dynamic behaviour of moisture and its uneven distribution within solid/liquid insulation can be gauged with the help of equilibrium charts.

Supported by fundamental knowledge of water partitioning in the steady state conditions, the moisture cloud algorithm uncovers the value of water in oil measurement to predict the amount of water available for drying out, to determine the safety margin of the insulation dielectric strength, to assess the residual water in new units undergoing temperature rise test, and to reliably rank transformers across the fleet in terms of water state.

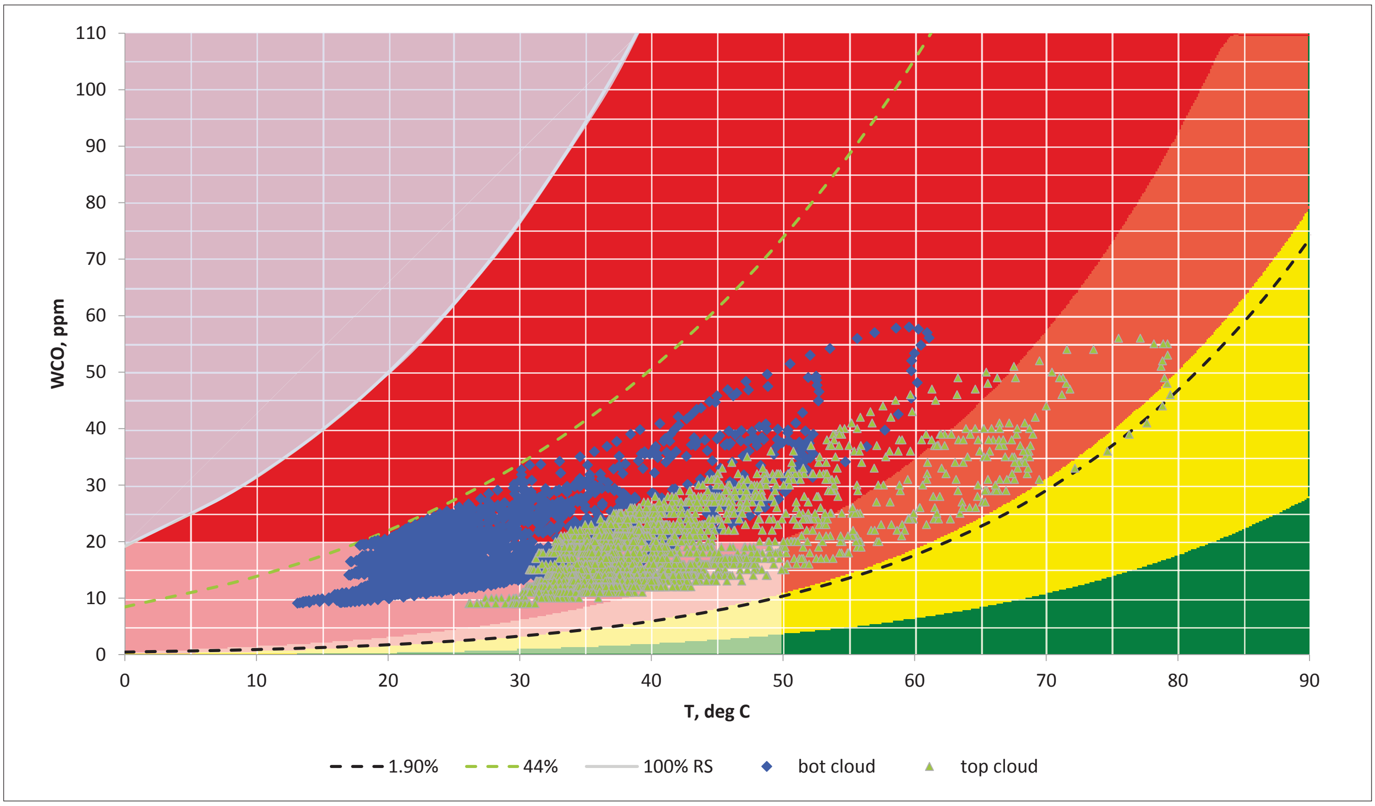


Figure 7. Top and bottom clouds for TR2 during dryout

Moisture cloud visualisation and assessment algorithms make diagnosis regarding transformer health as simple as plotting a scatter graph of temperature/ppm points on top of equilibrium chart and noting the position of the cloud on the diagram - how high or how low the cloud sits with respect to colour chart GYR zones.

Moisture cloud algorithm transforms the dynamics of water migration from paper to oil into two-dimensional space and measures the result with respect to its location on the equilibrium diagram.

This approach lifts the requirement of an existence of thermodynamic equilibrium before the moisture assessment can be made and shows an alternative way of solving many tasks related to moisture presence, migration and distribution within solid/liquid transformer insulation system.

> **Moisture cloud algorithm transforms the dynamics of water migration from paper to oil into two-dimensional space and measures the result with respect to its location on the equilibrium diagram.**

References

[1] O. Roizman, *Moisture equilibrium in transformer insulation systems: Mirage or reality? Part 1*, Transformer Magazine, vol. 6, issue 2, April 2019.

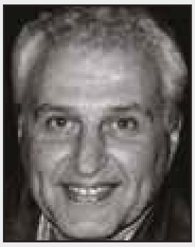
2] O. Roizman, *A New Algorithm for On-line Moisture Assessment in Transformers*, CIGRE SC A2 & C4 Joint Colloquium, Zurich, Switzerland, 2013

[3] IEEE C57.106-2015, IEEE Guide for Acceptance and Maintenance of Insulating Mineral Oil in Electrical Equipment

[4] IEC 60422:2013, Mineral insulating oils in electrical equipment - Supervision and maintenance guidance

[5] O. Roizman, *Water in transformers: All you wanted to know about it, but were afraid to ask*, Transformer Magazine, vol. 6, issue 1, p.p. 68-75, January 2019.

Author



Dr. Oleg Roizman is a founder and managing director of Intellpower Pty. Ltd. in Australia, an engineering consulting and services company with emphasis on continuous online monitoring and diagnostics of power transformers. Prior to forming IntellPower in 2000, Oleg was employed by Monash University in Australia as a R&D principal investigator. He was involved in developing analytics in areas of power system stability, power quality, monitoring and diagnostics of electrical plant. Dr. Roizman is an inventor, a speaker, an author of many technical papers and an active member of various working groups within IEEE PES Transformers Committee and CIGRE.