EXPERIENCE WITH IN-FIELD ASSESSMENT OF WATER CONTAMINATION OF LARGE POWER TRANSFORMERS

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Introduction

There have been several reasons stimulating interest in the subject of Transformer Water Contamination in recent years:

- Large population of aged equipment, which is apparently contaminated with some water. A question is raised: How to operate this equipment taking into account the well-known issues about effect of water on accelerating aging rate [1], possible reduction of dielectric strength with increasing moisture percent saturation in oil [2] and risk of bubbling at high temperature [3, 4].

- Uncertainty in effectiveness of methods available to assess a health of the equipment. In [5] e.g. is shown that in spite of low water content in the oil indicated by the normal oil sampling procedures a large amount of water can be revealed within a transformer. How to rank the transformer, which needs drying? How to assess a critical level of water contamination to prevent failure or to determine permissible operating conditions, e.g. overloading?

- New monitoring techniques – moisture sensors – becoming available to arrange On-Line condition monitoring [6]. The question comes how to develop an expert system allowing to detect abnormal water contamination and to prevent defective condition of the equipment.

Problems of deterioration and rehabilitation of the transformer insulation are subjects of particular interest of CIGRE WG 12.18 "Life Management" [7, 8]. On opinion of CIGRE experts, a deeper understanding the processes of water ingression, equilibrium, migration, dangerous effect, as well as selection of effective diagnostic methods, is necessary to define effective and efficient means of "Life management".

Experience of ZTZ-Service Co. has shown that in-service assessment of water contamination through oil (Water Heat Run Test [9]) and complementary inferring of water content in solid insulation through dielectric characteristics [10] could be useful alternative. However, On-Line technique is expected to be as a fruitful tool in the future.

This paper presents some theoretical and practical aspects of water contamination of Power Transformers based on CIGRE WG 12.18 activity and findings and experience of ZTZ-Service Co.

1. The Main Sources of Water Contamination

There are three sources of water build up in the transformer insulation:

- Residual moisture in the "thick structure" elements;
- Ingress from atmosphere;
- Aging decomposition of cellulose and oil.

Residual moisture

Excessive (2…4%) residual moisture can remain in some thick insulating components, particularly plastics, which need much longer drying time in comparison with pressboard. Typically, those are support of leads, LTC, support insulation of neutral coils of winding, bakelite cylinders, core support insulation, etc.

Sometimes this phenomenon is a cause of elevated insulation PF and its rise with temperature. During service this moisture gradually evolves into the oil increasing the water content in the thin insulation structure.

Ingressed moisture

Atmosphere water is the main source of the transformer contamination. Three mechanisms are acting: sorption of water while direct exposure of insulation to air (installation and repair works), ingress of moisture into the tank in the form of molecular (Knudsen) flow due to the difference in water concentration in atmosphere and the oil in the tank, and viscous flow of wet air into the transformer under action of difference in pressure (atmospheric and inside the tank).
Analytical interpretation of those mechanisms is presented in [7]. In the Table I some upper estimation of possible water contamination is shown (calculation by [7]). It comes to the following conclusion:

- Molecular flow of moisture is practically negligible. This mechanism can bring significant amount of water only into a transformer, which is treated under vacuum and unproperly sealed.

- The main mechanism of water penetration is viscous flow of wet air through "poor sealing" under action of the pressure gradient. The typical "sensitive points" are top sealing of drown lead bushings, sealing of explosion vent, places of oil leaks in the way of oil forced circulation between a transformer and its cooler. All of them being badly sealed really act as a "water (vapour) pump".

- Large amount of "live" water can be pumped into the transformer in a very short time (several hours), when there is a rapid drop of pressure and unproper sealings (of above mentioned weak points) are drown with rain water.

- Rate of possible water contamination of open-breathing transformer is significant, but limited.

Experience with evaluation of water content in the pressboard patterns removed from transformers after 6…20 years of service has shown that average rate of water contamination of open-breathing transformers is about 0.2% per year (tested about 100 units). However, it relates to some local (wet) zones, but not to the total mass of insulation.
Typically, only 25 – 30 kg of water is extracted during drying out from the transformers with water content up to 2.5% in the "thin structure".
Rate of water contamination of transformers with membrane-sealed preservation system is 0.03…0.06% per year (tested about 80 units).
In a case of unproper or broken sealings, over 50 kg of free water can be revealed in the transformers of both free-breathing and membrane-preserved design.
A large amount of free water can ingress into the tank from damaged "water – oil" cooler. Unproper in-field drying out can also turn out to be a cause of condensation of free water.
Table I shows that installation or repair works involving insulation exposure to air can bring in much more water than service with imperfect preservation system in the course of years.

Decomposition of insulating materials

Aging destruction of cellulose leads to furans formation, which is connected with water generation – three molecules of water per one elementary act. It means that a correlation between water generation and total furanic compounds can be found. Quantification of this process needs special study.
One can presume that aging can produce a substantial amount of water if insulation is subjected to high temperature and destructed significantly.
Lampe and Spicar [11] suggested that depolymerization up to 5 – 6 scissions leads to the formation of 2% of water. Endurance tests of winding models at 125…160 °C shown [12] increase of moisture content in some zones located below the hottest coils up to 1.5 – 2.8%.
D.Shroff and A.Stannet [13] has shown that degradation of cellulose to DP = 400 generates only 0.4% of water.
Anyway, the process of intensive water formation is located in some "hot spots", which comprise typically less than 5% of insulation.

Table I

Upper Estimating of the Rate of Water Contamination

Condition of transformer	Rate of water contamination

Direct exposure of insulation to air: a) RH = 75%, t = 16 h, 20 °C b) RH = 40%, t = 16 h, 20 °C	Sorption with surface 1000 m^2 in the vicinity of 0.5 mm 13.5 kg 8.1 kg
Molecular flow of vapour • Via sealings capillaries • Via loosed gaskets	≤ 1 – 5 g per year ≤ 30 – 40 g per year
Viscous flow of air (water) • Shipping condition, core and coil covered with oil - proper sealing - unproper sealing	600 g per year 15 g in a day
• Operation with open-breathing • Drown of unproper sealing with rain water	6,000 g per year 200 g in a hour

DISTRIBUTION OF WATER WITHIN INSULATION STRUCTURE

Components of oil-barrier transformer insulation can be divided into three groups:

1) “Thick structure” - basically supporting components. They comprise around 50% of the total insulation mass. There is a diminutive contribution of thick structure due to a large (few years) time constant of diffusion process, with the exception of cases with excessive residual moisture.
2) “Thin structure”, which operates at oil bulk temperature: pressboard barriers, end caps, etc. These components comprise 20 – 30% of the total mass. Moving force of water migration is difference in concentration of water by oil-insulation boundary.
3) “Thin structure”, which operates at the temperature close to the conductor temperature – turn-coils-layers insulation. Around 5% of this insulation have some elevated temperature, so called, hot spots. There could be three moisture moving forces there: water concentration gradient, temperature gradient and pressure gradient.

Experience has shown that the most of the water is stored in the components of the second group. Around 5 – 10% of this group (the coldest portion) form some “sensitive, wet” zones with water content by 1 – 1.5% more than average.
Components of this group are the main source of the oil contamination at some high temperature, when water concentration on the surface become greater than oil.
Water content in the components of the third group is definitely much less than in the second, however questionable one.
Oil is water-transferring medium. However, some water can be “stored” in the surfactant substance and as well in the particles.
In some cases free water can be accumulated on the bottom of the tank, on the core, in the coolers, etc. resulting from poor sealings and suction of rain water.

SORPTION EQUILIBRIUM. WHAT’S KNOWN AND UNKNOWN?

Sorption water is of a dynamic character: absorbed molecules of water are kept in intensive movement about active centers of cellulose molecules (OH-groups in glucose rings) and achieving sufficient kinetic energy, get free and its place is soon occupied with another water molecule.
Molecules of water (an gases) travel within microcapillares and within macrocapillares filled with oil independently (molecular flow). Diffusion leads to exponential growth of adsorbed water to equilibrium level. Temperature accelerates the process.

Sorption equation

The most important characteristic of sorption equilibrium is isotherm of sorption, which shows relation of water content (W) and relative humidity ($\varphi = p/ps$) or water vapour pressure (p).
The equation of sorption [7] can be expressed in the form [14]:

$$\frac{W}{W_0} \cong \frac{K \cdot \varphi}{(1-\varphi)(1-\varphi+K \cdot \varphi)}, \qquad (1)$$

where $K = \exp(678/T)$,
W_0 – moisture content in monolayer, which is characteristic of the material.

There are proposals to use the empirical equations as a mathematical model:

- Piper’s curves interpretation [15]

$$W = [p \cdot \exp(-21.92 + 6850) / T]^{0.75} \qquad (2)$$

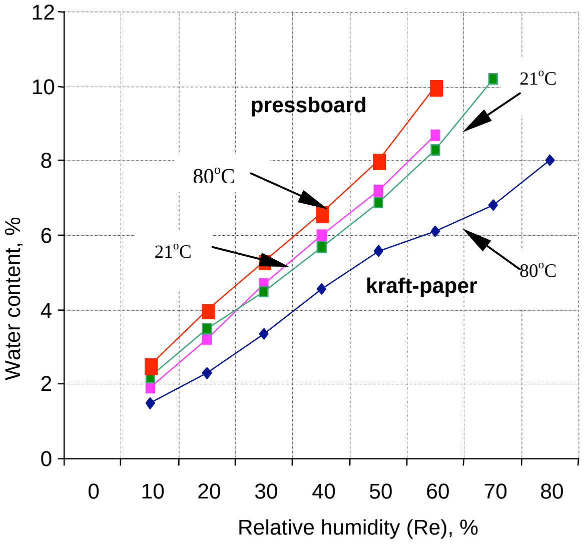
- Freunlich-Fessler interpretation [8]

$$P = 5.8869 \cdot 10^{9} \cdot W^{1.4495} \cdot \exp(-6996.7 / T) \qquad (3)$$

Equation (3) may bring to the form (2) with somewhat different numerical constants. Both (2) and (3) may be also deduced from the main sorption equation by means of some simplification and limitation of water content.
In the Table II comparative estimation of equilibrium parameters is shown using equations (1,2,3) and experimental data [24]. One can see that all results are in acceptable agreement as to minor humidity and quite different as to higher values.

It is apparent that one can utilize the empirical approximations only to estimate the level of moisture content, but not for precise determination.

It was also found that there is notable difference in sorption of pressboard and kraft paper (Figure 1) and essential difference between sorption of water in air and in vacuum (Figure 2). Process of sorption in vacuum is also much faster than in air.



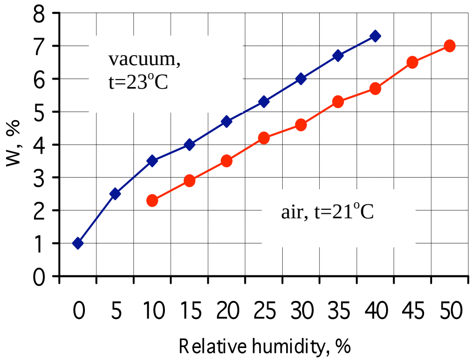


Figure 2

ption Isotherms in Vacuum and in Air

Kraft Paper

Table II

Comparative Estimation of Equilibrium Parameters: Kraft Paper, 70 °C

Paper Humidity, %	**Parameters**	**Empirical equation**		**Experiments**		**Theoretical**
		By Piper (2)	**By Fessler (3)**	**Oommen* [22]**	**By [24]**	**(1)****
1	P mm HG	7	8.1	9.3	8	8
	φ, %	3.0	3.4	4	3.46	3.42
2	P mm HG	17.7	22.2	28	20	20
	φ, %	7.5	9.5	12	8.5	8.5
3	P mm HG	30.4	40	56	46.7	49
	φ, %	13	17.1	24	20	21
4	P mm HG	44.7	60.7	88.8	70.1	58.4
	φ, %	19.1	25.9	38	30	25

* Sorption by wood pulp

** Moisture content in monolayer 4%

SOLUBILITY OF WATER IN OIL. EQUILIBRIUM IN “CELLULOSE – OIL” SYSTEM.

Oil is a water-transferring medium within a transformer. Water presents in oil in soluble form and also in hydrate form being adsorbed by polar aging products. Fiber particles in the oil also contain some water. Water content in oil is directly proportional to relative water concentration (relative saturation) up to saturation level. Water saturation – temperature [WS – T] relation is expressed by form

$$W_S = W_0 \exp(-B/T) \qquad (4)$$

Where W_0 and B are constants, which are typically different for different oils, mainly due to difference in aromatic content. Some information about estimated solubility constants and saturated water content are shown in the Table III.

Oils*	**Aromatics C_A, %**	**W_0**	**B**	**Solubility, ppm**		
				20 °C	**40 °C**	**70 °C**
1	5	$16.97 \cdot 10^6$	3777	42.8	97.5	279
2	8	$23.08 \cdot 10^6$	3841	46.8	108	316
3	16	$22.76 \cdot 10^6$	3783	56.2	128.3	369.2
4	21	$13.16 \cdot 10^6$	3538	75	162	436
5	Silicon-oil	$1.9525 \cdot 10^6$	2733	174	314.7	675.4

* [17, 18, 19]

Appearance of polar aging products results in increasing water solubility. Aging response of different oils is different, however, in accordance with data available the “full water” in the aged oil is typically twice as large as dissolved water.

Water equilibrium in “cellulose – oil” system follows the same law, as that in cellulose – water vapour, the difference being in slower process of reaching the equilibrium. Equation (1) is valid, but value of φ shall be substituted for relative saturation of oil.

MOISTURE MIGRATION UNDER INFLUENCE OF MOISTURE CONCENTRATION AND TEMPERATURE.

“MOISTURE” POTENTIAL

In general, there are three moving forces to activate moisture transfer: moisture concentration gradient, temperature gradient and pressure gradient.

Mechanism of water travelling through microcapillares and through oil in macrocapillares is the molecular movement, which is ruled by the law similar to the Ohm’s law for electric current:

$q = R_W \cdot U_W$,

where q = dm/dt – mass of moisture flow (analogous to dQ/dt = i – electricity flow).
R_W – moisture (gas, vapour) resistance for cylindrical tube it is equal.

$$R_W = \frac{8}{3} r^3 \sqrt{\frac{\pi\mu}{2R}} \cdot \frac{1}{l},$$

where r and l – radius and length of the tube; μ - molecular mass of water; R – gas constant.
$U_W = \Delta \varphi_W$,
where φ_W is “moisture potential”.

$$\varphi = P / \sqrt{T}, \qquad (5)$$

where P is vapour pressure; T – absolute temperature.
Change of vapour pressure or temperature meant the advent of moisture potential and water movement.

Moisture migration in the major insulation of a transformer

Oil is heat-transfer medium. Increasing of the oil temperature leads to reducing of relative saturation and appearance of the difference in water concentration by oil – insulation surface. So that moisture gradient in the pressboard is in contradiction with temperature gradient. This phenomenon relaxes the processes of moisture transfer, both of sorption and desorption. Unequal distribution of water across the layers with elevated concentration in the vicinity of the surface layers makes additional obstacle to sorption.
Amount of adsorbed water may be determined using solution of Fick’s second law [7].

$$\Delta W_a \cong (W_e - W_o)\cdot\left[1 - F_{(Z)}\right]\ \% \qquad (6)$$

where W_e and W_o – equilibrium and residual water content; Z – diffusion parameter.

$$Z = \frac{D \cdot t}{d^2} \qquad (7)$$

D – diffusion coefficient, sq ·m/sec
d – insulation thickness, m

Diffusion function $F_{(Z)}$ has form of series. The process may be quantified through sum of the exponents and accordingly there is a number of the time constants. However, if $W / W_e > 0.5$ the function may be simplified to one exponent with constant.

$$T = \frac{d^2}{\pi^2 D} \qquad (8)$$

This equation may be used for rough estimation of the process. In a similar way one can determine amount of desorbed water

$$\Delta W_d \cong \left(W - W_e\left[1 - F_{(Z)}\right]\right)\ \% \qquad (9)$$

Equations (6) and (9) correspondingly underestimate and overestimate the amount of adsorbed and desorbed water in the “oil – cellulose” system since moisture concentration and value of W_e is decreasing (by sorption) and increasing (by desorption).
Diffusion coefficient D depends on the structure of cellulose, temperature and water content. There are several empirical equations [16, 15]. However, only a conventional value may be taken for practical application. ZTZ-Service Co. utilizes the following simplification [19]:
$D = 10^{-13}$ sq. m/sec at 20 °C for estimation of water contamination of insulation directly exposed to air (installation and repair works).
$D = 2 \cdot 10^{-14}$ sq. m/sec at 20 °C for estimation of water migration process in operating transformer. Values of D are doubled with increasing the temperature by 20 °C.

The time of establishment of the water equilibrium may be estimated roughly (with underestimation) using equation (8) (interpretation of the process through the first exponent). Assuming D = 8 · 10^{-14} sq. m/sec at (≈ 60 °C) and D = 3 · 10^{-3} m we have $T_o = \frac{9 \cdot 10^{-6}}{\pi^2 \cdot 8 \cdot 10^{-14}} \cong 132 days$ If to take a thinner pressboard: d = 1 · 10^{-3} m and D = 1.6 · 10^{-13} sq. m/sec (≈ 80 °C), the time constant can be reduced to ≈ 7.3 days.

In the closed system of a transformer one can consider only approaching to equilibrium and establishment of some stationary state.

To activate moisture desorption into the oil, equilibrium water concentration on the surface (W_e) shall be essentially less than the questionable (W).

MOISTURE MIGRATION AND STATIONARY MOISTURE DISTRIBUTION IN TURNS AND COILS WINDING INSULATION UNDER INFLUENCE OF TEMPERATURE FIELD.

Moisture and temperature gradients coincide in the conductors insulation. Cellulose insulation of turns and coils may be represented as a wall severing the copper of a coil from the oil without. There is a drop of temperature across this wall in a transformer under load, and this results in a drop of moisture potential in insulation with initially uniform distribution of water content in the wall layers. Then migration of water molecules will begin from inner to outer layers until leveling off moisture potential of all layers. This phenomenon will result in non-uniform distribution of water in the layers.

Using the equation (1) it is possible to find this distribution for given temperature drop, initial moisture content and maximum temperature. Figure 3 shows that non-uniformity may be notable even at rather low average water content.

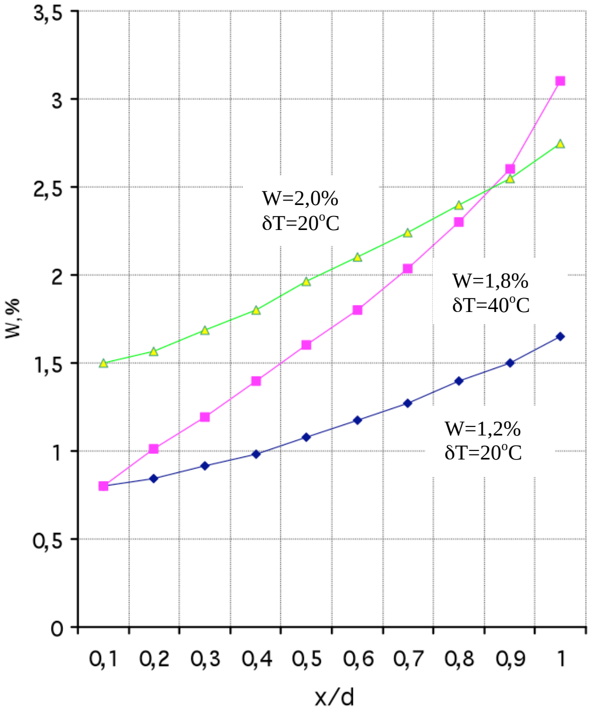


Figure 3
Moisture Distribution in Turn Insulation under Effect of Temperature

MECHANISM AND CRITERIA OF BUBBLES EVOLUTION

Water travels through microcapillaries when water content and temperature, and vapour pressure are low enough. Rapid rise of temperature causes rapid evaporation of absorbed water followed with rapid rise of vapour pressure. Pressure within inner layers may become as great as to press oil out of macrocapillaries of insulation. This phenomenon may change the mechanism of water movement from molecular flow to viscous flow through macrocapillaries and results in two dangerous effects:

- Apparition of vapour-filled cavities on the insulation surface (so called “bubbling”).
- Partial or entire deimpregnation of the turn’s insulation.

Macropores in insulation are flat capillaries between neighboring cellulose fibres. The condition of pressing out the oil is

$$P \geq \frac{2\sigma}{d}, \qquad (10$$

where σ - interfacial tension between oil and vapour inclusion in the flat capillary,
d – the capillary interstice.
The ultimate (minimum) pressure may be found using sorption equation (1), and bubbling criteria may be expressed as a function of water content and temperature.

$$\frac{\varpi}{W_o} \cong \frac{2KB}{(B+2)\left[2k-(B+2)\right]} \qquad (11$$

$$\mathrm{B} = \frac{4\sigma(\mathrm{K}-1)}{P_S d}$$

where P_S – saturation vapour pressure of water,
K – exp (678 / T).

Thus, the condition of bubbles evolution depends on the temperature and water content, but on cellulose structure and quality of oil as well.
d is a certain function of material density. Studying in [20] has shown that the capillary interstice can vary in the range of 0.01…7 μm.
σ - interfacial tension is function of temperature and presence of polar impurities – typically oil aging products.

Figure 4 shows that the influence of oil condition and pore size is significant. In a case with aged oil and insulation material with large macrocapillaries one can expect the bubbles evolution at lower content and water content that was shown in [3].
In [3] it was also demonstrated that saturation of insulation with nitrogen stimulates bubbles formation. Indeed, any strange molecule in the vicinity of an active center in cellulose

molecule is to produce some screening effect on its field and relax its influence on water molecules and strange molecules as well.

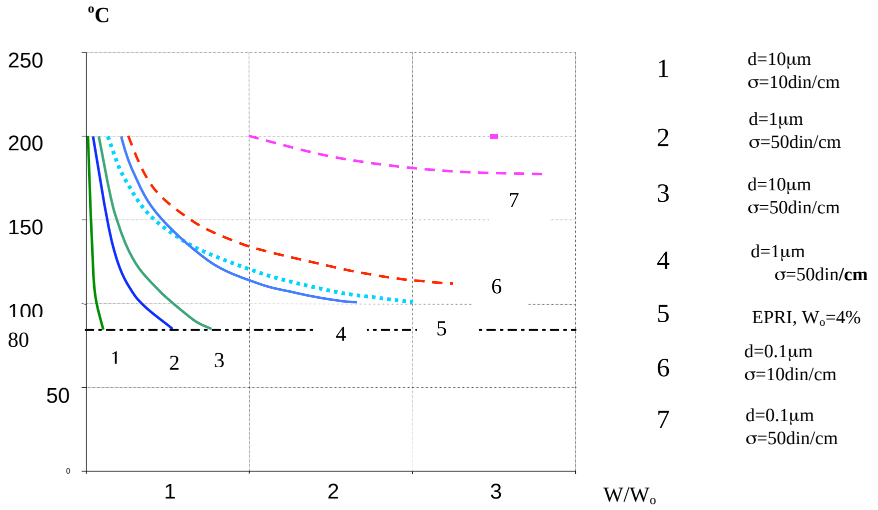


Figure 4
Conditions of Bubbles Evolution

DANGEROUS EFFECT OF WATER. EXPERIMENTS AND EXPERIENCE

Studying the models of the transformer insulation [12, 21] has shown that dielectric safety margin of both major and minor insulation contaminated with water is still determined by dielectric withstand strength of the oil. Dangerous effect of dissolved water is a sharp reduction of dielectric strength of oil with increasing its relative saturation due to increasing conductivity of the particles available or emulsion formation in the vicinity of surface-active substance

[19]. Dissolved water is a problem of a “cold” transformer. A number of failures have happened particularly after energizing the contaminated transformers in a winter time [21].

Presence of free water in the oil is basically a problem of “frozen” transformer. In spite of the fact that oil density is specified to be less than density of ice, forced or even convective oil flow can be strong enough to pick up the ice into a critical zone. This phenomenon have been typical cause of the breakdown of LTC insulation [19]. Moreover, a drop of water in viscous oil may work as a particles generator being exploded under effect of electrical field. Unusual reduction of the dielectric withstand strength to 0.2…0.4 kV/mm has been observed.

All of sudden ingress of free water may kill the transformer immediately. E.g. 400 MVA, 220 kV transformer felt due to breakdown of the oil space between the bushing and the tank after sharp cooling with rain-fall and ingress of about 500 g of water through the broken sealing of the drow-lead bushing.

Bubbles evolution is a problem of a “hot transformer”. On our experience, that is basically hypothetical danger since no relevant failures have been observed. However, this problem involves not only elevated water content, but oil aging products as well.

At last water accelerates aging decomposition, and depolymerization of cellulose is proportional to the water content. However, this process becomes much more dangerous in presence of acids.

Thus, the condition monitoring of the transformer contaminated with water shall consider also contamination of the oil with particles and aging products. It’s desirable (but not always possible) to quantify the water content in the components of solid insulation. It’s necessary to predict the condition, when relative saturation of the oil can rise significantly. It’s also necessary to detect the defective condition of a transformer, when "live" water can penetrate into the tank.

CLASSES OF WATER CONTAMINATION

The main idea for definition of Classes of Water Contamination is to predict defective condition of a transformer, namely critical decrease of dielectric withstand strength due to build up water in oil at a high temperature and subsequent cooling the transformer, following with increase of the oil relative saturation.
The following classification has been advised and approved by experience.

CLASS I: "good" – dry transformer, water content in the insulation is 0.5…1.0% or less. There is no essential change of water content with temperature (it remains typically below 15 ppm). Relative saturation of the oil reduces exponentially with temperature and makes up around 3% or less at 60 – 70 °C.

CLASS II: "fair" – normal condition of a transformer, which maintains a relatively low percent saturation of water in oil (< 40-50%) within a range of the lowest operating temperature.
The characteristics of this condition are: maximum water content in insulation 1…1.5%. Slight (typically less than in two times) rise of water content in oil after heating and maintaining the test temperature. Relative saturation of the oil is expected around 5% at 60-70 °C.

CLASS III: "probably wet" – the condition of a transformer, which may result in an increase of the relative saturation of water in oil over 50% in the range of service temperature.

CLASS IV: "wet" – the condition, which may result in emulsion formation at service temperature.

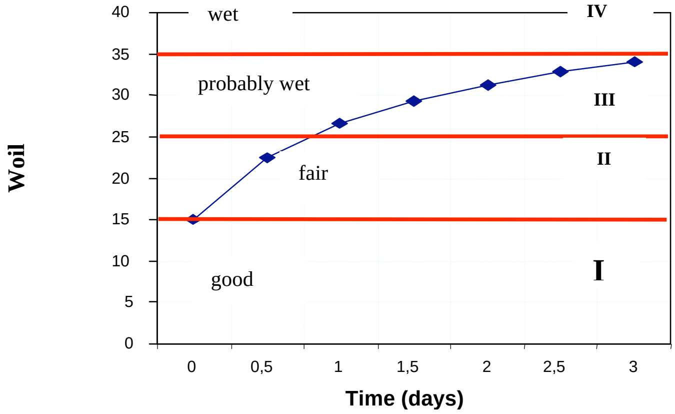


Figure 5
Classes of water contamination
(moisture content 2% in 1000 kg of 3 mm pressboard)

CONCEPTS OF THE TRANSFORMER CONDITION ASSESSMENT USING "WATER HEAT RUN TEST"

<u>The objectives of the method are:</u>

- Assessment of the transformer health under rated conditions – maximum permissible temperature.
- Assessments of the level of water contamination using build up water content in oil with time at the temperature.
- Assessment of possible state of water and distribution of water within a transformer using rate of building up water in oil.

DEFINITION OF WATER HEAT RUN TEST PARAMETERS

<u>Temperature:</u>

- The maximal permissible service temperature is desirable to simulate the worst condition for water desorption.
- The temperature of the oil shall be high enough to "charge" moisture potential and to detect the level of questionable water contamination.
- The temperature of the oil shall be high enough to "discharge" insulation and allow extracting a sufficient amount of water from "wet zones".

To detect water contamination level over 2%, relative humidity of the "hot" oil shall be $\varphi <$ 8%. Assuming initial water content in the oil 15 ppm, using (4), e.g. for oil # 2 (Table III), we have

$$T = \frac{(-B)}{\ln\left(\frac{W_{oil}}{\varphi \cdot W_o}\right)} = \frac{(-3841)}{\ln\left(\frac{15}{0.08 \cdot 2.308 \cdot 10^{6}}\right)} = 328K\left(\approx 55^{\circ}C\right) \qquad (12)$$

Amount of "discharged" water shall be "good enough" to measure a notable change of water. Assuming rate of water desorption, e.g. 10 ppm/day, one can show that on these conditions the equilibrium water content shall be $W_e \leq (1.0 - 1.5)\%$ and accordingly, the test temperature t ≥ 65 – 75 °C.

<u>Time:</u>

Duration of the test shall allow "to discharge" the insulation to detect a questionable water contamination level. Thus, time of the test was advised as 3 days taking into account the following considerations:

- Detect average water contamination of a "thin structure" operating at oil bulk temperature (≈ 20% of the total mass) over 1.5 – 2.0%.
- Detect an excessive water contamination of some local zones (≈ 10% of the total mass) over 3%.

Force stirring the oil

Time constant of heat transfer in oil and correspondingly time constant of water distribution in oil by self-convection is tens of minutes. The process must be accelerated by means of artificial stirring the oil.
In this case time constant of heat transfer has the form: $\tau_0 = M / 4q$, where M – mass of the oil; q – rate of the flow.
Assuming M = 60 ton, q – shall be 100 ton/hr to reduce time constant to 0.15 hr.
Another purpose is to pick up free water, which may be present on the bottom or elsewhere.

Estimation of the level of water contamination

Assuming that the main source of water contamination is a “thin” structure of transformer insulation, the level of water content can be estimated using (9) as

$$W > W_e + \frac{\Delta W}{1 - F_{(Z)}} \ \%, \qquad (13)$$

where ΔW is amount of “discharged” water related to mass of thin structure.
W_e – equilibrium moisture, which can be determined from sorbtion equation for given relative saturation.

$$\varphi = W_{oil\,in} / \left(W_{oe}^{-B/T} \right) \qquad (14)$$

where $W_{oil\ in}$ – initial water content in oil before heating,
T – test temperature,
W_o, B – oil solubility parameter.
$[1-F_{(Z)}]$ is calculated for Z = Dt/d.
Assuming $d = (2\ldots3) \cdot 10^{-3}$ m, $D = 10^{-13}$ sq.m/sec, t = 24 hr, we have $[1 - F_{(Z)}] = 0.07 - 0.1$

EXPERIENCE WITH IN-SERVICE ASSESSMENT OF WATER CONTAMINATION OF LARGE POWER TRANSFORMERS

In 1992 – 1998 the condition of over 150 questionable transformers rated 25 – 1250 MVA have been assessed using ZTZ-Service methodologies including Water Heat Run Test.
53 units, predominantly of open-breathing design, were recognized as defective due to predicted water contamination. In the most of cases the defective condition has been confirmed by the tests with estimation of water content through dielectric characteristics [11], direct measurement of water content in pressboard patterns removed from the transformers and (in many cases) by the amount of water extracted during drying out. Some typical cases are given below.

The experience may be summarized to the following:

- All the transformers contaminated with water have shown a clear rise of water content in the oil after heating up and holding at the test temperature. There is a good correlation between advised classes of water contamination and real water content in insulation patterns removed from the transformers: case “dry” (W = 0.85%), case “probably wet” (W = 1.8%), cases 1..3 “wet” (W = 2.5 – 4:7%).

- It was turned out that a level of water content in contaminated transformer may be advised using rate of water build up in one day only. Estimated water content in “thin structure” is a result of calculation using equation

- There is a poor correlation between water content in the oil and solid insulation at temperature below 60-70 °C. Tests at 25-40 °C have shown typically overestimation of the moisture in insulation.
  A special “two-steps” test at 50 and 70 °C was carried out with 200 MVA, 347 kV, open-breathing transformer after 27 years in service, shown after heating the unit from 30 up to 50 °C and holding in 24 hours, water content increased from 10 to 12.7 ppm only. However, the similar test at 70 °C has shown significant rise of water up to 34 ppm. Contami- nation of “thin structure” over 2.5% has been advised.

- It is difficult to distinguish desorbed water and water, with originated from accumulation of free water (cases 6 and 7). Some accelerated rate of water build up is perhaps a symptom of the latter phenomenon, but not in transformer with ON cooling.

- To provide Water Heat Run test, the transformer can be easily heated with On-Load losses by means of reducing cooling (switching off some fans (of cooling) or shat off some radiators (ON cooling).

Cooling conditions shall be calculated preliminary under restriction: not to exceed maximal winding temperature (typically, 95 °C). Temperature equation by IEC-354 may be utilized. Heating process up to the test temperature (60-75 °C) takes typically 10-12 hr. Some problems have been experienced with heating the transformer with ON cooling.
Experience has shown that besides of assessment of water contamination, a set of problems can be settled by means of Heat Run Test:

- Malfunction of the oil level in the transformer and bushings (rate of pressure rise in sealed bushings);
- Detection of the oil leakage place and poor sealing using effect of low oil viscosity;
- Malfunction in the cooling components.

CASES OF HISTORY

Case 1: 250 MVA, 242/15.7 kV, GSU, OF, open-breathing, 12 years.
General contamination of the thin structure.

Time	t, °C	W_{oil}, ppm	φ %	P_s, mmHg	W_e %	Estimated water content in thin structure	Real water content
Initial	25	18	19.6	4.6	5.6	> 2.5% in 1000 kg of 2 mm	In the PB (2 mm) patterns–2.5% Extracted 25 kg Of water
24	65	42	4.8* 11.2	8.98* 20.9	1.3* 2.36		
48	65	44	11.7	21.8	2.4		
72	65	48	12.8	24	2.6		

Case 2: 250 MVA, 400/15.7 kV, GSU, OF, membrane-sealed, 12 years.
Local contamination of outer barriers.

Time	t, °C	W_{oil}, ppm	φ %	P_s, mmHg	W_e %	Estimated water content in thin structure	Real water content
Initial	40	15	9.2	5.05	28	> 3% in 500 kg of 3 mm	In the PB closed In the tank–4.7% Close to the winding - <1% Extracted 27 kg of water
24	65	32	4* 8.5	7.5* 15.9	1.1 2		
48	65	35	9.3	17.4	2.1		
72	65	35	9.3	17.4	2.1		

Case 3: 200 MVA, 347/15.7 kV, GSU, OF, open-breathing, 27 years.
Excessive water contamination.

Time	t, °C	W_{oil}, ppm	φ %	P_s, mmHg	W_e %	Estimated water content in thin structure	Real water content
Initial	40	24.2	15	8.2	3.9	> 2.5% in 1000 kg Of 2 mm	In the PB (2 mm) 2.75% Extracted 36 kg of water
24	70	44.2	5.5 10.1	13 23.6	1.38 2.1		
48	70	47.2	10.8	25.2	2.2		
72	70	49	11.2	26.2	2.24		

* After reaching the test temperature

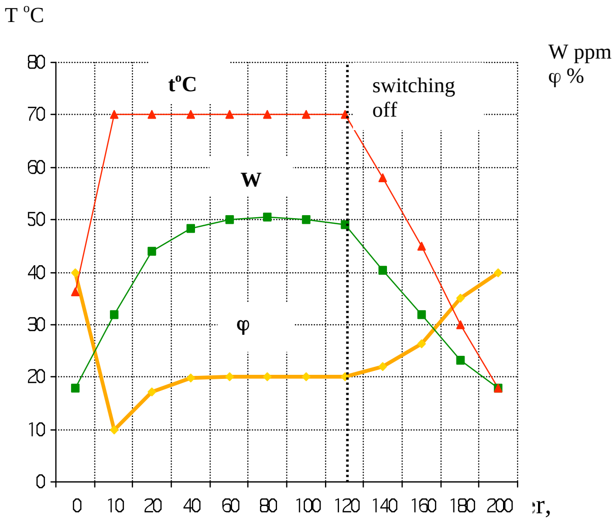
Case 4: 125 MVA, 400/15.7 kV, GSU, OF, open-breathing, 22 years.
Moderate water contamination.

Time	t, °C	W_{oil}, ppm	φ %	P_s, mmHg	W_e %	Estimated water content in thin structure	Real water content
Initial	40	10	6.2	3.4	2.1	> 1.5% in 1000 kg of 3 mm	In the PB (3 mm) patterns – 1.8% Extracted 12 kg of water
24	65	22	2,7* 5.9	5.0 11	0.88 1.5		
48	65	16	4	7.5	1.2		
72	65	24	6.4	12	1.6		

Case 5: 250 MVA, 400/15.7, GSU, OF, membrane-sealed, 12 years in service.
Dry transformer

Time	t, °C	W_{oil}, ppm	φ %	P_s, MmHg	W_e %	Estimated water content in thin structure	Real water content
Initial	40	6.6	4	2.2	1.6	≈ 1% in 1000 kg of 3 mm	In the PB (3 mm) pattern – 0.85%
24	70	10	1.5 2.3	3.54* 5.37	0.56 0.75		
48	70	10.5					
72	70	10	2.3	5.37	0.75		

Case 6: 180 MVA, 220/18 kV, GSU, OF, open-breathing, 18 years.
Presence of free water.
Build up of water in oil is practically followed to rise of temperature.



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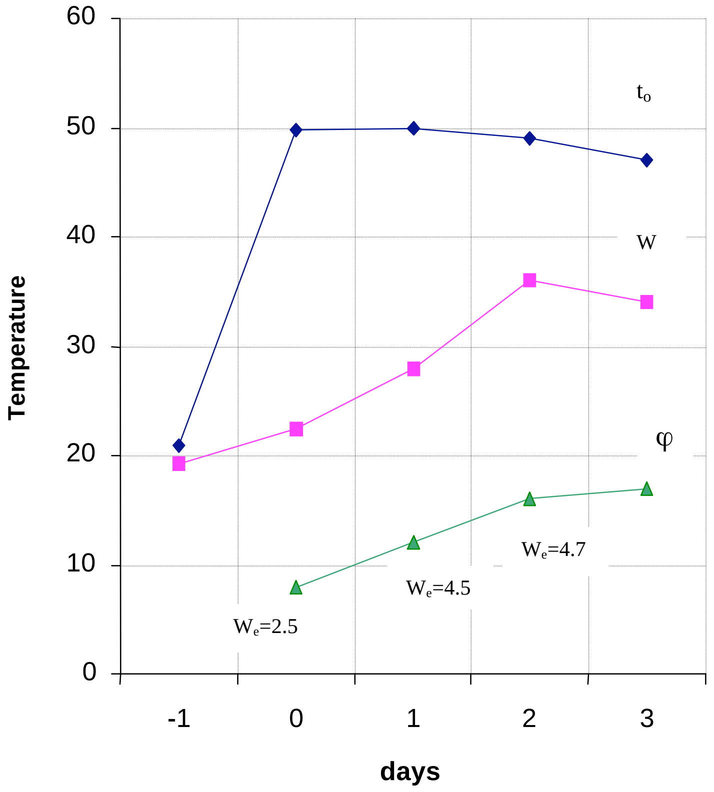
Contaminated with Some Free Water.

Case 7: 25 MVA, 110 kV, ON, open-breathing, 17 years.

Transformer was heated to 50 °C only, so that it was possible to detect moisture content in solid insulation only above 3%.
Water build up was due to mixing up some free water.
Time of mixing took more than two days.



CONCLUSION

1. Both theoretical analysis and experience have shown that the main source of transformer water contamination is atmospheric moisture, and the main mechanism of water penetration is viscous flow of wet air or "live" water through poor sealing under action of pressure gradient, The amount of ingressed water may be estimated and limited. Distribution of moisture in a course of transformer life is kept quite non-uniform. The most of the water is supposed to store in the "thin" insulation structure operating at oil bulk temperature.

2. The moving force of water transfer is "a moisture potential", which is different for minor (turn-coil) insulation of windings (greater) and major insulation (essentially weaker). Parameters of moisture equilibrium, as well as diffusion coefficient, depend on structure of cellulose, temperature, presence of gases, water-in-oil solubility. Empirical approximations available may be used only to estimate level of moisture content , but not for precise determination of water content.

3. Influence of temperature field in turn and coil insulation makes non-uniform distribution of water in the layers. Rapid rise of temperature causes rapid rise of vapour pressure in microcapillaries and pressing out oil from macrocapillaries followed with bubbles

evolution. The conditions of the latter phenomenon depend not only on water content and temperature, but also on density of cellulose and oil quality.

4. The condition monitoring of the transformer shall be aimed for the detection of defective condition: some level of water contamination, which may result in significant rise of relative saturation of the oil. the level of water contamination may be estimated using the rate of amount of water "discharged" by "active" part of solid insulation at some elevated temperature, when relative saturation of oil becomes essentially lower than concentration of water in surface layers of insulation.

5. Experience with in-service assessment of water contamination of transformers has shown good correlation between predicted and real conditions of the equipment using Water Heat Run Test technique, however, a bad correlation between water content in the oil and solid insulation at temperature 50 – 40 °C or lower. This experience can be used for application of On-Line monitoring technique as well.

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