

MOISTURE EQUILIBRIUM AND MOISTURE MIGRATION WITHIN TRANSFORMER INSULATION SYSTEM

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*SOURCES OF WATER CONTAMINATION.MOISTURE DISTRIBUTION
WITHIN INSULATION STRUCTURE.MOISTURE EQUILIBRIUM-WHAT'S
KNOWN & UNKNOWN.SOLUBILITY OF WATER IN OIL “MOISTURE
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OF WATER CONTAMINATION.*

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 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 the risk of bubbling at high temperature [3, 4].
- **Uncertainty in effectiveness of methods available to assess a health of an equipment.** In [5] e.g. is shown that in spite of low water content in the oil indicated by 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]. In opinion of

CIGRE experts, a deeper understanding the processes of water ingress, equilibrium, migration, dangerous effect, as well as selection of effective diagnostic methods, is necessary to define effective and efficient means of “Life management”. Due comprehension of physics and feasible presentation of mathematics of moisture ingress into a transformer, moisture migration and moisture equilibrium in a transformer are wanted yet still lacking in power engineering. These are items of discussion of this paper.

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 bulky insulating components, particularly in plastics, which need much longer drying time in comparison with pressboard. Typically, those are supports of leads, LTC, support insulation of neutral coils of winding, bakelite cylinders, core support insulation, etc. Sometimes this phenomenon is a cause of elevated value of insulation PF and its rise with temperature. During service this moisture can gradually evolve into 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 these 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 while transformer is treated under vacuum.
- **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 draw- 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 (vapor) pump”.
- **Large amount of “live” water can be pumped into a transformer in a very short time (several hours),** when there is a rapid drop of pressure (after rapid drop of temperature) combined with insufficient sealing down with rain water.

This phenomenon is particularly dangerous when transformer is stored partly filled with oil with no preservation system.

- Rate of possible water contamination of open-breathing transformer is significant, but limited.[7].

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 only and not to the total mass of insulation. Typically, only 25 – 30 kg of water is extracted during drying out of about 5000 kg of insulation with water content in the “thin structure” up to 2.5 %.

Rate of water contamination of transformers with membrane-sealed preservation system is 0.03...0.06% per year (tested about 80 units).

In the case of insufficient or broken sealing, over 50-kg of free water have been revealed in transformers of both free-breathing and membrane-preserved design.

A large amount of free water can ingress into transformer tank through damaged “water – oil” cooler. Inadequate in field drying out also can be a cause of condensation of free water.

Table I shows that works involving insulation exposure to air can bring in much more water than service with imperfect preservation system in the course of years.

Table I

Upper estimating of the Rate of Water Contamination

Conditions	Rate of contamination
<u>Direct exposure insulation to air:</u> a) RH = 75%, t = 16 h, 20 °C b) RH = 40%, t = 16 h, 20 °C	Sorption with surface 1000 m ² up to 0.5 mm depth 13.5 kg 8.1 kg
<u>Water vapor molecular flow</u> • Via sealing capillaries • Via loosed gaskets	Less then 1 – 5 g per year Less then 30 – 40 g per year
<u>Viscous flow of air;shipping condition : ,</u> core and coil covered with oil - Adequate sealing - insufficient sealing	600 g per year 15 g in a day
• <u>Operation with open-breathing</u> • <u>Insufficient sealing drowned with rain water</u>	6,000 g per year 200 g in an hour

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 the total of furanic compounds can be found. Quantification of this process needs special study.

Findings of different authors differ essentially.

Lampe and Spicar [11] suggested that depolymerization up to 5 – 6 scission leads to formation of 2% of water. Endurance tests winding models at 125...160 °C detected [12] increase of moisture content up to 1.5...2.8 % in some zones located below the hottest coils. Shroff and A.Stannet [13] have shown that degradation of cellulose to DP = 400 generates only 0.4% of water.

It is to be noted that the process of intensive water formation is expected to be localized in some “hot spots”, which comprise typically less than 5% of insulation. Fig 1 shows the sources of moisture contamination in transformers in service.

MOISTURE DISTRIBUTION WITHIN INSULATION STRUCTURE

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

- 1) “**Thick structure**” (about 50 % of the total insulation mass-, basically supporting components) comprises about 50% of the total insulation mass but provides a diminutive contribution to moisture migration due to a large (a few years) time constant of diffusion process.
- 2) “**Thin cold structure**”, which operates at oil bulk temperature: pressboard barriers, end caps, etc. These components comprise 20 – 30% of the total mass. They are the main storage of water. Moving force of moisture migration is water concentration difference at oil-insulation boundary.
- 3) “**Thin hot structure**”, which operates at the temperature close to the conductor temperature (turn-coils-layers insulation). About 5% of its mass has somewhat elevated temperature (so called, hot spots). There can be three moisture moving forces there: water concentration gradient, temperature gradient and vapor (vapor +gas) pressure gradient.

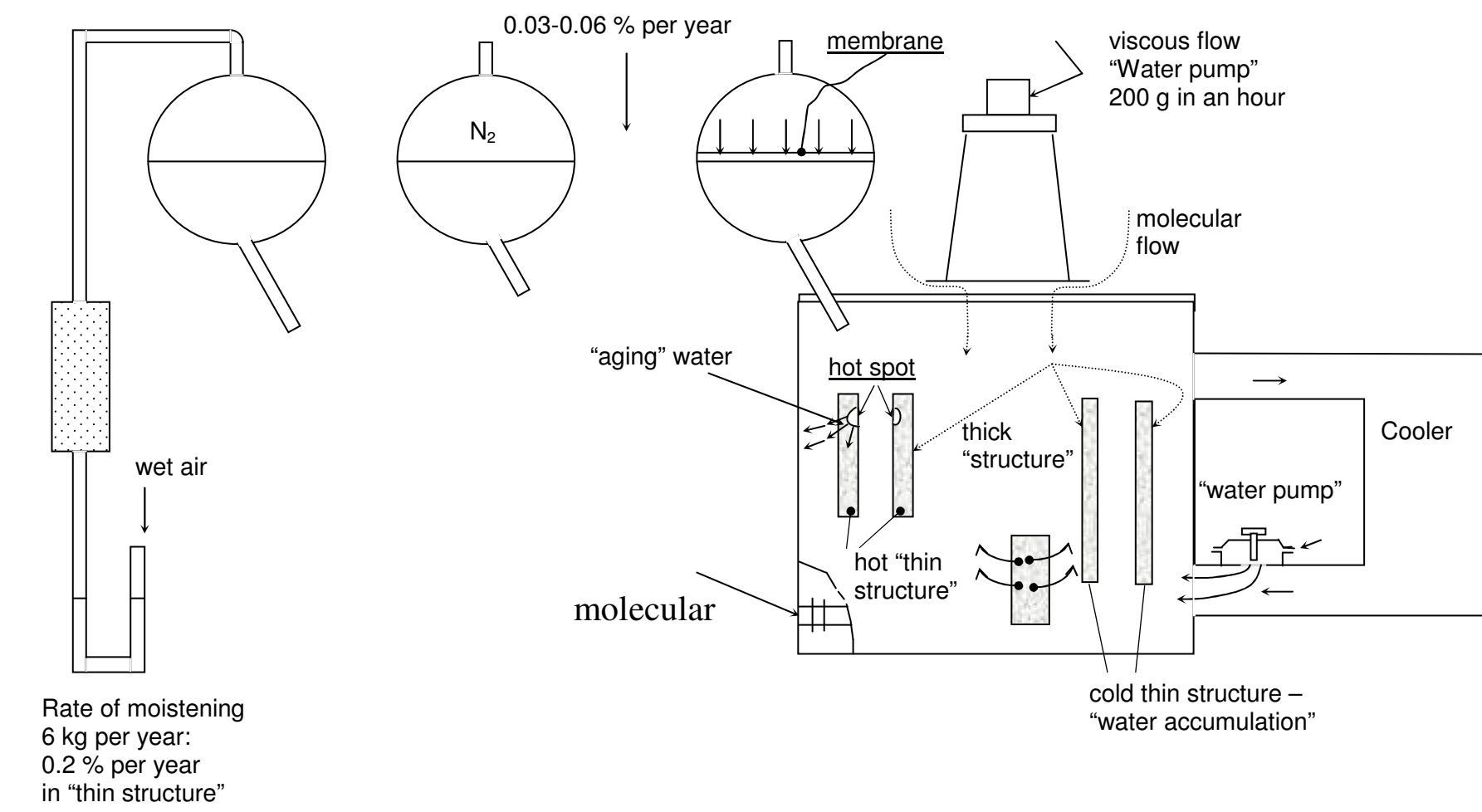
Experience has shown that the most of moisture is stored in the components of the second group. About 10% (by mass) of this group (the coldest portion) forms some “wet” zones with water content by 1 – 1.5% more than average.

Components of this group are the main source of the oil contamination at elevated temperatures, when moisture concentration in the surface cellulose layers becomes greater than in the neighboring oil.

Moisture content in the components of the third group is markedly less than in the second one, however its harmful effect may be greater because of greater temperature.

Oil at large is only moisture transferring medium, however, some water can be “stored” in the surfactant substance in it.

In some cases free water can be found spread on the bottom of a transformer tank, on the core, in the coolers, etc. resulting from suction rainwater through poor sealing.



.Fig.1 Sources of water contamination.

MOISTURE EQUILIBRIUM. WHAT'S KNOWN AND UNKNOWN?

ABSORPTION AND ADSORPTION

There are two ways of sorption vapors and gases in substances and media:

Absorption-when molecules of gas (vapor) become part of the substance;

Adsorption-the adhesion of gas (vapor) vapor molecules to the surface of solid bodies or liquids.

Adsorbed molecules still are gas (vapor) molecules but limited in motion. They constitute two-dimensional gas at the adsorbent body in constant motion along its surface. From time to time molecules get free and again become part of three dimensional gas constituting adsorbate medium, new of free molecules taking their place, equilibrium adsorption, thus, being of dynamic nature. Equilibrium takes place practically in no time.

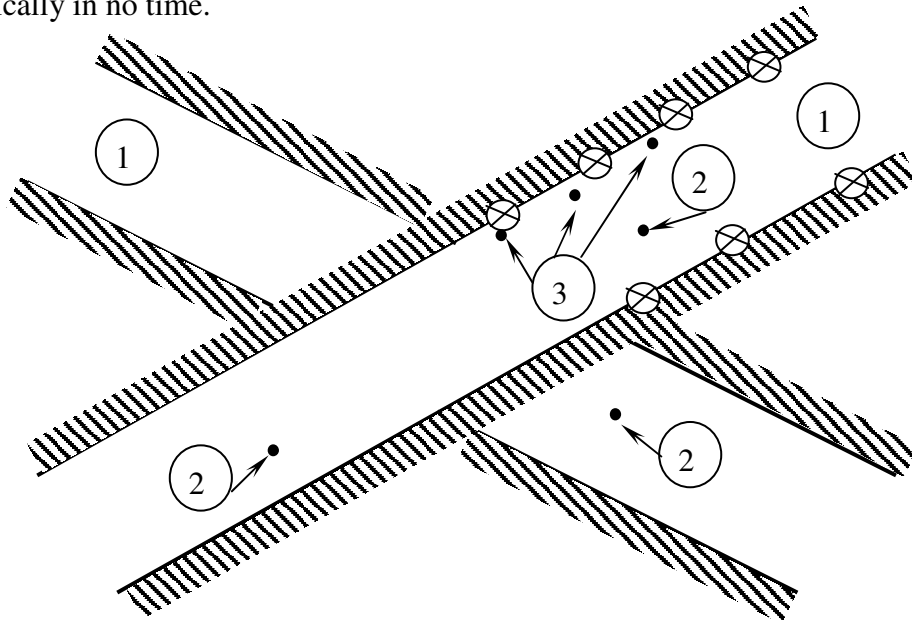


Fig.2. Adsorption water (vapor) molecules with active sites of cellulose material in microcapillaries:

- ① - microcapillaries;
- ② - free water molecules;
- ⊗ - active sites at capillaries boundaries;
- ③ - gas molecules adsorbed at active sites.

ADSORPTION OF WATER VAPOR IN CELLULOSIC MATERIAL

This case of adsorption has specific features because of porosity of material and presence of polar groups in cellulose molecules. [26] Polar groups make cellulose very active in attracting and adsorption water molecules. The process of adsorption is practically instantaneous in any location as soon as vapor reaches this locality, but the process of vapor diffusion itself is slowed down because of slow advance of water molecules through the labyrinth of microcapillaries. Therefore general equilibrium is hardly achieved.

Desorption is the still more slow process because it requires some activation energy, while adsorption is followed with evolution of some energy.

Sorption water is of a dynamic character: adsorbed molecules of water are kept in intensive movement about active centers of cellulose molecules (OH-groups in glucose rings) and acquiring sufficient kinetic energy, get free and its place is soon occupied with another water molecule. The process is shown in Fig.2.

Dynamic equilibrium comprises constant interchange vapor molecules between free water and active sites and right between adjacent active sites with molecules practically not getting free. The first mechanism takes place basically at moisture content $W < W_0$ where W_0 - the conditional moisture content equal to that imaginary one when all active sites would be occupied with one adsorbed molecule (So called “monomolecular layer” or “monolayer”). The second mechanism being realized basically at $W > W_0$.

Molecules of water (and gases) travel within microcapillaries and within macrocapillaries filled with oil independently (molecular flow). Diffusion leads to exponential growth of adsorbed water to equilibrium. Temperature accelerates the process.

SORPTION ISOTHERM

Sorption Isotherm is adsorbed water content against Relative Humidity or Water Pressure in Equilibrium State.

Typical adsorption isotherms (Fig3) are of S-shaped form with a twist point dividing an isotherm into two parts. The left one shows a slowing increase and is characteristic of formation first conditional “monolayer”. The right one shows a growing increase which means accelerated capture water molecules with amplified water molecules’ assemblies at active sites. This phenomenon is often called conditionally “polylayer” adsorption.

SORPTION EQUATION

The general view of sorption isotherm may be expressed by the following equation, as it is known in molecular physics

$$\frac{W}{W_0} = \frac{K \cdot \varphi}{(1 - \varphi) \cdot (1 - \varphi + K \cdot \varphi)} = Y = \frac{K \cdot x}{(1 - x) \cdot (1 - x - Kx)} \quad - \quad (1)$$

Where $Y=W/W_0$ -number of conditional “monolayers” adsorbed

$X=\phi=P/P_s$ -relative humidity;

P – vapor pressure;

P_s – saturation vapor pressure;

K – function of temperature representing ratio of probabilities for a molecule to escape: free water surface and an active site of adsorbed material.

The equation (1) well represents as it's shown in Fig4 that adsorption isotherms have the twist point which travels the path “**0-M-L 1**” as temperature coefficient K grows in the range of $2 \leq K < \infty$.

It is of importance to distinguish experimental data taking into account the different mechanisms of sorption before and after the twist point.

In power engineering two well known approximations are used, namely,;Piper's and Fessler's[25],which are grounded on Freundlich's approximation $W=A p^a$

Where A is function of temperature.

This approximation is valid only for the parts of an isotherm bellow the twist point.

Piper and Fessler did not exclude experimental data above the twist point of isotherm using Freundlich's equation. They suggested the following expressions:

$$\text{Piper- } W=[P \exp. (-21.92 + 6850/T)]^{0.75} \quad (2)$$

$$\text{Fessler- } W=2.173 \cdot 10^{-7} \cdot P^{0.6685} \cdot \exp(4725.6/T) \quad (3)$$

Where P, mm Hg-vapor pressure;

W, %-water content;

T,K-thermodynamic temperature

The both expression underestimate moisture content at low concentration and overestimate it at concentration up to 10 %

The equation (1) is in much better agreement with experimental data.

Equation (3) may bring to the form (2) with somewhat different numerical constants.

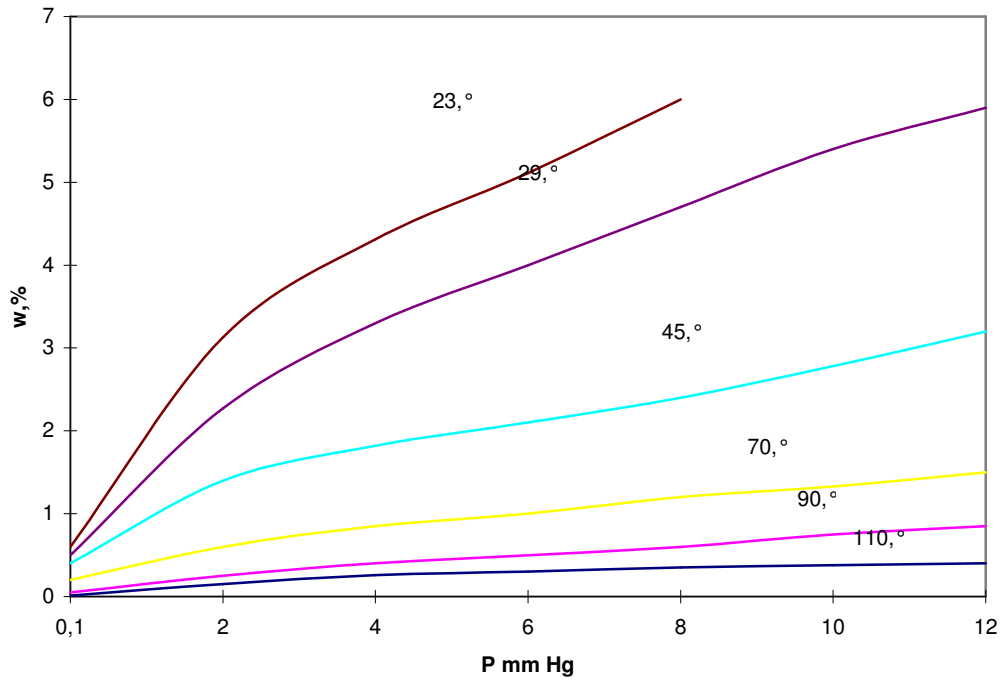
Both (2) and (3) may be also deduced from the main sorption equation by means of some simplification and limitation of water content.

In Fig 5 and 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 (about 2..4 %) 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 6) and essential difference between sorption of water in air and in vacuum (Figure 5). Process of sorption in vacuum is also much faster than in air. This is because “strange” molecules of air are adsorbed with cellulose materials along with water molecules which relaxes the field strength of active sites. So adsorption in air is always quantitatively less then in vacuum at equal temperature.

Fig.3 Kraft paper K-120 and water-paper in vacuo isotherms.



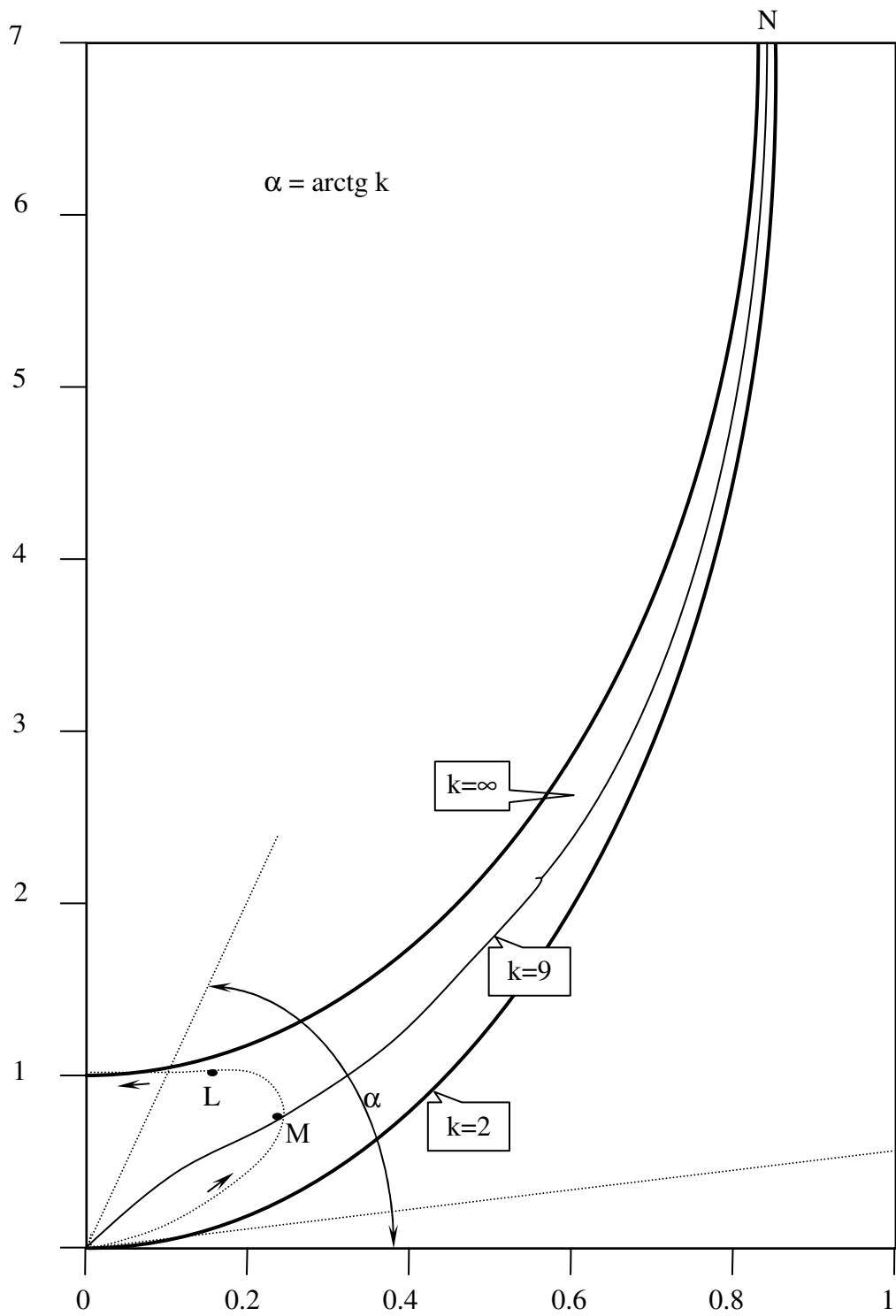


Fig.4. Ultimate forms of adsorption isotherms with $2 \leq k < \infty$.

With $k=9$ the twist point M is at the farthest distance ($x_m = 0.25$) from zero point ($x=0$).

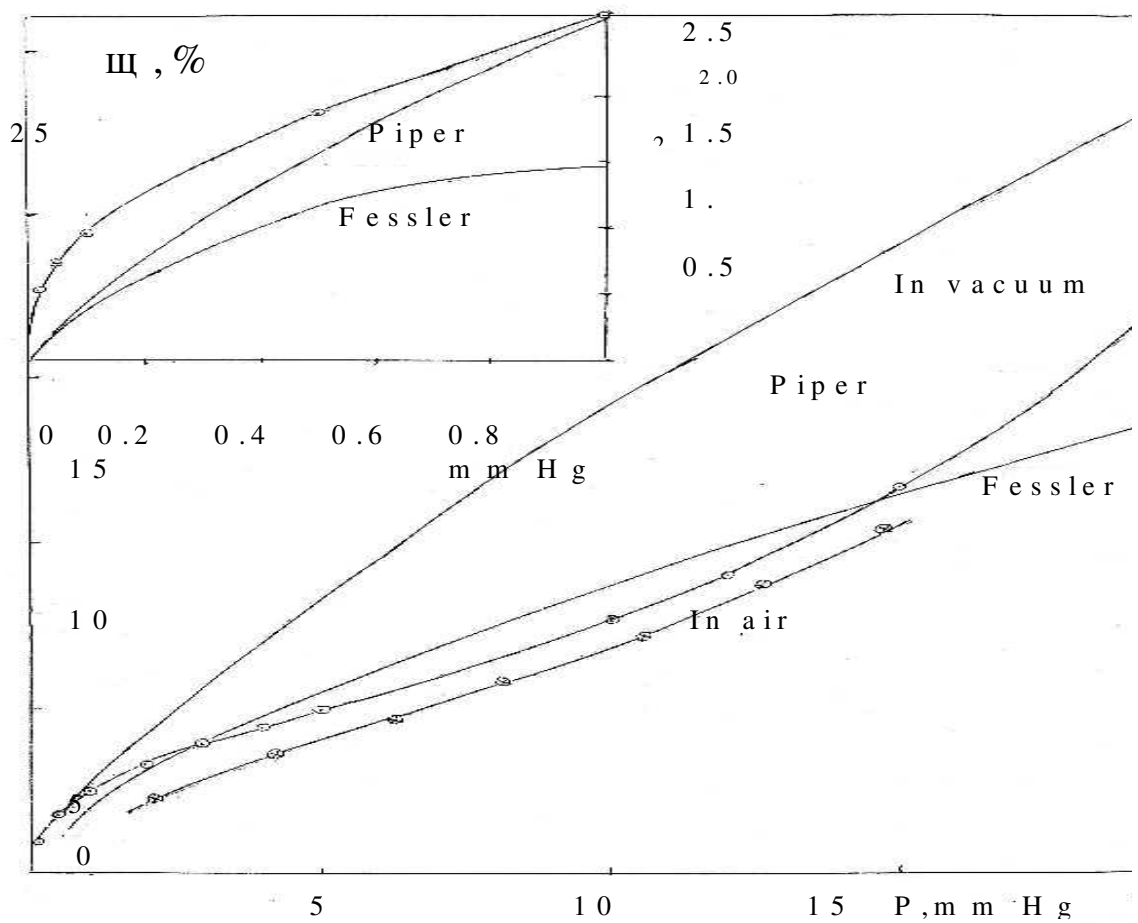


Fig 5 Water-Paper Isotherms (23C) experimental and stylized in the form of Piper and Fessler formulas

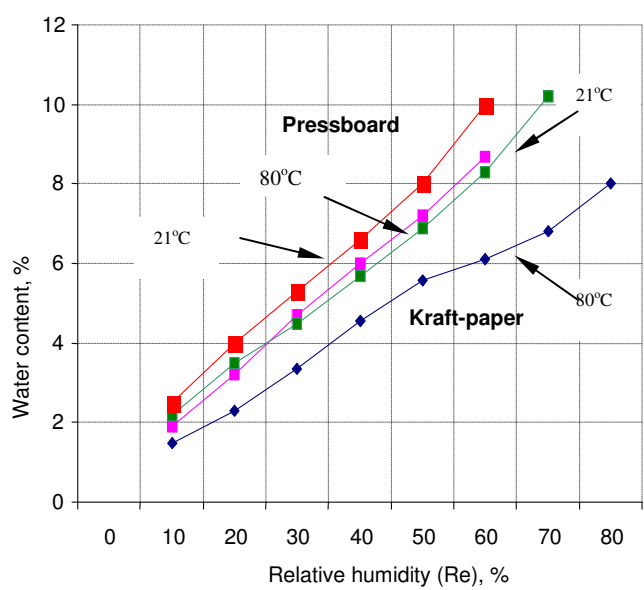


Fig 6 Moisture equilibrium in pressboard and paper

Table II

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

Paper	Humidity, %	Parameter s	Empirical equation		Experiments		Theoretical (1)**
			By Piper	By Fessler	Oommen*	By [24]	
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 is present 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.[27] Water saturation – temperature [$W_s - T$] relation is expressed by form

$$W_s = W_0 \exp. (- B / T)$$

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. At elevated temperature some amount of “hydrate” water may transfer in dissolved water.

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 transfer through microcapillares and through oil in macrocapillares comprising all three moving forces is the molecular movement, which is ruled by the law similar to the Ohm’s law for electric current, where **“moisture transfer”potential**

$$\varphi_w = \frac{P}{\sqrt{T}} \quad (4)$$

‘Moisture potential’ plays the role analogous to that of electric potential. Change of vapor pressure P or temperature T means the advent of moisture transfer potential and moisture movement.

In view of (4) the second Fick’s law may be presented in essentially simplified form. For practically important one-dimensional case it looks like

$$\frac{\lambda}{\rho} \cdot \frac{\partial^2 \varphi_w}{\partial x^2} = \frac{\partial \omega}{\partial t} \quad (5)$$

Where: λ -moisture conductivity of a material which is its specific quality and depends neither on moisture concentration ω , nor on temperature; so the test at only one chosen temperature is needed to determine λ ; ρ -density of the material. Diffusivity of a material (its diffusion coefficient D) may be presented (using base equation 1) as

$$D = \frac{\lambda}{\rho \sqrt{T}} \cdot \frac{\partial P}{\partial \omega} \quad (6)$$

MOISTURE MIGRATION IN THE MAJOR INSULATION OF A TRANSFORMERS

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. Uneven distribution of water across the layers with elevated

concentration in the vicinity of the surface layers somewhat counterbalances the aforesaid obstacle to sorption.

It is feasible to use some constant value for Diffusivity **D**. Correspondingly the amount of adsorbed water may be roughly estimated using solution of Fick's second law [7]

$$\Delta W_a \cong (W_e - W_o) \cdot [1 - F(Z)] \quad \% \quad (6)$$

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

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

D – diffusivity, sq. ·m/sec

d – insulation thickness, m

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

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

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

$$\Delta W_d \cong (W - W_e) \{ [1 - F_z] \}, \quad \% \quad (9)$$

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.e.g., 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 · 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

$$T_o = \frac{9 \cdot 10^{-6}}{\pi^2 \cdot 8 \cdot 10^{-14}} \cong 132 \text{ days. If take a thinner pressboard: } d = 1 \cdot 10^{-3} \text{ m and } D = 1.6 \cdot$$

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 conductor's 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 it 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 7 shows that non-uniformity may be notable even at rather low average water content.

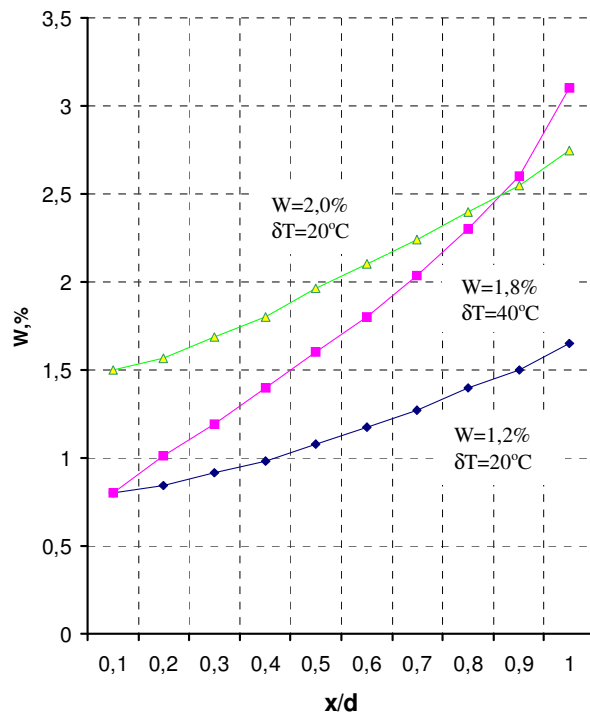


Fig 7 Moisture Distribution in Turn Insulation under Effect of Temperature

MECHANISM AND CRITERIA OF BUBBLES EVOLUTION

Water travels through microcapillaries when water content and temperature, and vapor pressure are low enough. **Rapid rise of temperature causes rapid evaporation of absorbed water followed with rapid rise of vapor 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 vapor-filled cavities on the insulation surface (so called “bubbling”).*
- *Partial or entire de-impregnation of the turn insulation.*

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

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

Where σ - interfacial tension between oil and vapor 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.

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

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

Where P_s – saturation vapor pressure of water,

$K = \exp(678 / T)$.

Thus, the condition of bubble evolution depends not only on the temperature and water content, but also 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 8 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 temperature 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

a cellulose molecule is to produce some screening effect on its field and relax its influence on water °C iles and strange molecules as well.

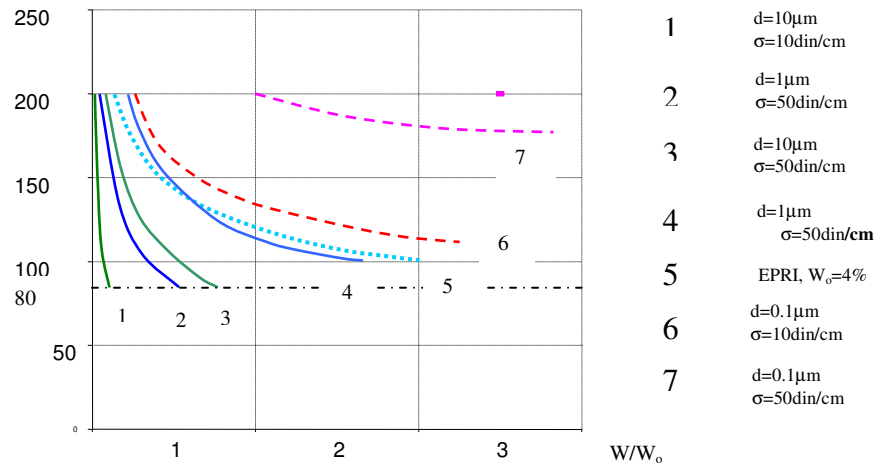


Figure 8
Conditions of Bubbles Evolution

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 has been observed as a typical cause of the breakdown of LTC insulation [19]. Moreover, a drop of water in viscous oil may work as a particle generator being exploded under effect of electrical field. Unusual reductions of the dielectric withstand strength to 0.2...0.4 kV/mm has been observed.

All of a sudden ingress of free water may kill the transformer immediately. E.g. 400 MVA, 220 kV transformer fell 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 draw-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. *In all 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 a 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 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, followed 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 in oil with temperature (it remains typically below 15 PPM). Relative saturation of the oil reduces exponentially with temperature and makes up about 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 by two times) rise of water content in oil after heating and maintaining the test temperature. Relative saturation of the oil is expected about 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.

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