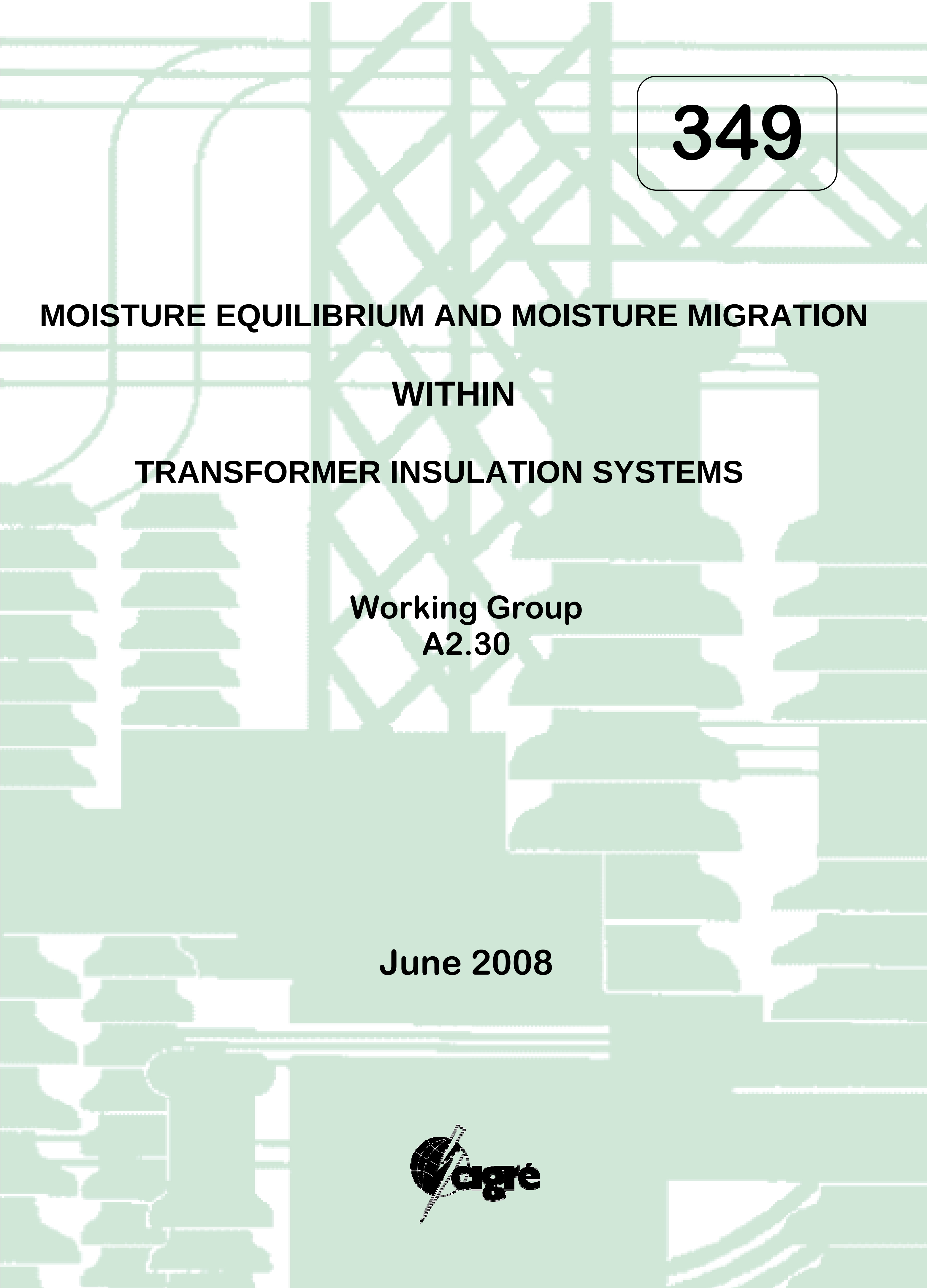

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MOISTURE EQUILIBRIUM AND MOISTURE MIGRATION

WITHIN

TRANSFORMER INSULATION SYSTEMS

Working Group
A2.30

June 2008

cigré

CIGRE WG A2.30

Moisture equilibrium and moisture migration within Transformer insulation systems

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Foreword

WG A2.30 (previously TF A2.30) was set up in 2005.

The topic of moisture in transformers is an important aspect related to the understanding the migration of moisture during drying process, on-site repair, risk estimation in case of overloading, etc.

As their main objective the group elaborates the CIGRE brochure ‘Moisture in Transformers’ on the basis of early CIGRE WG A2.18 work “Moisture equilibrium and moisture migration within transformer insulation systems” considering relevant works presented on the subject at the colloquiums of SC A2.

Shortly after completing this brochure our convenor Dr. Viktor Sokolov passed away on the 6th of January 2008. We always appreciated his profound knowledge and the valuable discussions with him. It is a sad loss of an expert and a true friend. His memory will stay with us.

The members of CIGRE WG A2-30 ‘Moisture in Transformers‘

In Memoriam

Victor SOKOLOV

Dr. Victor Sokolov, aged 67, passed away suddenly on the 6th of January 2008. He obtained his MSEE in 1962 from the Kharkov Polytechnic University/Ukraine and completed a postgraduate programme in Moscow with a major in Physics of Dielectrics. He obtained a Ph. D. in High Voltage Technology in 1982 from the Kiev Polytechnic University in the areaof EHV transformer diagnostics.

Dr Sokolov was a world-class expert in the area of reliability of transformer equipment: his area of expertise included analysis and improvement of designs, functional diagnostics for the prevention of damage and, restoration of characteristics and prolongation of service life of power transformers. He began his professional career at the Zaporozhye Transformer Factory (ZTZ). In 1992 he founded the Centre of Science-Engineering Service "ZTZ-SERVICE“ of which, until recently, he remained the technical head (Director).

From 2006 he was Transformer Project Manager in the Kelman Service Company, simultaneously co-operating with the power enterprises of Russia, Ukraine and CIS countries.

Victor Sokolov has brought a huge contribution to the creation of a system of analysis of performance of transformer installations in power supply networks and methods of development of the generalized decisions for prevention of non-staff (emergency) situations in power transformers. He was always distinguished by his professional approach and deep level of understanding of complex physical processes when solving problems. Simultaneously he understood that these problems are the same general problems for all world power systems and, accordingly, in such a way he joined CIGRE.

Dr Sokolov assumed multiple tasks within CIGRE, in particular in Study Committee A2 “Transformers” and D1 “Materials and Emerging Technologies“. He was convenor of the WG A2.18 "Transformer Life Management" and was Special Reporter on the preferential subject "On-Site Operation" at the CIGRE Transformers Session in 2004.

When Victor passed away, he was convenor of a team titled WG A2-30 ‘Moisture in Transformers‘. The work had just completed and was on the way to be sent to Electra for publication as a brochure.

Dr Sokolov was also liaison officer between CIGRE SC A2 and SC D1 and was a member of the Advisory Group ‘Strategy’ of SC A2.

In the working group D1.01 "Impregnated insulation systems for transformers" of CIGRE Victor formed the link between the more "academic" specialists in this group and the real world challenges. He was always very open for new work and also happily shared his experience with others.

Possessing encyclopedic knowledge as well as experience in popularizing scientific and engineering ideas; Victor placed the greatest emphasis of his professional life on combining professional experts from the different countries of the world to develop a general understanding of common problems and their solution.

Victor Sokolov received in 2000 the CIGRE Technical Committee Award. This award is granted as a reward for a remarkable technical contribution.

He published over 100 papers in the field of transformer issues and Victor was one of the authors of a popular transformer handbook and this year he was going to participate in creation of the second part of a transformer handbook (transformer service problems).

The death of Victor is a great loss which came suddenly. It is the loss of an expert in the preparation of CIGRE brochures and reports for the coming generations.

On behalf of all members of CIGRE working bodies, we would like to present our deepest condolences to the family of this great colleague and friend of us, in particular to his wife Ludmila, his daughter Victoria and his son Sergey.

Victor Sokolov's spirit will stay with us for ever.

Pierre Boss
Chairman CIGRE SC A2 'Transformer'

Alexandr Drobyshevski
Regular member and delegate from Russia in CIGRE SC A2 'Transformer'

Lars Lundgaard
Convenor CIGRE WG D1.01'Impregnated insulation systems for transformers'

January 2008

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1. INTRODUCTION

1.1 Moisture in Transformers - a Frequently Discussed Problem

There has been renewed interest in the subject of water contamination in transformers in recent years, which can be attributed to the following reasons:

1. A large population of aged equipment is apparently contaminated with some water. Questions are being raised on how the affected equipment should be operated considering the well-known issues of the effects of water on:

    - accelerated rate of aging for cellulosic materials such as paper and pressboard [1], [11]
    - reduction of dielectric strength with increasing the relative saturation of moisture in oil [2]
    - reduction of the dielectric strength of paper and pressboard materials
    - risk of bubble evolution at high temperatures [3], [4]

2. Uncertainty of the effectiveness of available methods to assess the moisture content of the insulation system and hence the health of equipment. In reference [5] it is shown that in spite of routine measurements showing low water content in the oil, a large amount of water was contained in the transformer insulation. To prevent in-service failures, reliable techniques are needed to determine whether a critical level of water contamination has been reached and what the permissible operating conditions are. This information can be used to prioritize which transformers require drying.

3. New moisture sensors have become available for continuous on-line condition monitoring [6]. To fully utilize the data from these sensors an expert system needs to be developed that will detect excessive amounts of water to prevent operation of transformers under defective conditions.

The problems of insulation deterioration and rehabilitation of transformers are subjects of particular interest of the CIGRÉ Working Groups 12.18 "Life Management" and 37.27 "Ageing of the System. Impact on Planning", that has resulted in two technical brochures, [7] and [72]. The relevant standards pay special attention to moisture assessment as IEC 60814 for water measurements by Karl Fischer titration and IEC 60422 for supervising and maintaining mineral insulating oils in electrical equipment. Nevertheless, the approaches of IEC 60422 to limit moisture by means of ppm of water in oil may lead to misjudgements, since temperature-induced moisture migration and influences of oil ageing are not appropriately regarded.

In the opinion of CIGRÉ experts, a deeper understanding of the processes of water ingress, equilibration and migration, the dangerous effects of excessive water, and effective diagnostic methods, are necessary for effective and efficient "life management". This paper describes the physical processes and mathematics of moisture ingress, migration and equilibration in transformers. Some of the knowledge gained about moisture in transformers is empirical and has been acquired during the investigation, repair and dry out of power transformers.

Experiences with utilities have shown their limited understanding of moisture. The temperature of oil sampling, though very important for moisture assessment and breakdown measurements, are often disregarded. Thus the condition of the insulation system becomes underrated. Traditional assumptions, which have been a basis for moisture assessment and treatment, have to be substituted by actual scientific findings. Early recommendations related to bubble evolution were too simplified. During overloading or short-circuit vapour bubbles can start at 100 °C but not at 130-140 °C as considered before. Reasons for overestimation of water in cellulose through water in oil are explained in detail and essential improvements are given. Dielectric response methods to estimate moisture in cellulose are introduced with valuable comments. The authors intend to base this document on scientific evidence to clarify most common misunderstandings about moisture in transformers and to provide reliable practical recommendations.

1.2 Definitions

Absolute Moisture Content – Moisture Related to Weight

The water mass m_{H2O} in a material related to its weight m results in *water content W.* For *moisture in cellulose* the measure is per cent of weight (%) and for *moisture in oil* it is parts per million of weight (ppm). To measure water mass the coulometric Karl Fischer titration is mostly used (IEC 60814 and p. 40). In chemical laboratories it is usual to calculate contents related to the mass as sampled m_{as}, however the relevant international standards use also the dry weight m_d for the calculation. For the weight determination at oil-impregnated samples it is important to separate the cellulose from oil.

ISO 287 for non-impregnated paper and board:

$$W = \frac{m_{as} - m_d}{m_{as}} \cdot 100\% \qquad (1)$$

IEC 60814 for oil impregnated paper and board:

$$W = \frac{m_{as} - m_d}{m_d} \cdot 100\% \qquad (2)$$

IEC 60814 for oil in ppm:

$$W = \frac{m_{H2O}}{m_{as}} \cdot 1'000'000 \qquad (3)$$

Moisture Related to Gas Volume

For gases it is common to relate the water mass to the volume (g/m³). This quantity is proportional to the *moisture concentration [7]*.

Dissolved or Adsorbed Water

Dissolved water forms a mixture composed of water as a solute, dissolved in oil or adsorbed by cellulose. Generally the polar solute water will only dissolve in polar solvents.

Water Saturation Level in Liquids

When no more water can be dissolved into a liquid, the solution is said to be saturated. This maximum capacity to absorb water is called *water saturation level* W_S. However, the point at which a solution can become saturated changes significantly with environmental factors such as temperature, pressure and contamination.

Free Water

“Free water” is water that exists in droplets. E.g. if in oil the water content exceeds the saturation level, water will form droplets of free water. In cellulose materials free water may exist in macro pores.

Water Vapour Pressure

The partial pressure exerted by water vapour is called the *water vapour pressure p*. In a mixture of ideal gases the partial pressure of one component is proportional to its concentration in the mixture. Summing up all partial pressures in a mixture one receives the total pressure P. At the surface of boiling water the saturation water vapour pressure becomes equal to the atmospheric pressure. Water vapour pressure is an intrinsic property of pure water and increases with temperature. Moisture dissolved in oil or cellulose also generates a vapour pressure [15].

Relative Humidity

Relative humidity RH is defined as the ratio of the partial pressure of water vapour p in a gaseous mixture of air and water to the saturated vapour pressure of water p_S at a given temperature and pressure. Relative humidity is expressed as a percentage and is calculated by (4). Chilled mirror dew point instruments indicate this measure (p. 44). Relative humidity refers to water vapour in gases only, whereas water in solids or liquids is described by *relative saturation*.

$$RH = \frac{p}{p_S} \cdot 100\,\% \tag{4}$$

Relative Saturation

Relative saturation RS in *ideal gases and liquids* is the ratio of the actual water content W to the saturation water content W_S.

$$RS = \frac{W}{W_S} \cdot 100\,\% \tag{5}$$

Relative saturation in *solids* is the ratio of the partial water vapour pressure exerted by the solid in a gas space under equilibrium conditions to the saturation water vapour pressure.

$$RS = \frac{p}{p_S} \cdot 100\,\% \tag{6}$$

Water Activity

Equivalent to relative saturation, *Water activity* a_w is defined as ERH/100, where ERH is the relative humidity measured in the proximity of a hygroscopic material under equilibrium conditions. A value of unity indicates water saturation whereas zero indicates the total absence of available water molecules. Its measurement bases on moisture equilibrium. In a closed container the water activity in a sample (oil or paper) determines the relative humidity in the gaseous space. So this relative humidity is equivalent to the water activity in the sample given equilibrium is established.

Water activity a_W reflects the relative availability of water in a substance. When water interacts with solutes and surfaces, it is unavailable for other interactions. Thus water activity is the measure of water in the material which is available for exchange with the surrounding environment.

If water activity is measured in the air above the transformer oil then it could be called water-in-oil activity. Similarly, if water activity is measured in the oil in the vicinity of cellulosic insulation then we could call it water-in-paper activity a_{WP}. Capacitive probes measure water activity (p. 42).

Water activity gives information about water molecules available for interactions with materials such as chemical reactions (depolymerization by hydrolysis), dissociation of acids (oil conductivity, breakdown voltage) and evaporation (bubble effect). Therefore water activity represents an apposite value to describe the detoriating impacts of water in oil-paper-insulations.

2. MAIN SOURCES OF WATER CONTAMINATION

For a good life management of transformers, the moisture content of the insulation should be retained at low concentrations. Transformers are dried during the manufacturing process until measurements or standard practices would yield a moisture content in the cellulosic insulation of less than 0.5 to 1.0 % depending upon purchaser's and manufacturer's requirements. After the initial drying, the moisture content of the insulation system will continually increase. There are three sources of excessive water in transformer insulation:

- Residual moisture in the "thick structural components" not removed during the factory dryout or moistening of the insulation surface during assembly, generally reduced by evacuation of the tank
- Ingress from the atmosphere (breathing during load cycles, site erection process)
- Aging (decomposition) of cellulose and oil.

2.1 Residual Moisture

Excessive residual moisture can remain in some bulky insulating components, particularly in wood and plastic or resin-impregnated materials, which need much longer drying times in comparison to paper and pressboard. Typically, these are supports for leads, support structures in the load tap changer (LTC), support insulation for the neutral coils of the winding, cylinders, core support insulation, etc. A commonly used family of plastic impregnants are phenolic resins.

Sometimes local excessive moisture can be detected because it causes the insulation power factor to be high, particularly at elevated temperatures. During service, this excessive local moisture will gradually become redistributed spatially, driven by heat. The excessive moisture will migrate, in part, from the bulky insulating components to the thinner insulation structures, which will have a net increase in moisture content on average. This will occur over many temperature cycles with the oil serving as the mobile carrier.

Different insulation materials require different drying durations. The drying time is roughly inversely proportional to insulation thickness in square. However the structure of material is an important factor as well. Pressboard featuring a high density requires more time than low density pressboard. Laminated pressboard is typically glued together. The adhesive layer prevents practically any drying perpendicular to the lamination. Drying therefore works only parallel to the layer direction, it requires accordingly more time [64].

2.2 Moisture Ingress

The main source of the buildup of water in transformers is the atmosphere. There are three mechanisms for moisture ingress from the atmosphere. One source of moisture is the sorption of water while there is direct exposure of the insulation to air (installation and repair). Ingress of moisture into the tank can also occur by molecular (Knudsen) flow due to the difference in water vapour pressure in the atmosphere and the transformer gas space or oil. The term Knudsen or molecular flow describes the diffusion of gases through very small ducts and tubes (e.g. gaskets). The third mechanism, viscous flow of wet air into the transformer, results when there is a difference in total pressure, that is the atmospheric pressure is higher than the pressure inside the tank. Viscous flow as fluid movement in which all particles of the fluid flow in a straight line parallel to the axis of a containing pipe with little or no mixing occurs e.g. through the conservator system of free breathing transformers.

A mathematical analysis of moisture ingress is presented in reference [7]. In Table I some upper estimates of possible water contamination are shown based on these calculations. The results lead to the following conclusions:

- Molecular flow of moisture into transformers is practically negligible. This mechanism is not of significance unless the transformer is treated under vacuum, thereby reducing the internal partial pressure of moisture.
- The main mechanism of water penetration in transformers is through poor seals by the viscous flow of wet air created by a total pressure gradient. Typical leaks are the top seal of draw-lead bushings, the seals in explosion vents, and leaks in forced-oil circulation systems between the main tank and the coolers. Even though oil does not leak out of the oil circulation system, air can be sucked in when the pumps are operating because of the “negative” pressure created behind the pumps. These leaks result in viscous flow of air that occurs under a pressure gradient effectively behave as a “water vapour pump”. Furthermore at water cooled systems water may penetrate from the cooler even if the oil is kept at higher pressure than the water in the cooler.
- Large amount of rainwater can be sucked into a transformer in a very short time (several hours), when there is a rapid drop of pressure (after a rapid drop of temperature that can be induced by rain) combined with insufficient sealing. This phenomenon is especially of concern when transformers are stored partly filled with oil without their conservator preservation system.
- The rate of water contamination possible for transformers because of free breathing in conservator tanks is significant, but limited.

Information about the moisture content of service–aged insulation has been developed using an initial assessment consisting of moisture-in-oil measurements and electrical tests followed by direct measurements [8], [9]. Direct measurements of the water content of pressboard samples removed from about 100 transformers after 6 to 20 years of service have shown that the rate of water contamination of transformers with open-breathing conservators is up to 0.2 % per year. Most of this water is retained in local (wet) zones, and is not evenly dispersed throughout the total mass of insulation. Typically, only 25 to 30 kg of water are extracted during drying out of about 5000 kg of insulation, which is equivalent to 0.5-0.6 % water in the cellulosic insulation. Yet the water content of the moister “thin structures” can be as high as 2.5 %.

The rate of water contamination for transformers with membrane-sealed conservator preservation systems is about 0.03 to 0.06 % water in the cellulosic materials per year based on a study of about 80 units.

In cases of insufficient or broken sealing, over 50 kg of free water have been revealed in transformers of both open-breathing and membrane-sealed conservator designs. Large amounts of free water can ingress into water-cooled transformers because of damage to the heat exchangers.

Table I shows that maintenance activities with the solid insulation exposed to air result in greater moisture ingress than it would happen within service use with an imperfect preservation system for many years. Field drying will remove some of this moisture. However, inadequate field drying of transformers can leave significant residual moisture. The results of the table were obtained by measurements.

Table I Upper Estimate of the Rate of Water Contamination [23]

Conditions	Rate of Water Contamination
Direct exposure of oil-impregnated insulation to air:	Sorption of water in pressboard with surface of 1000 m^2 up to 0.5 mm depth:
Relative humidity RH = 75 %, 20 °C RH = 40 %, 20 °C	13.5 kg in 16 hours 8 kg in 16 hours
Water vapour molecular flow:	
Via capillaries in seals (pores in gaskets) Via loose gaskets	Less then 1 – 5 g per year Less then 30 – 40 g per year
Viscous flow of air:	
Shipping condition: core and coil covered with oil	
Adequate sealing Insufficient sealing	0.6 kg per year 15 g in a day
Operation with open-breathing conservator	6 kg per year
Insufficient sealing with rain water present	200 g in an hour as free (liquid) water

Moisture Contamination during Exposure of the Active Part to the Atmosphere

The process of moisture absorption by the insulation's outer layers is very fast, but diffusion of moisture molecules into inner layers takes a very long time. The relative humidity of the air is a critical factor. For example, during 4 days exposure of 3 mm thick pressboard to air of 50 % RH we can expect the water content to increase by 5 %, see Figure 1. Of this adsorbed moisture, 95 % will usually be confined to insulation depths of 0.3-0.35 mm. Moreover moisture is concentrated mainly in the outer insulation components.

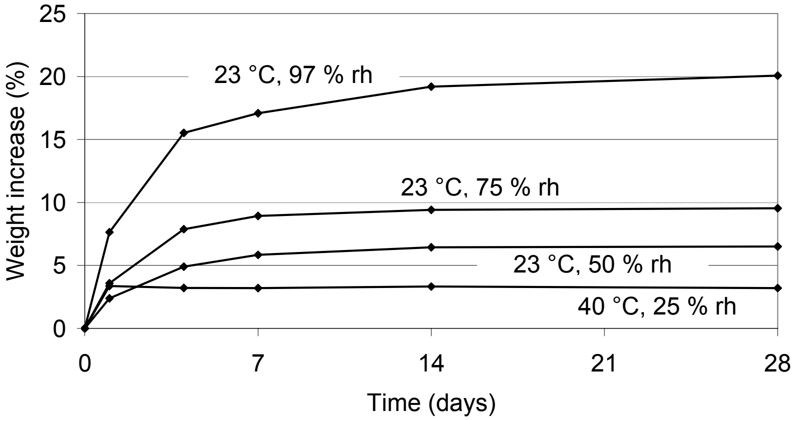

Figure 1: Moisture Adsorption of 3 mm High-Density Pressboard at 23(40)°C at Various Humidity's of the Ambient Air [74]

2.3 Decomposition of Insulating Materials

The aging of cellulosic materials leads to molecular chain scission and the formation of byproducts including water and furanic compounds. There are some differences found in the literature on the amount of water formed from the aging of paper under various conditions. Lampe and Spicar [10] suggested that depolymerization from up to 5 to 6 scissions leads to the formation of about 2 % water in paper. Endurance tests performed on winding models at temperatures from 125 to 160 °C caused increases in moisture content from 1.5 to 2.8 % in some zones located below the hottest coils [68]. Shroff and Stannet [12] have shown that degradation of paper in laboratory experiments to a DP of 400 generates only 0.4 % of water. If a DP of 400 is considered to be at least half life or greater aging, then their findings suggest less water is formed by paper aging than indicated by the others. Figure 2 shows the increase of moisture in cellulose during aging found in laboratory studies by various research groups [48], [49], [50], later confirmed by [65]. After five chain scissions a paper starting at a degree of polymerization of 1200 has ended up with a DP of 200. As scatter is high between results the curves should only be considered as indicators on the order of magnitude of the water producing effect.

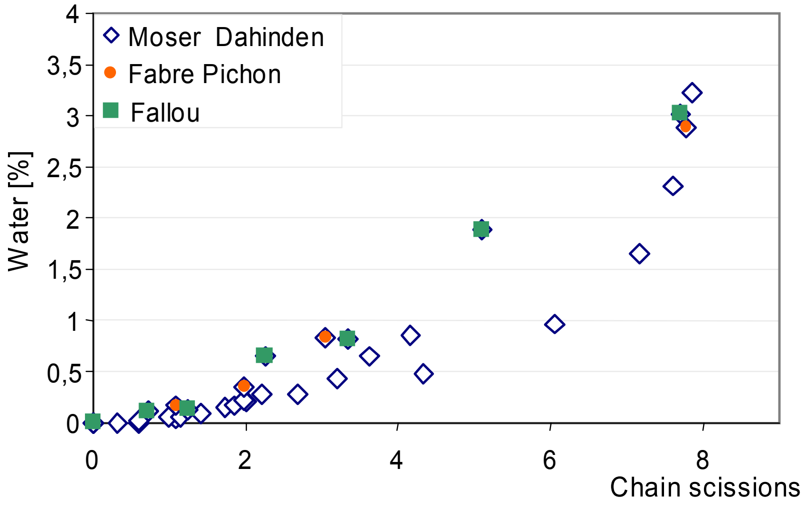

Figure 2: Increased Water Content in Cellulose as a Function of Chain Scissions

Emsley et al. [73] from an extensive literature review concluded an equation for a “thermally activated” paper aging process:

$$\frac{1}{DP(t)} - \frac{1}{DP(0)} = t \cdot A \cdot e^{-\frac{E}{R \cdot T}} \qquad (7)$$

Where:
DP(t) – Degree of polymerisation after aging
DP(0) – Degree of polymerisation before aging
A – Depending on chemical environment, e.g. on moisture in paper, acidity
E – Activation energy of the chemical process, e.g. 95-111 kJ/mol for hydrolysis
R – Molar gas constant
T – Kelvin temperature
t – elapsed time during aging

In transformers the process where the most intensive water formation is caused by the aging of cellulose materials is expected to be localized in some “hotspots”, which comprise typically less than 5 % of the insulation. The aging model proposed by [7] indicates oxidation, pyrolysis and hydrolysis of cellulose and oxidation of oil as reactions which contribute to water contamination. Further research is needed to better quantify the total amount of water generated by aging of paper and pressboard. Figure 3 shows the sources of moisture contamination for transformers in service.

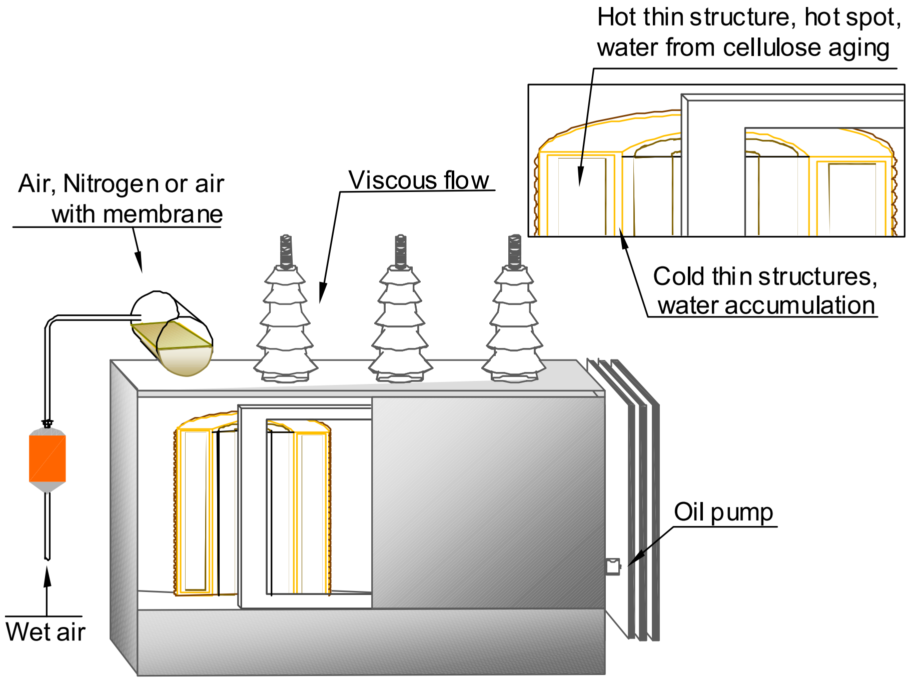

Figure 3: Sources of Water Contamination in Power Transformers

2.4 Preservation Systems

The problems experienced when water is present in transformer insulation were introduced in section 1.1. It is necessary to find an effective way of preventing water from ingressing into a transformer. The usual solutions adopted to control water contamination are:

- Free breathing
- Breathing via a desiccant
- Flexible diaphragm or “rubber bag”
- Nitrogen cushion either at atmospheric or high pressure
- Refrigerated drier
- Hermetical seal
- Molecular sieve

Liquid cooled transformers are fitted with conservators mounted above the main tank, and connected to it by pipework. As the oil expands and contracts with temperature variations, the oil moves between the main tank and the conservator. The area of oil surface in the conservator is much less than the horizontal sectional area of the tank to reduce the area of contact between the oil and the atmosphere.

Breathing Freely or Through a Desiccant

Allowing a transformer to breathe freely to the atmosphere can only be considered for low voltage transformers or transformers installed in a low humidity environment. A simple solution is to allow the transformer to breathe through a desiccant such as silica gel which will remove water from the air as it passes through the material and changes its colour when the gel should be changed or regenerated. Well maintained silica gel breathers will dry air down to a relative humidity of less than 5 %, but the efficiency quickly falls and becomes inadequate for the duty required.

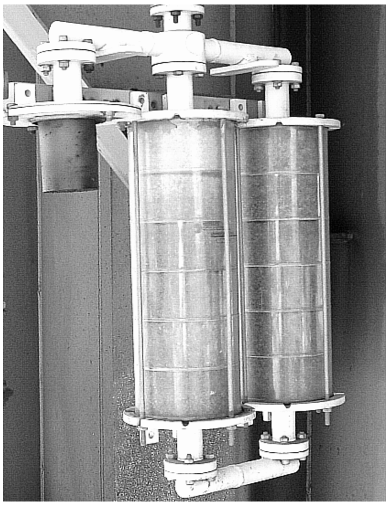

Figure 4: A Silica Gel Filter System

A typical silica gel filter system is shown in Figure 4. Here air passes through an insect filter shown on the left of the picture, down through a first silica gel column and up through a second column on the right of the picture for connection by pipe to the transformer conservator. The first cylinder has started to show a color change at the entry of the air path.

Diaphragm Seal

A flexible diaphragm or “rubber bag” is widely used in some countries such as the USA to prevent moisture from the air making contact with the oil, but the flexible materials age and allow moisture migration through the seal.

Hermetic Sealing

The accumulation of moisture and oxygen can be prevented by hermetically sealing of the active part [62]. In order to enable an alteration in the oil volume without conventional conservator an expansion radiator is used. Besides the abandonment of the conventional conservator, this type of design offers the advantage of a reduced ageing speed of the oil-paper insulation system due to the hermetically sealing and savings of maintenance costs, because there is no longer a need for the inspection or exchange of the silica gel filled air breathers.

Nitrogen Blanket

A nitrogen gas above the oil has been used in some countries. Under heavy cyclic loading super-saturation of the oil can occur leading to gas bubble formation and electrical breakdown due to high electrical stress in the bubbles.

Refrigerated Breather

As an improvement on the silica gel breather a refrigerated breather has been widely used, particularly in the UK. A refrigerated breather is shown in Figure 5.

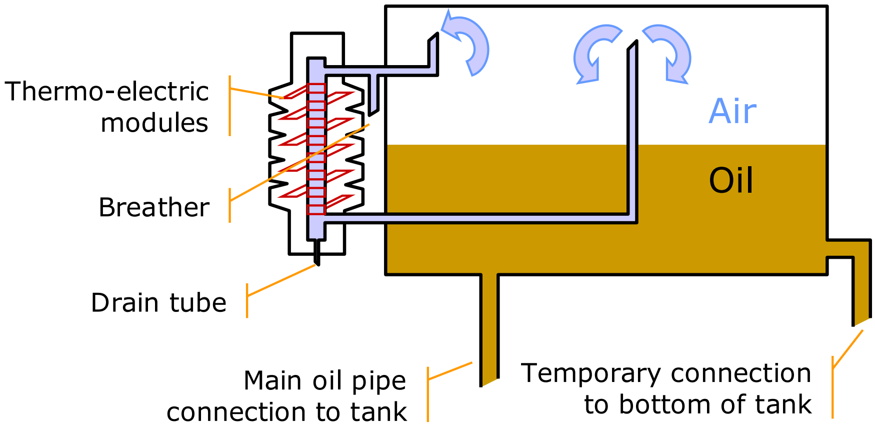

Figure 5: A Refrigerated Breather

The refrigerated breather uses Peltier thermo-electric modules to convert electrical energy to thermal energy in order to condense or freeze the water in the air in contact with the metal surface. The breather comprises a finned heat sink that is connected via Peltier modules to a central conducting tube. A DC current in the Peltier device creates a thermal gradient between the outer fins and the inner tube. This, in turn, creates a thermal flow of wet air from the conservator and condenses the moisture in that circulating air on the inner tube. The induced thermal flow returns the dry air to the conservator. Towards the end of a 6-hour cycle, the current in the Peltier device is reversed, thus increasing the inner tube temperature compared with the atmosphere and melting any ice formed in it. Free water can drain from the base of the tube. The air vent allows the transformer to breathe and ensures that the conservator remains at atmospheric pressure throughout.

It is important to be able to remove water from the air in the conservator as an equilibrium is formed between the water content of the oil and the water content of the air in contact with it. As water is removed from the conservator and the air is dried, water diffuses from the oil into the dry air, this way drying the oil.

2.5 Water Contamination during Installation and Repair

To preserve the insulation from moisture, dust and other contaminants is one of the most important repair procedures. Preservation is, in many respects, much more efficient that subsequent drying. During the drying process, water from the wet surface layers migrates toward the dry medium (into vacuum) as well as toward the dry layer (into the depth of the insulation). Experiences have shown that in order to remove 90 % of the moisture adsorbed by insulation from ambient air at 20°C, the time of drying out at 80°C is approximately 4 times longer than time of exposure to the ambient air.

A proper preservation can be maintained by the following procedures:

- Maintaining a low relative humidity of ambient air. Enclosing the transformer or active part in a plastic housing and blowing dry air (positive pressure of dry air) is an efficient technique.
- Special preservation of thick insulation structures and their pre-drying in a case of a long storage should be considered.
- Monitoring the temperature and relative humidity around the transformer.

- Measurement of moisture content in thin pressboard patterns located in areas of high relative humidity.

3. SOLUBILITY OF WATER IN OIL

Oil serves as a water-transferring medium within a transformer. Water is attracted in oil by aromatic components or impurities. It may also become adsorbed as hydrates by polar aging products. Particles, such as cellulose fibers in the oil, contain some water too. The absolute water content in oil is linearly proportional to the water vapour pressure up to the saturation level [20]. The temperature dependence of the saturation solubility of water in oil (W_S) is expressed by:

$$W_S = W_{Oil} \cdot e^{-B/T} \qquad (8)$$

Where, W_{0il} and B are constants, which are similar for many transformer oils but may be different for some products, mainly due to differences in aromatic contents. As oils become oxidized with increasing amounts of polar aging byproducts, their water solubility characteristics also increase. Some information about estimated solubility constants and saturation water contents for mineral oils and a silicone fluid are shown in the Table II and Figure 6. The appendix “Methods for Moisture Determination in Transformer Insulations” (p. 40) gives information about moisture measurements in oil and the related difficulties.

Table II Solubility of Water in Mineral Oils and Silicone

Oils*	Aromatics C_A, %	W_{0il}	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
Silicone	0	$1.9525 \cdot 10^6$	2733	174	314.7	675.4
Oommen	NA	$24.65 \cdot 10^6$	3835	53	122	358
Aged**	NA	$1.84 \cdot 10^6$	2752	153	279	757

* Data from references [19], [21], [22], [23],

** Service aged oil with a total acid number of 0.49 mg KOH/g oil [31]

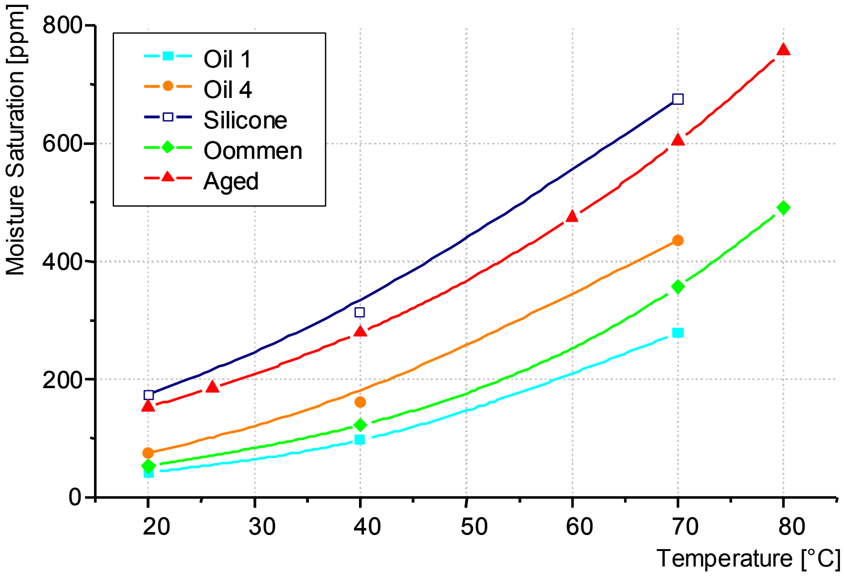

Figure 6: Solubility Curves of Water in Mineral Oils

IEC 60422 gives an example of an oil with a neutralisation number of 0.3 where moisture solubility has increased by about a factor of two. However, recent studies indicate that it is not the total acidity as such, but rather low molecular water soluble acids, measured via water extraction, that are responsible for the increased water solubility of service aged oils as shown in Figure 7, [66], [67].

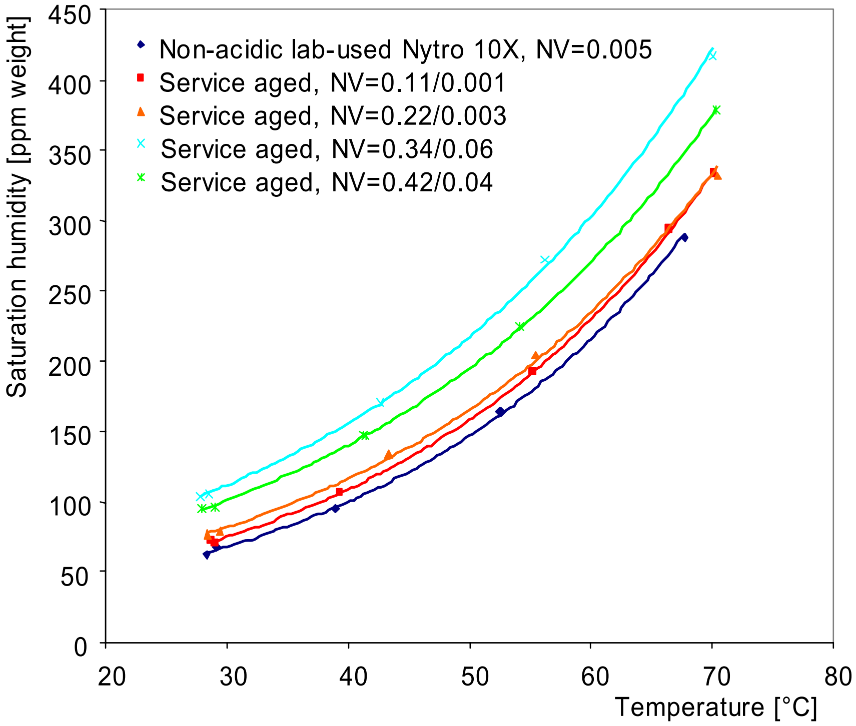

Figure 7: Moisture Solubility in Four Service Aged Oils Compared to a Non-Aged Laboratory Used Oil. In the legend for each oil is given the neutralisation value = value for all acids / value for water soluble acids [mgKOH/g]

At elevated temperatures some amount of hydrated water or water from cellulose particles may transfer into dissolved water. Clear increase of water content in different transformer oils during aging is shown in [30]. In the latter is also shown that the impacts of temperature (80-100 °C) and time (150-400 hr) result in an increasing water content in aged oil and in a substantially decrease of the breakdown voltage of oil due to the conversion of molecularly bound water into the dissolved state. This phenomenon should be considered and further investigated.

4. ADSORPTION OF WATER TO CELLULOSE MATERIALS

Moisture migration in cellulosic materials is a process of diffusion through porous structures and adsorption to surface polar groups [25] or active sites, see Figure 8. These polar groups make cellulose very active in attracting and adsorbing water molecules. Adsorption of gas (vapour) molecules in cellulose materials occurs mostly in microcapillaries. The microcapillaries are small channels in the microstructures of the cellulose fibers that cannot be oil impregnated. The adsorbed molecules remain gas (vapour) molecules with limited motion because of their electromagnetic attraction to the oppositely charged polar portion of cellulose molecules at the active sites . From time to time, adsorbed molecules get free and move through three-dimensional space until they get re-adsorbed. Other molecules can then move in to take their place at the previous site. Thus, there is a rapid dynamic equilibration process occurring at the surface. Unlike the nearly instantaneous adsorption process, the process of vapour diffusion is quite slow because water molecules are physically deterred from moving rapidly by the labyrinth of microcapillaries. Therefore, general equilibrium is rarely achieved. De-sorption of water molecules from the surface of active sites on the cellulose micellas surfaces occurs still more slowly because energy is required to break the bond. This is in contrast to the adsorption process which not only does not require any activation energy but evolves some energy in the bonding process.

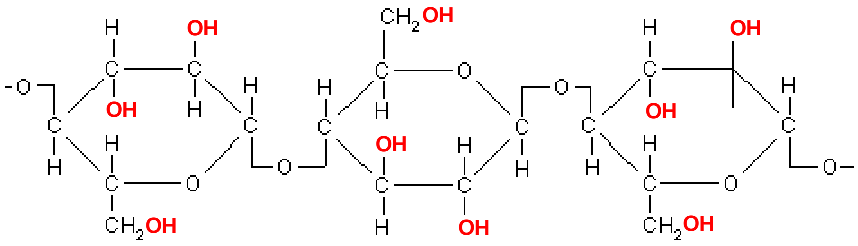

Figure 8: Molecule Structure of Cellulose Consisting of Glucose Rings with Unsaturated OH-Groups

Moisture adsorption and migration are affected by the number of water vapour molecules which can be attracted to the surface. Once all of the active sites have adsorbed water molecules, additional water molecules will be attracted to those already adsorbed, forming multiple layers. The first mechanism takes place basically at moisture contents $W < W_k$, where W_k is the conditional moisture content equal to that imaginary one when all active sites would be occupied with one adsorbed molecule (the so called “monomolecular layer” or “monolayer”). The second mechanism begins when $W > W_K$. Increasing temperature accelerates the moisture movement and sorption.

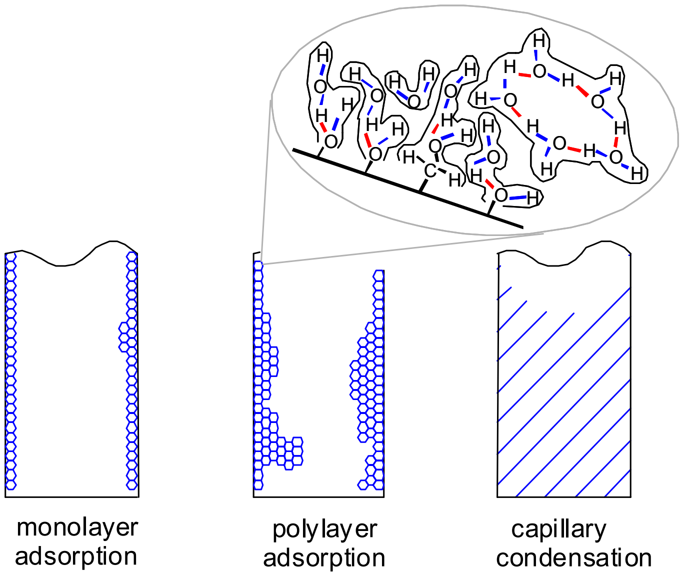

Figure 9: Adsorption of Water Vapour Molecules at Active Sites in Microcapillaries of Cellulosic Material

4.1 Sorption Isotherms

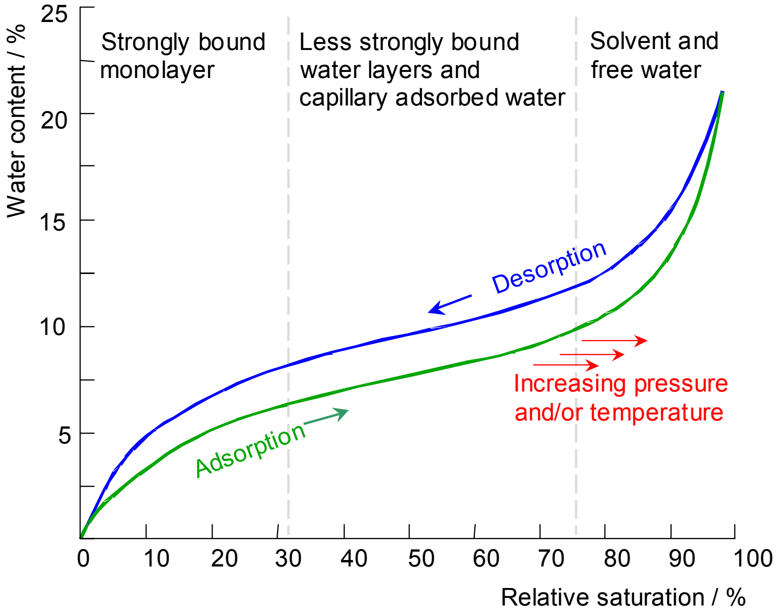

Figure 10: General Moisture Adsorption and Desorption Isotherms with Influence of Water Bonds [76]

Sorption isotherms relate the amount of water in cellulosic materials to the water vapour pressure or relative saturation in the state of equilibrium [77]. Typical adsorption isotherms are S-shaped with a twist point dividing the isotherms into two parts (Figure 10). The left area, at lower water contents, shows the rate of increase in moisture content being decelerated with increasing vapour pressure (after an initial rapid rise) that is characteristic of the formation of the “monolayer” of water at the cellulose surface. The right area, which is for higher water contents, shows a more rapid increase in water content with increasing vapour pressure associated with “polylayer” adsorption. According to Figure 11 cellulose materials differ in their absorption capacity [41]. This is primarily due to different suppliers, content of lignin etc. and rather not because of the type of end products as pressboard or paper.

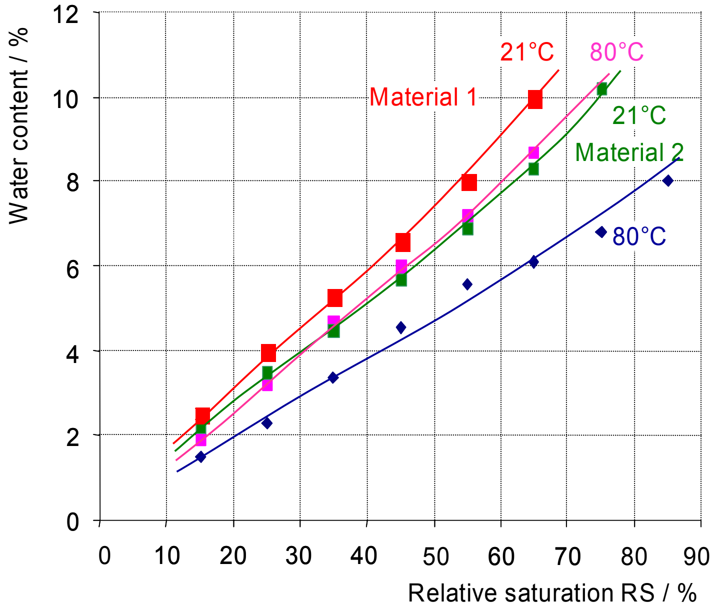

Figure 11: Water in Paper Isotherms for Two Cellulose Materials [18]

4.2 Sorption Equations

The general view of sorption isotherms may be expressed by the following equation, as it is known in molecular physics [14], [29], valid for impregnated and nonimpregnated cellulose too:

$$\frac{W}{W_k} = Y = \frac{k \cdot RH}{(1 - RH)(1 - RH + k \cdot RH)} \qquad (9)$$

where:

W - water content;
W_k - water content corresponding to the full monolayer,
Y - number of layers of adsorbed water molecules,
k - probabilities' ratio for a water molecule to escape a free water surface and an active site of adsorbent,
RH - relative humidity of the water vapour in the vicinity of adsorbent active sites,
RH = p/p_s,
p - vapour pressure at active sites of adsorbent,
p_s - the same for the saturated state of vapour.

In the original BET (Brunauer – Emmett – Teller) theory K is supposed to be the function of temperature only, and p_s is the saturation pressure of vapour above and adsorbent, so that RH = φ = relative humidity of the surrounding medium (air, vacuum). The theory is quite good to qualitatively explain adsorption of gases and vapours on adsorbents with surfaces exposed to external media: it naturally falls into Henry law Y = $k\varphi$ with $0<\varphi<<1$ and shows an infinite raise at $\varphi \rightarrow 1$ ($\varphi \rightarrow 100\%$), and it accounts for the twist point too, which is at

$$X_T = \frac{\sqrt[3]{K-1}-1}{\sqrt[3]{(K-1)^2}}. \qquad (10)$$

The monolayer adsorption Y = 1 is found at $X_K = \frac{1}{1+\sqrt{K}}$.

The twist point travels from $X_T = 0$ to $X_T = 0.25$ as K grows from 2 to 9 and from $X_T = 0.25$ to $X_T = 0$ again as K grows from 9 to infinity. It may be seen that with K large enough (very active adsorbent) a monolayer is formed with the slightest relative moisture possible. Many adsorbents, and cellulose too, appear to have the twist point near $X_T = 0.25$ at room temperature, which is characteristic of monolayer formation approximately at the same point.

Quantitatively the theory is good enough, when the function of temperature K(T) is defined according to sorption isotherms' tests. In the vicinity of adsorbent surfaces the saturation pressure p'_S is not equal that of the vapour in the surrounding medium p_S. De Boer [14] suggested that p'_S (T) should be found from treating the isotherms' test results alongside with K(T). This turned out to be satisfactory in application to adsorbents with open surfaces.

With cellulose materials, considering their micro capillary structure, the BET theory and its improvement by De Boer are not quantitatively satisfactory and further improvements are necessary. This implies that in micro capillaries the process of vapour saturation is quite different from that of the vapour saturation in the open space. In the latter the saturation is due to quick raise of the probability of adsorption resulting collisions between vapour molecules and in micro capillaries – to quick raise of the probability of adsorption resulting collisions between vapour molecules and active sites. So, in the capillaries p'_S becomes less as the number of layers Y increases and accordingly the size of active sites is increased. Accounting for this, the function p'_S must include moisture content in form of Y, as well as temperature. In this manner K must be a function of both: Y and T. This correction would allow to produce the highly wanted form of equation (10) with numerically determined parameters K, p'_S.

It is of importance to examine experimental data taking into account the two different mechanisms of sorption for moisture contents at concentrations below that needed to form a mono-layer (below the twist point on the curve) and then at higher water contents. In power engineering two well known approximations are used, namely, Piper's [15] and Fessler's [16], which are based on Freindlich's approximation, $W = A \cdot p^{\alpha}$, where A is a function of temperature, P is the vapour pressure, and α is a constant. This approximation cannot be valid above the part of the isotherm where a monolayer of water would be formed and it cannot be valid at very small pressure. Lampe [17] used Pipers curves to derive this form of mathematical expression. Lampe (Piper data) and Fessler did not exclude experimental data above the twist point of the isotherms using Freindlich's equation. They suggested the following expressions:

(Lampe/Piper): $$W = \left(p \cdot e^{-21.92+6850/T}\right)^{0.75} \qquad (11)$$

(Fessler): $$W = 2.173 \cdot 10^{-7} \cdot P^{0.6685} \cdot e^{4725.6/T} \qquad (12)$$

Where:

W, water content in %
p, water vapour pressure in mm Hg in (11) or abstract unit P in (12)
T, temperature in Kelvin

Both expressions will somewhat underestimate moisture content at lower concentrations and overestimate it at higher concentrations (Figure 4). This is because experimental data above the twist points (more rapidly increasing vapour pressure with increasing water content) was included in the calculations of the constants in (11) and (12). The form of equation (9) covers the experimental data much better. Equation (11) is of a similar form as (12) with somewhat different numerical constants. [59] gives an additional equation for moisture determination as a function of temperature.

It is apparent that one can utilize the empirical approximations (11) and (12) only to estimate the level of moisture content, but not for precise determination over a wide range of values. There is also a significant difference between sorption of water in air and in vacuum (Figure 12), the process being much faster in vacuum than in air. This is because some molecules, other than water molecules, are adsorbed on cellulose materials along with water molecules, which relaxes the field strength of active sites. So adsorption in air is always quantitatively less than in vacuum at equal temperatures.

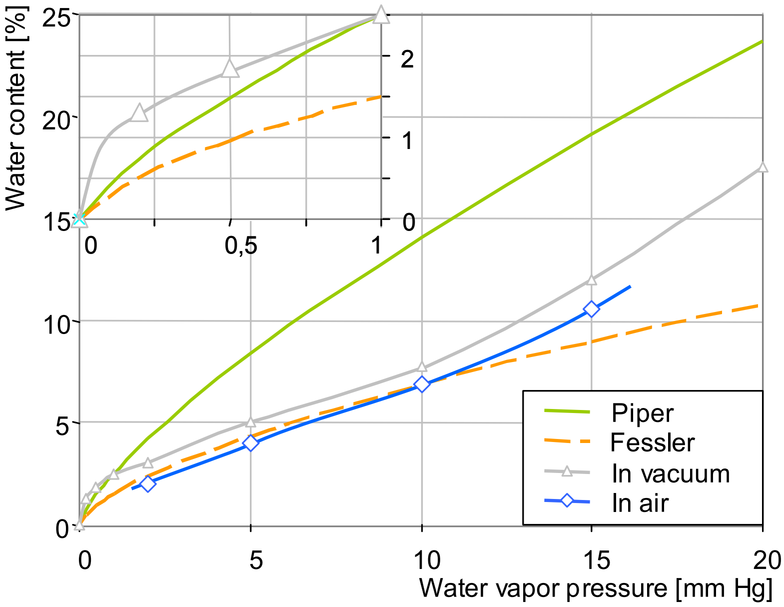

Figure 12: Water-Paper Isotherms (23°C) Experimental and Based on the Formulas of Piper and the Measurements of Fessler

5. MOISTURE DISTRIBUTION IN TRANSFORMERS

5.1 Moisture Distribution in the Solid Insulation

The transformer cellulosic insulation can be divided into three groups based on different moisture characteristics, which arise from dissimilar dimensions (especially thickness) and operating temperatures:

1. “Thick structures” are mostly supporting components and comprise about 50 % of the total cellulosic insulation mass. Although they contain a significant amount of moisture they provide a diminutive contribution to moisture migration to the total insulation system due to their large (a few years) time constants for the diffusion processes at normal operating temperatures. Diffusion of moisture through bulky components, which are thick with relatively small surface areas, occurs slowly over many temperature cycles.

2. "Thin cold structures" are those that operate at bulk oil temperatures: pressboard barriers, end caps, etc. These components comprise 20 – 30 % of the total mass of the cellulosic materials. However, they retain a large amount of the water which is available for migration over relatively short periods of time such as during diurnal temperature cycles. These structures should be considered the main storage area for water which is available for migration between oil and cellulosic materials in transformers. Water migration will occur to satisfy the natural equilibration process. The driving force for moisture migration is heat and differences in moisture potential. Moisture is driven from the warmer structures into the oil tending towards the maximum concentration of water in oil which would be reached at equilibrium. The colder structures will adsorb water from the oil with the maximum gain being that attainable at equilibrium. About 10 % (by mass) of the cellulosic insulation in this group which is at the coldest temperature, forms " wet" zones, where water contents can be 1 – 1.5 % (absolute water content) higher than the average value. Components of this group are the main source of high water in oil during temperature cycling.

3. "Thin hot structures" are those which operate at temperatures close to the conductor temperature (paper wrapped on conductors in turn-coil-layer insulation). About 5% of the mass of cellulosic materials operate at elevated temperatures at what is referred to as the hot-spot temperature. Moisture migration will be most rapid in this region because of the higher operating temperatures. However, the moisture content of the components in this group is markedly less than that in the thin cold structures and therefore the overall contribution to total moisture migrating in and out of the oil is small.

Figure 13 depicts the clamping plate and spacer blocks as thick structures, angle rings and cylinders as thin cold structures and the insulation paper as thin hot structures.

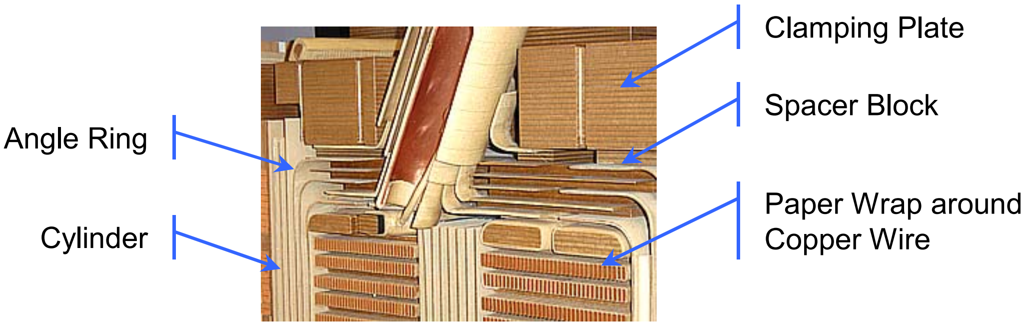

Figure 13: Main Insulation Components of a Core-Type Transformer

Examples of the proportion of mass and surface areas of cellulosic materials comprised of thick structures and thin cold structures are given in Table IV and Figure 14.

TABLE IV Mass and Surface Area of Insulation Structures

Rated Power and Voltage	Total Mass of Insulation	Total Open Surface Area	Thin Insul. Barriers Mass and Surface area		Thin Insul. Conductors Mass and Surface area		Thick Insul. Mass and Surface area	
Three Phase Transformer	kg	m^2	kg	m^2	kg	m^2	kg	m^2
25 MVA 110/35/10 kV	1,900	466	420	194	750	249	730	23
400 MVA 18/347 kV	10,121	1,237	2,260	730	3,500	468	4361	39
Single Phase								
167 MVA 500/220/35 kV	4,017	1,044	1,740	573	807	419	1470	52
417 MVA 750/500/15 kV	16,558	2,572	3,240	1,300	4,200	1,142	9,118	130

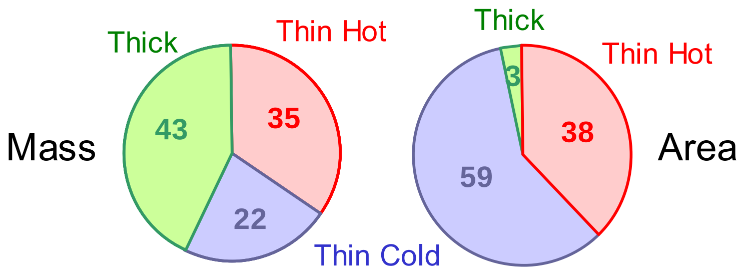

Figure 14: Insulation Structures Classified by Mass and Area for a 400 MVA GSU Transformer 18/347 kV

The oil generally retains a small portion of the total moisture in the transformer insulation system and effectively serves as a transfer medium. Fortuitously, oil retards moisture ingress from atmospheric sources to the cellulosic insulation. In some cases free water can be found spread on the bottom of a transformer tank, on the core, in the coolers, etc. This can result from suction of rainwater through poor sealing or from condensation of excessive moisture in the oil during a cooling cycle. Free water will very slowly move to the cellulosic insulation as it dissolves into the oil.

5.2 Moisture Distribution Based on Temperature Zones

If the ambient conditions and loading could be held constant, it would be possible for moisture to equilibrate within temperature zones. These hypothetical temperature zones might be divided as follows:

- Hottest-spot insulation
- Conductor wrapped insulation – top of transformer
- Conductor wrapped insulation – bottom of transformer

- Bulk insulation – top of transformer
- Bulk insulation – bottom of transformer

An example of the difference in moisture in the solid insulation possible for a transformer operating without pumps and fans (OA mode) can be estimated by establishing thermal zones and examining the equilibrium moisture contents of the cellulosic insulation assuming that the bulk water-in-oil content is uniform. In the OA mode, the temperature of the top oil is likely to be 10-20 °C higher than that of the bottom oil and so a difference of 15 °C is used in our example. The temperature of the conductor wrapped insulation at full load can be 10-20 °C higher than the bulk oil temperature and a value of 15 °C was selected. The hottest-spot insulation can be 5-10 °C higher than the average conductor wrapped insulation and for our purposes 8 °C was chosen. Two moisture contents were selected, 10 and 30 ppm, which represent values normally found in service aged transformers. Estimated water contents for the paper insulation, based on equilibrium values [19] using the top oil temperature, are 0.9 and 1.6 % respectively as shown in Table V. However, it can be seen that the range of temperatures and moisture-in-paper-contents is significant. It is in some ways fortunate that at the hottest temperatures the insulation is significantly drier. The propensity to generate water vapour bubbles and the rate of aging of cellulosic materials are decreased at reduced water contents.

Overall it can be seen that significant moisture gradients can develop along thermal profiles in regions of transformers.

TABLE V Moisture Distribution Caused by Insulation Temperatures

Location	Temperature in °C	Water in Oil 10 ppm	Water in Oil 30 ppm
Bottom oil non-conductor	60	1.4	2.4
Bottom oil wrapped conductor	75	0.9	1.6
Top oil non-conductor	75	0.9	1.6
Top oil wrapped conductor	90	0.5	1.0
Hottest spot	98	0.4	0.7

Temperature and Moisture Distribution in a Transformer Model

Figure 15 shows the impact of operating temperature on moisture content and degree of polymerisation for a winding model after 1200 days of thermal aging at 125 °C. Moisture content has a reciprocal distribution compared to temperature, since moisture absorption capacity of cellulose decreases with temperature. In this example, the conductor insulation is moister than the barrier but usually the opposite occurs. Because thermal energy has the major impact on paper degradation, the degree of polymerisation is lowest on top of the winding where temperature is the highest.

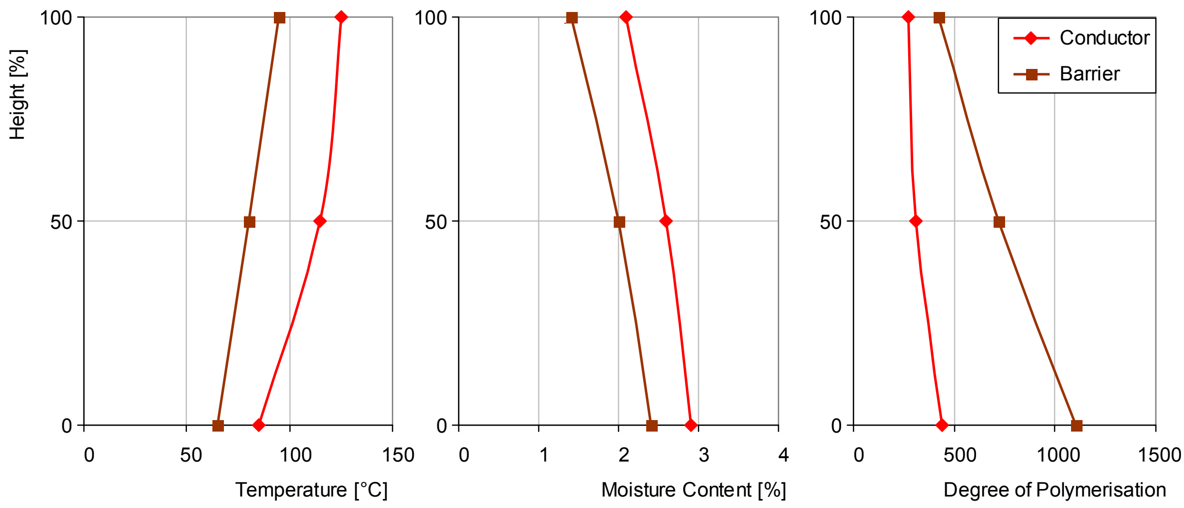

Figure 15: Distribution of Temperature, Moisture and Degree of Polymerisation in the Conductor and Barrier Insulation of a Winding Model [45]

6. MOISTURE EQUILIBRIUM

In the dynamic operation of a transformer the moisture distribution tends towards equilibrium and establishment of a steady state. The degree to which equilibration has progressed depends on temperature, geometry and moisture content of the insulation. In practice, the transformer can be viewed as several insulation systems at different temperatures and thickness which are tending towards equilibrium with the oil being the exchange medium between them.

6.1 Thermodynamic and Moisture Equilibrium

Moisture equilibrium bases on thermodynamic equilibrium, that is established by three conditions: thermal equilibrium (temperature), mechanical equilibrium (e.g. pressure) and chemical equilibrium. Thermodynamic equilibrium is reached, if the mentioned macroscopic observables do not change with time *and* place. At operating conditions of a transformer only an equilibrium regarding the time aspect is possible, the observables will not change with time but will change with place. Equilibrium for time *and* place can be reached only in locally limited areas, e.g. between cellulose and the adjacent oil at high temperatures and slow oil flows.

At equilibrium the migration of moisture molecules inside materials and between oil and cellulose goes to zero. Moisture migrates until the water vapour pressure p gains the same value, thus differences in the moisture vapour pressure are the driving force for moisture migration, (13).

$$p_{Cellulose} = p_{Oil} = p_{Air} \tag{13}$$

Supposed the same temperature and pressure rules, moisture exchange can be described in terms of relative saturation. The moisture content relative to saturation level in adjacent materials becomes equal (14).

$$RS_{Cellulose} = RS_{Oil} = RH_{Air} \tag{14}$$

Since relative saturation is numerically – but not physically – equivalent to relative humidity, moisture exchange can be expressed also in terms of water activity (15), [56].

$$a_{W,Cellulose} = a_{W,Oil} = a_{W,Air} \tag{15}$$

The different quantities used reflect the different descriptions in the literature.

Importance of Temperature for Moisture Equilibrium

Since the water solubility in oil and the adsorption capacity of cellulose materials are temperature dependent, a change of temperature results into moisture diffusion inside materials and between cellulose and oil. With increasing temperature the water solubility in oil increases (Figure 6) while the water adsorption capacity of cellulose decreases (Figure 11). Thus the equilibrium process (13) forces water molecules to migrate from cellulose to oil. At decreasing temperatures the cellulose materials again take up water molecules from the oil.

In transformer windings the axial and the horizontal temperature distribution generate a moisture distribution because of the temperature dependent moisture vapour pressure. This results in a low moisture content at high cellulose temperatures.

Moisture equilibrates faster between the outer layers of the insulation surface and neighbouring oil than in the total volume of thick materials. With decreasing temperature level the process focuses to layers with a reduced thickness range. Therefore the moisture of oil is in a first approach an image of the average cellulose surface and not of the total insulation material. On the other hand the moisture level in the bulky material will not vary during the daily load. Typically the quick temperature variations take place in the thin insulation materials. In this context the lack of total equilibrium is not of importance. In any case there are restrictions to gain equilibrium. The time constant to achieve an average moisture level in the bulky material is determined by equation (20).

6.2 Use and Misuse of Equilibrium Diagrams

Many operators of power transformers apply equilibrium diagrams to derive the moisture by weight (%) in cellulose from the moisture by weight in oil (ppm). This approach consists of three steps: (1) Sampling of oil under service conditions, (2) Measurement of water content by Karl Fischer Titration and (3) Deriving moisture content in paper via equilibrium diagrams (e.g. by Fabre-Pichon [49], Oommen [19], Du, Zahn [40]) from moisture in oil.

This procedure is affected by substantial errors:

1. Sampling, transportation to laboratory and moisture measurement via Karl Fischer Titration (p.41) cause unpredictable errors.
2. Equilibrium diagrams are only valid under equilibrium conditions (depending on temperature established after days/months).
3. A steep gradient in the low moisture region (dry insulations or low temperatures) complicates reading.
4. The user obtains scattered results using different equilibrium charts.
5. Temperature and therefore moisture distribution in transformer windings with gradients of up to 30 K are often not considered in the calculation.
6. Equilibrium depends on moisture adsorption capacity of solid insulation and oil.

The validity of equilibrium diagrams is restricted to the original materials that were used to prepare these diagrams. Especially aging changes the moisture absorption capacity substantially. The following Figure 16 displays the graphs for moisture equilibrium of new Kraft paper with new oil at 20, 40, 60 and 80°C. Additionally for 60 °C it shows moisture equilibrium for new pressboard in new oil and for aged Kraft paper and aged pressboard in aged oil. Assumed the moisture content in oil is 20 ppm these curves lead to a moisture content in new paper of 2.9 %, in new pressboard of 2.6 %, in aged paper and aged oil it is 2.1 % and for aged pressboard and aged oil 1.5 %. Thus equilibrium diagrams not adapted to the material and its aging state are inapplicable to calculate moisture in paper from moisture in oil.

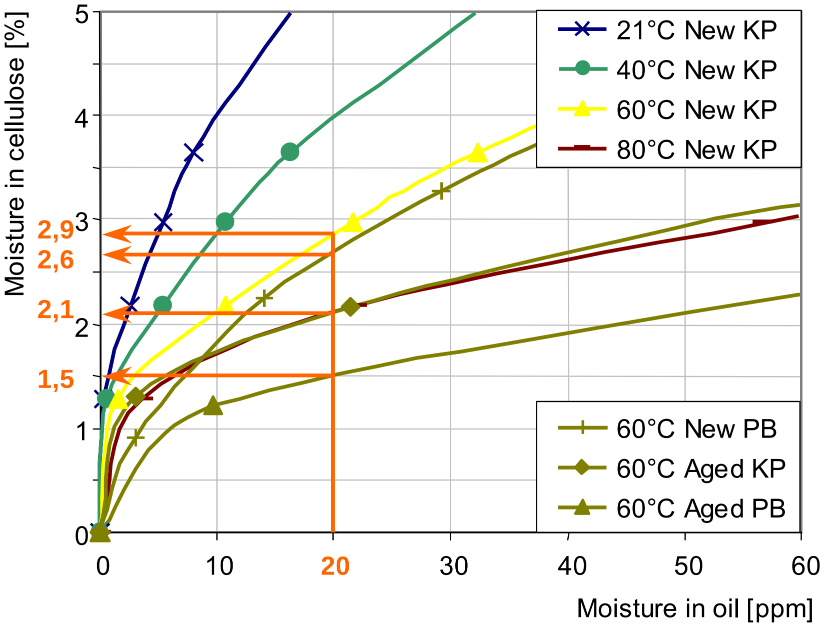

Figure 16: Equilibrium Diagram for Moisture in Kraft Paper KP and Oil with Additional Graphs for New Pressboard PB and Aged Kraft paper and Pressboard [41]

Aging byproducts such as alcohols, ketones, aldehydes and acids are polar by nature and thus *increase* the ability of oil to dissolve water molecules. These byproducts can attach water through hydrogen and Van Der Waals bonds. Aging of paper affects its moisture absorption capacity too, where various researchers came to different results. Anyway the oil is the most important factor.

Improved Moisture Equilibrium Diagrams

One step to improve equilibrium diagrams is to use the *relative saturation* in oil (%) or *water activity* instead of the moisture by weight (ppm). Furthermore the diagrams should be adapted to the moisture absorption capacity of cellulose [41]. This results in advantages:

- Oil aging and its influence on moisture saturation level becomes negligible, since it is already included into relative saturation.
- Moisture absorption capacity is less temperature dependent, see Figure 17.
- Using onsite measurements errors due to transportation to the lab and titration are excluded.
- Capacitive sensors measure the relative moisture in oil continuously and are easy to integrate into a monitoring system.

Obviously the dependability of this approach depends on the accuracy, response time and long term stability of the various commercially available probes.

Figure 17 shows the moisture by weight in new Kraft paper as a function of relative saturation [41]. Here it is sufficient to measure the relative saturation in oil onsite using a capacitive probe (p.42) and read the moisture by weight in cellulose at the specific oil temperature, e.g. 5 % RS at 40 °C lead to 2,5 % moisture by weight in paper.

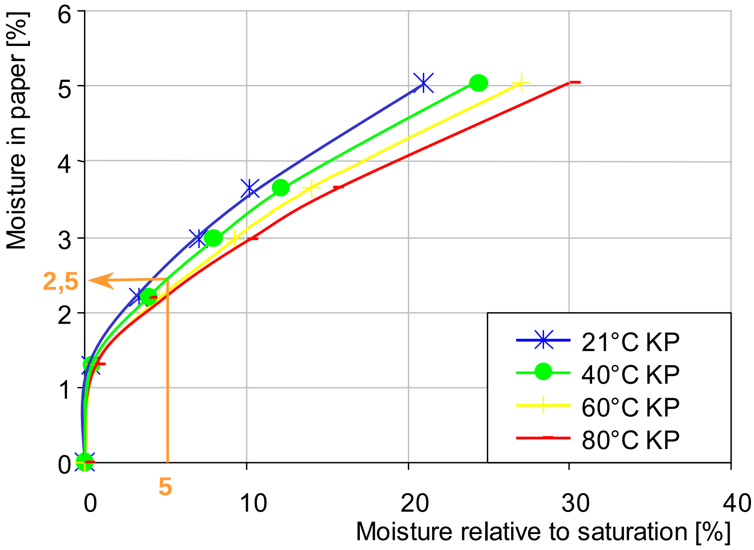

Figure 17: Moisture Sorption Isotherms for New Kraft Paper [41]

7. MOISTURE MIGRATION

7.1 Influence of Moisture Saturation and Temperature

In general, there are two causes of moisture transfer in oil-cellulose structures: the vapour vapour pressure gradient and the temperature gradient. A change of water vapour pressure or temperature diversifies the moisture transfer potential, inducing moisture movement. The diffusivity of a material expressed as a diffusion coefficient D may be presented using equation (9) as:

$$D = \frac{\lambda}{\rho\sqrt{T}} \cdot \frac{\partial P}{\partial W} \qquad (16)$$

Where:
λ - Material property
P – Pressure
ρ - Density
T - Temperature

Equation (16) is the basis for the mathematical description of the process of moisture diffusion in cellulosic insulations. Diffusivity is a function of temperature and moisture content. Unfortunately about diffusivity values we know only some experimental approximations [18], [23], [25]. For instance, S. Foss and L. Savio [25] suggested to use Howe's approximation which is

$$D = 10.64 \cdot 10^{-12} \cdot p_S \cdot e^{0.52W} m^2/h \qquad (17)$$

Where:
p_S - saturation vapour pressure, mm Hg,
W - moisture content in % in cellulose

7.2 Moisture Migration in the Main Insulation of Transformers

A primary function of the oil is to serve as a heat-transfer medium. When the oil temperature increases a temporary reduction in the relative water saturation occurs until moisture is driven from the conductor-wrapped insulation, which is heated first. This drives the moisture from the conductor-wrapped cellulosic insulation to the major or bulk insulation. As the bulk insulation heats up some of the collected surface moisture will begin to migrate to the oil. The moisture content in pressboard will develop a water vapour pressure distribution such that the highest value is at the surface where it is warmer. This is because the diffusion time constants for significant moisture movement to the inner bulk material is so long. When these bulk insulation surfaces in the cooler regions are warmed their relatively higher surface potentials will contribute significantly to the water content of the bulk oil. As ambient temperatures and loads change during the day, the temperature of the oil and solid insulation will vary forcing moisture to migrate to and from surfaces.

The diffusion of moisture in cellulosic materials can be roughly estimated by solving Fick's second law equation [7] using a temperature independent value for diffusivity (D). This should be used only for a chosen narrow interval of temperature and moisture contents. For example, a small water gain, ΔW_a with a material in a wet atmosphere may be calculated as follows:

$$\Delta W_a \approx (W_e - W_i) \cdot (1 - F_Z) \qquad (18)$$

Where:
W_e - water content in oil-impregnated paper in equilibrium with the wet atmosphere
W_i - initial water content of the paper
F_Z - sum of functions
Z - diffusion parameter:

$$Z = \frac{D \cdot t}{d^2} \qquad (19)$$

D - diffusion coefficient, sq. m/sec
d - insulation thickness, m

The diffusion function F_Z is a sum of exponential functions. However, if the average water content to be reached (W) is large enough ($W_e > W > 0.5\, W_e$) the expansion may be simplified to one exponent with a constant diffusion coefficient τ.

$$\tau = \frac{d^2}{\pi^2 \cdot D} \qquad (20)$$

This equation may be used for a rough estimation of the process, but it cannot be used for a continuous model as the time constants are too varied under different conditions.

When the process of desorption takes place (the initial water content is larger than the equilibrium water content: $W_i > W_e$) equation (21) can be used to estimate the amount of desorbed water ΔW_d:

$$\Delta W_d \approx (W_i - W_e)\cdot(1 - F_Z) \qquad (21)$$

The diffusion coefficient depends on the structure of the cellulose, temperature and water content. Equation (16) provides the general form for determining the diffusion coefficient. However, for practical applications, sometimes simplifications can be used.

Findings in [23] have shown that e.g. for estimation of water contamination of a dry oil-impregnated insulation directly exposed to air (installation and repair works) a diffusion coefficient D = 1 10^{-13} m^2 / sec may be used. Values of D approximately double for every 20 °C increase in temperature, so that D = $8\cdot10^{-13}$ m^2 / sec may be suggested at 80 °C. Correspondingly the time constant for thin piece of pressboard d = 1 mm at 80 °C (353 K) may be estimated as

$$\tau = \frac{1\cdot10^{-6}}{\pi^2\cdot8\cdot10^{-13}} \approx 1.46\ d \text{ or 11.6 d at 20 °C}$$

The diffusion coefficient given by Howe [25] gives similar trends but the absolute values are different. Assuming in the equation (17) W = 1 %,T = 353 K, thickness of the pressboard 1 mm, and

$$p = 760\cdot e^{14-\frac{5200}{T}} \approx 366 \text{ mm Hg}$$

We have D ≈ 1.819 10^{-12} m²/s; assuming d = 1 mm, we have

$$\tau = \frac{1\cdot10^{-6}}{1.819\cdot10^{-12}\cdot\pi^2} \approx 15{,}5h\,.$$

A study in [4] has shown that at 88 °C the time constant of water migration is about 5 hr.

On the other hand findings by [75] have shown that water exchange for rather short time (several hours) can be expected practically only between a thin surface layer of the pressboard and oil and at some elevated temperature. No water migration has been observed between wet oil (35-45 ppm of water) and dry insulation at the temperature range 20-40°C. The accuracy of the diffusion coefficients and the conditions of water migration needs to be verified.

7.3 Moisture Migration and Distribution in the Coils of the Winding Insulation

The water vapour pressure and temperature gradients coincide in direction in the conductor insulation. There is a temperature drop from the conductor through the tightly wrapped solid insulation to the oil coolant in a transformer under load. This results in a non-uniform distribution of water vapour pressure in the insulation, an initially uniform distribution supposed. Now migration of water molecules will begin from the inner to the outer layers until the water vapour pressure of all insulation layers becomes equal. This phenomenon will result in a non-uniform distribution of the absolute moisture content in the paper layers.

Using equation (9), it is possible to estimate the moisture distribution for a given temperature distribution, if the initial moisture content and temperature distributions are known given that equilibrium has been reached. Figure 18 shows such a non-uniform moisture distribution. It is notable that even at rather low average water contents the moisture distribution is quite non-uniform.

The thermal gradients and moisture distributions in the radial direction may be from the conductor to the outer wrap of insulation and from the oil to the center of the non-conductor wrapped insulation. The temperature gradient from high to low is in opposite directions for these two types of insulation as the conductor is the source of heat for wrapped insulation and the oil for non-conductor wrapped insulation. Where W is the local moisture content in the paper in %, x is the distance from the conductor, d is the insulation thickness and δT is the temperature differential.

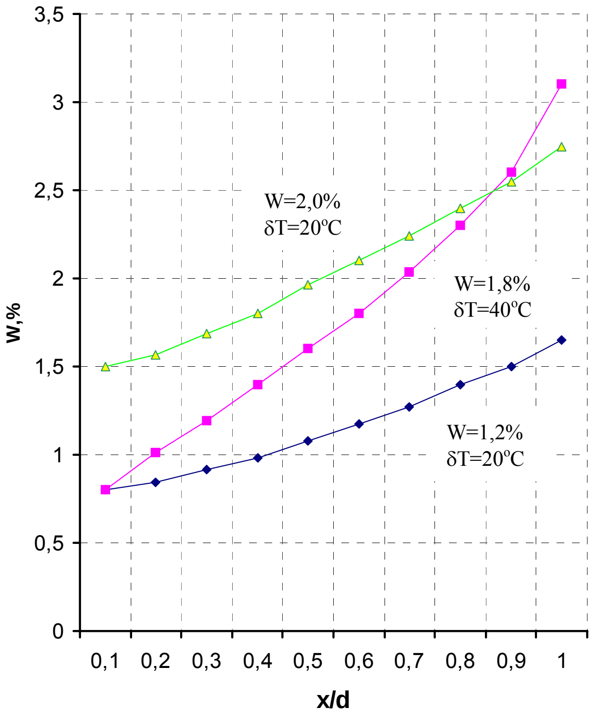

Figure 18: Effect of Temperature on Moisture Distribution in Turn Insulation

8. MECHANISM AND CRITERIA FOR BUBBLE EVOLUTION

A rise in temperature, especially at thick insulation layers, causes evaporation of adsorbed water with a high vapour and gas pressure within the inner layers of paper. This pressure may become so high as to press out the oil of the macrocapillaries of paper insulation. This phenomenon results in two dangerous effects:

- Formation of vapour-filled cavities (bubbles) on the insulation surface with subsequent decrease of the dielectric strength,
- De-impregnation of the turn insulation.

8.1 Conditions and Development of Bubbles

The exciting pressure is the internal moisture vapor pressure p_{in}, which must overcome the external pressure of the liquid p_{ext} and all hampering forces like interfacial surface tension and friction in the fibers p_σ. The condition that will force the oil out of these macropores can be described by:

$$p_{in} = p_{external} + p_\sigma \tag{22}$$

The bubble inception temperature depends on the following parameters:

- Amount of evapourable water in paper
- Microstructure of paper (diameter of capillaries and pores), depends on aging
- Gaseous residues in paper
- Surface tension of oil, depends on polar impurities (aging) and temperature
- Gradient of temperature rise
- Extrinsic pressure – the static pressure in the liquid
- Dissolved gases in oil [3]

At low water contents (below 1-2 % moisture by weight) the water molecules are strongly bound to active sites by hydrogen bonds forming a monolayer. With increasing water content weaker Van Der Waals and capillary forces attract the water molecules to polylayers (p. 4). This water may evaporate as bubbles.

Insulation paper consists of cellulose fibres forming micro capillaries which may contain gaseous remnants (micro bubbles) and water. A microscopic bubble generates a visible bubble. At increasing temperature gases and water diffuse into the micro bubble increasing its volume. Condition for a stable macroscopic bubble is an internal pressure p_i higher than the external pressure p_e and hampering forces, Figure 19. Therefore the temperature must rise with a steep gradient to evaporate the free water in the capillary. Only rapid evaporation detaches the bubble from the capillary because the volume of evaporated water is 1700 fold the volume of the liquid phase.

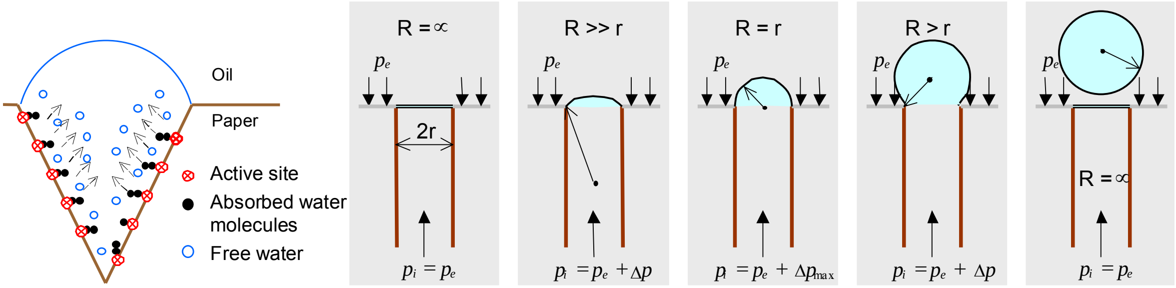

Figure 19: Bubble Evolution from a Macro Capillary, p_i = intrinsic moisture vapour pressure, p_e = extrinsic pressure, $\Delta p = 2\sigma / d$

It has also been demonstrated, that supersaturation with nitrogen, a common blanket gas, will stimulate bubble formation [3], [16], [27]. Carbon monoxide formed by the degradation of cellulosic insulation may also contribute to the total pressure required to generate bubbles.

Thus, the condition of bubble evolution depends not only on the temperature and water content, but also on the cellulose structure and quality of oil as well. The value for d is a function of material density. A study [26] has shown that the capillary interstice diameter can vary in the range of 0.01 to 7 µm. The interfacial tension σ is a function of temperature and polar impurities, typically oil aging byproducts.

8.2 Experimental Investigations on the Bubble Inception Temperature

The diagram to the left of Figure 20 shows the bubble inception temperature in new oil Shell Diala D with new Kraft paper, thermally upgraded paper and thermally degraded (aged) Kraft paper [42]. New Kraft paper has the lowest inception temperature. At thermally upgraded paper the bubble inception starts at higher temperatures because of its microstructure. The capillary force increases and bubbles will be driven out at higher temperatures.

Astonishingly also for thermally degraded Kraft paper the inception temperature increases. During thermal aging the active parts of the cellulose chains (OH-groups) become attracted to each other. The number, diameter and volume of pores diminish and the capillary forces increase.

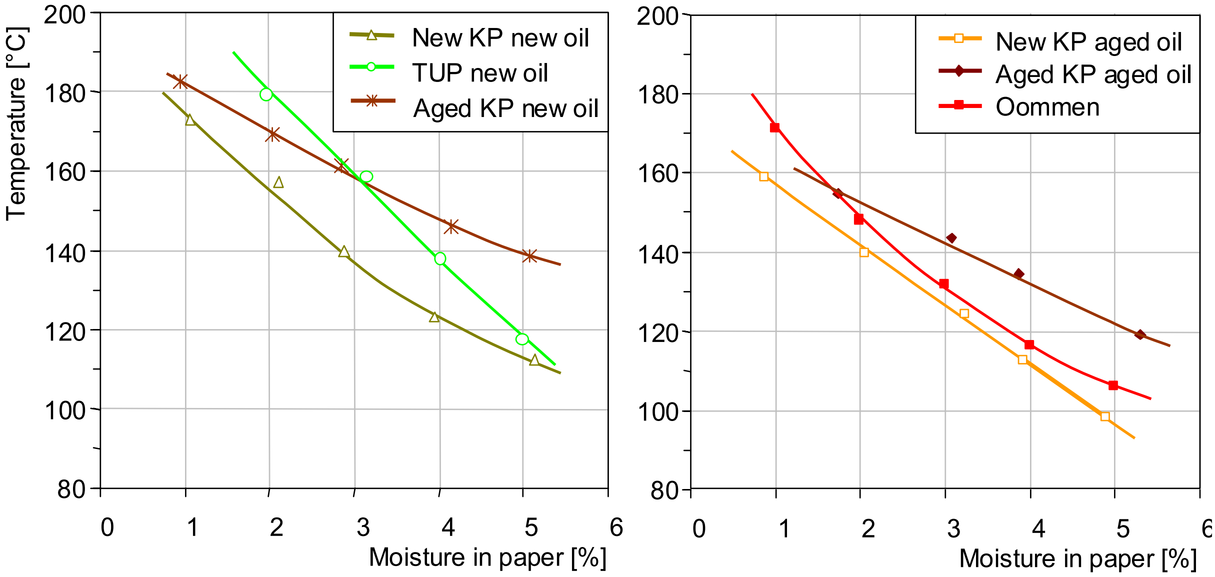

Figure 20: Inception Temperature for New Kraft Paper, Thermally Upgraded Paper and Thermally Degraded Kraft Paper in New Shell Diala D (left) and for New Kraft Paper in Service-Aged Oil, Thermally Degraded Kraft Paper in Service-Aged Oil and Data from Oommen [3] (right) [42]

Aging of oil is beside paper aging of vital importance for the inception temperature. Aging byproducts decrease the surface tension and therefore the bubble inception temperature. The diagram to the right of Figure 20 illustrates this effect for a service-aged transformer oil Shell Diala K 6 SX from 1965 with a total acid number of 0.5 mg KOH/g oil.

For a few thin layers of paper the water won't evaporate but diffuses into the oil. Here only an abrupt temperature rise enables the vapour bubbles to overcome the capillary pressure. Figure 21 shows this dependence for four layers of new Kraft paper having 4.3 % moisture in aged transformer oil as an extreme example to demonstrate the influence of the temperature rise [42]. A typical value for a fast temperature increase in a transformer windings is 2 K/min, under some conditions 8 K/min.

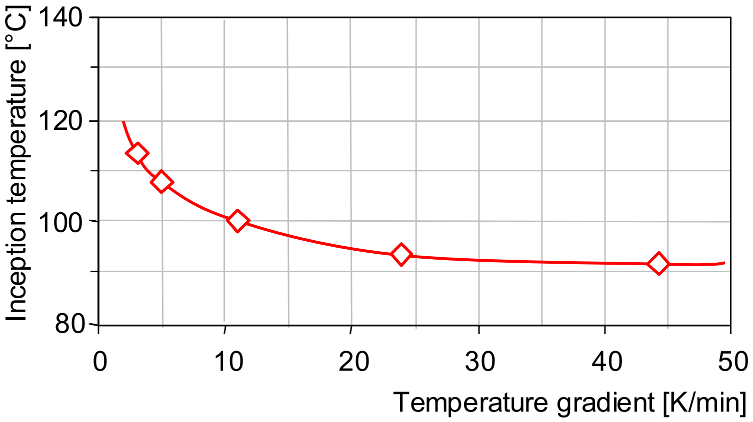

Figure 21: Inception Temperature as a Function of Temperature Rise

8.3 Risk of a Dielectric Breakdown due to the Bubble-Effect

A list of preconditions restrains a possible dielectric breakdown due to emitted water vapour bubbles:

- Moisture content in paper must be high. Just the “Hot Spot” of a winding which has sharp temperature gradients and high operating temperatures is rather dry. Furthermore this area has less gaseous remnants compared to other insulation structures.
- A sharp temperature rise accelerates bubble evolution (Figure 21). This applies for interleaving windings, tap windings with radial ducts, tap leads and HV layer type windings.
- A partial discharge or a dielectric breakdown is limited to areas with a high field strength. The insulation design determines if bubbles enter into a critical area.
- Large bubbles might be torn by the electric field.

IEC 60 354 “Loading Guide for oil immersed transformers” concedes a hot spot temperature of 120-160 °C for a short term overload of ONAN cooled transformers. In this case the operator has to reckon on bubble evolution, assumed a moisture content in paper above 1.5 % by weight and a sharp temperature rise. Transformers which were out of service for a long time behave even more critical since the hot spot is moistened due to moisture migration.

As a conclusion, the risk of a dielectric breakdown due to bubble evolution is considered to be low.

9. DANGEROUS EFFECTS OF WATER: EXPERIMENTS AND EXPERIENCES

Breakdown of Oil Gaps in HV Transformers

Studies on electrical models of oil-paper-insulation-systems [28], [68], [69], [70] have shown that the dielectric safety margin of both the major and minor insulation contaminated with water is still determined by the dielectric withstand strength of the oil. The dangerous effects of dissolved water occur as its relative saturation in oil increases, which also increases the conductivity of particles that adsorb water, both of which reduce the dielectric strength of the oil [23]. Additionally the formation of emulsions in the vicinity of surface-active substances may further reduce the dielectric breakdown voltage of the insulation.

Experience has shown that positive results of HV tests and common insulation conditions are not a guarantee for a reliable service of insulations unless the level of oil particle contamination is considered and the insulation construction is protected from direct effect of particles. Major factors that cannot be stimulated during the HV tests are oil stirring, temperature variation and a long time duration. The following failure modes were repeatable experienced on normal insulation condition:

- Breakdown of large oil gaps between bushing shield and turret,
- Breakdown between windings in a place, which is not reliably divided by barriers,
- Breakdown between bare bas-bars (not wrapped with paper), particularly in location of input oil flow from the cooler.

A high relative saturation of moisture in oil combined with particles and a high acidity of oil essentially decreases the breakdown strength. It is worth to emphasize that the breakdown voltage of oil depends on its relative saturation (%) but not on absolute water content (ppm). Reasons of this phenomenon are that available water as reflected by a high relative saturation increases the particle conductivity and enables acids to dissociate which results in initial charge carriers.

Up to a relative saturation of 15 % the influence on breakdown voltage is insignificant. A further increase in moisture saturation reduces the dielectric properties of the oil. A RS of 70-80 % means nearly a full lost of the dielectric strength. The fewer particles are available, the weaker the effect of water on the dielectric strength of mineral oil, see Figure 22.

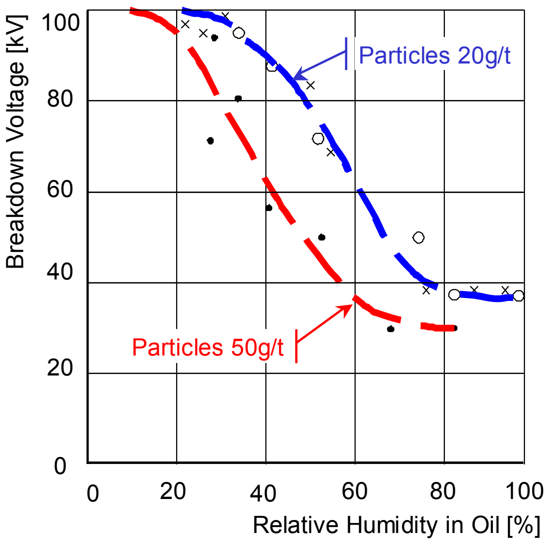

Figure 22: Impact of Particles and Relative Saturation on Breakdown Voltage in Oil [46]

Studies in [46] have shown that just stressed oil ducts in a coil type windings are mostly susceptible to moisture contamination. Presence of moisture within oil ducts can reduce the dielectric strength 3 folds (Figure 23 curve 1A and 1C) down to the level of the operation voltage between the coils of HV and tap windings. On the other hand wet conductor paper reduces the withstand strength only by 20% (curve 3 and 2).

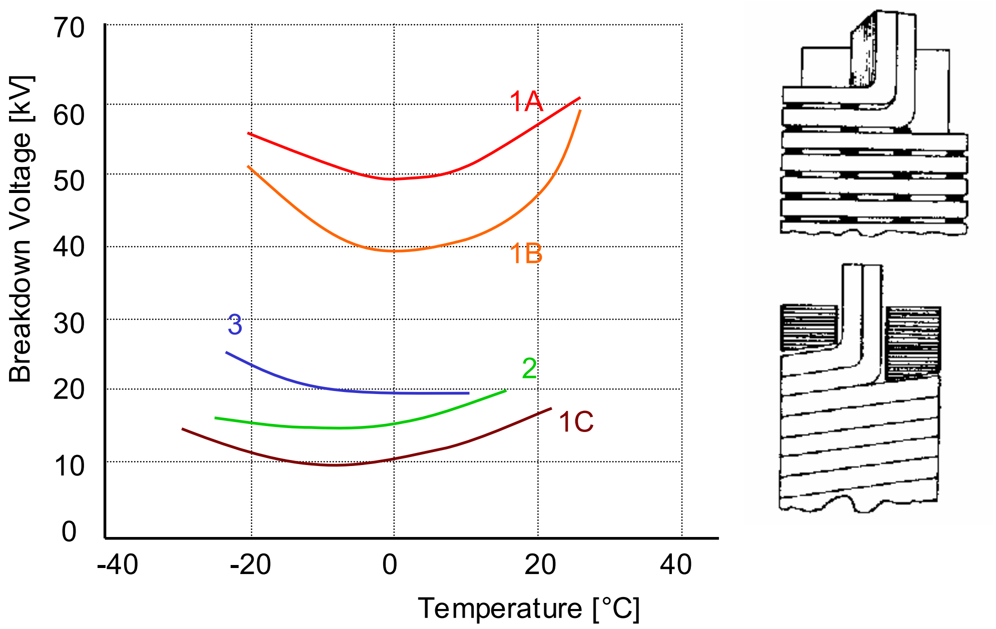

Figure 23: Impact of Moisture on Dielectric Withstand Strength of a Winding Insulation
1 Disc winding with radial cooling duct (sensitive construction)
1A - Dry insulation and oil;
1B - Wet (not dried) insulation (strength reduction by 20%);
1C - high moisture in oil and on surface (strength reduction by 5 times)
2 Disc winding without paper insulation, high moisture in oil
3 Helical type winding without cooling ducts, high moisture in oil and on surface.

Operation at Cold Temperatures

Dissolved water (high relative saturation) is a problem of a “cold” transformer as the solubility of water in oil decreases exponentially with decreasing temperature and the diffusion of moisture into the solid insulation is retarded. A number of failures have happened after energizing wet transformers in winter time [28]. Condensation of free water in transformers can occur and if deposited in the solid insulation lead to discharge activity and failure.

The formation of free (liquid) water in oil is most likely to occur under very cold conditions where it may become frozen. In spite of the fact that the oil density is generally specified to be less than the density of ice, forced or even convective oil flow can be strong enough to move ice into a critical zone. This phenomenon has been observed as a cause of the breakdown of load tap changer insulation [23]. Moreover, a drop of water in viscous oil may work as a particle generator, with the water being exploded under the effect of an electrical field. Unusual reductions of the dielectric withstand strength to 0.2-0.4 kV/mm has been observed under conditions of presence of the drops of water in oil of high viscosity at negative temperature.

Other moisture problems that have been discussed include ingress of free water and bubble evolution. For example a sudden failure of a 400 MVA, 220 kV transformer was due to breakdown of the oil space between the bushing and the tank. This occurred after the transformer quickly cooled because of rainfall, creating a partial vacuum inside, which sucked in about 500 g of water through a broken seal in the draw-lead bushing.

Formation of Water Drops during Overload

In [57] and [58] a new dangerous phenomenon has been described: during overload tests on a test model, water drops were released from winding paper after bubble evolution. The water drops were observed in the oil at hot spot temperatures 5-10 K higher than that for bubble inception.

Rapid Cooling of a Transformer Insulation

Rapid cooling of a wet transformer after high loading may result in supersaturation of oil in the cooler and formation of free water in the form of micro-droplets suspended in oil ("foggy oil") [58]. The foggy oil affects the transformer insulation next to the cooler outlet.

Under the same conditions, when cool oil from the conservator enters the main tank containing wet oil, the incoming oil may become instantly oversaturated at this very location. The reason for the local supersaturation is a mixture of cool oil featuring a low solubility limit with wet oil. This results in formation of water drops at the conservator inlet. The water drops float downwards and present a real hazard to the transformer. This phenomenon was observed in the experiments described in [58].

Cooling down without pumps could increase the risk of oversaturation of oil – the oil should flow along the insulation to transfer moisture into the solid insulation. On the other hand the moisture absorption of cellulose is reduced by the slow migration velocity. In any case the transition to very low temperature makes a risky situation. Relative moisture sensors will help to indicate this situation.

Practical Evidence of the Bubble Effect

Bubble evolution occurs when transformers are overloaded. Some failures have been attributed to discharges that occurred when bubbles were formed or when they traveled through high stress areas. Maintaining transformers in the dry state permits operation at higher temperatures without risk of the evolution of water vapour bubbles.

Classification Based on Relative Saturation

Based on the potential for transformer insulation systems to develop high relative saturation of water in oil under operating conditions, a classification scheme can be derived. Classes of water contamination are used to predict the potential for the formation of excessive moisture in the oil from temperature cycling with the consequent reduction of the dielectric withstand strength of the oil.

The following classification has been devised and found satisfactory by experience. The classification is based on performing an analysis on transformers by raising the operating temperature from close to ambient to a 60-70 °C operating temperature for several days.

CLASS I: **"good"** – dry transformer, water content in the insulation is 0.5 to 1.0 % or less on average. There is little change in water content of the oil with temperature (it remains typically below 15 ppm). The relative saturation of the oil is typically about 5 % or less at a constant operating temperature of 60 – 70 °C. With increasing operating temperature of a transformer, initially the relative saturation of water in oil decreases exponentially.

CLASS II: "fair" – under normal operating conditions the relative saturation of water in oil remains below 50 % even at the lowest operating temperatures. The characteristics of this condition are maximum water contents in the solid insulation of 1 to 2 %. There is a slight (typically less than two times the initial value) rise of water content in the oil after increasing and maintaining the temperature test. The relative saturation of water in oil is expected to be about 5 % at 60-70 °C, but less than 8 %.

CLASS III: **“probably wet”** – under normal operating conditions the relative saturation of water in oil may exceed 50 % at the lowest operating temperatures.

CLASS IV: **“wet”** – under normal operating conditions an emulsion of water in oil can form as the relative saturation exceeds 100 %.

10. CONCLUSIONS

Excessive moisture in transformers continues to be a problem today. Empirical evidence has revealed some of the problems and moisture distribution within the insulation structures of service-aged transformers. The solid insulation (paper, pressboard and wooden construction elements) attracts the bulk of water. Oil serves as a transfer medium only. However its ability to dissolve water increases especially with aging.

A mathematical description for moisture ingress, adsorption and partitioning has been given. Moisture diffusion tries to establish equilibrium in the way, that water vapour pressure is the same at every location in the system. Differences in the water vapour pressure are the driving force of diffusion processes.

The conventional application of equilibrium diagrams to derive moisture in cellulose (%) from moisture in oil (ppm) is effected by substantial errors. To exclude the interference due to oil aging the moisture in oil relative to saturation level (%) is more appropriated instead of moisture in oil in ppm. Before onsite sampling the operating temperature is recommended to be held constant (above 50°C) for several hours.

Bubble evolution in a wet oil-paper-insulation depends beside temperature and moisture distribution on the properties of oil and paper, e.g. influenced by aging. The probability to form water vapour bubbles at a given temperature can be determined if the moisture content of the cellulosic insulation is known or can be estimated. Standard operation temperatures induce a very low risk for bubble evolution only.

11. APPENDIX: METHODS FOR MOISTURE DETERMINATION IN TRANSFORMER INSULATIONS

11.1 Karl Fischer Titration Method

Titration basically means to add a reagent of known concentration (titre) to a unknown substance until the concentrations are balanced. As shown in equation (23) below, the Karl Fischer method uses a reagent, which reacts quantitatively and selectively with water, to measure moisture content. The Karl Fischer reagent consists of iodine, sulfur dioxide, a base and a solvent such as alcohol.

$$I_2 + SO_2 + 3Base + ROH + H_2O \rightarrow 2Base + HI + Base + H_2SO_4 \qquad (23)$$

This method can be used in both volumetric and coulometric titration systems.

Volumetric Titration

At first a dehydrating solvent suitable for the sample is placed in a flask. A titrant is used to remove all moisture from the solvent. Then the sample is added. Titration is carried out using a titrant, which titre (mg H_20 / ml) has been determined. A stoichiometric equation will calculate the moisture content of the sample from the titration volume (ml). The end point is detected using an electro-chemical measurement method. Figure 24 shows the components of a typical commercially available automatic volumetric titration system. The sensitivity of volumetric titration is limited to some 10 μg of water so that it is not applicable for dry insulation oils used in power transformers.

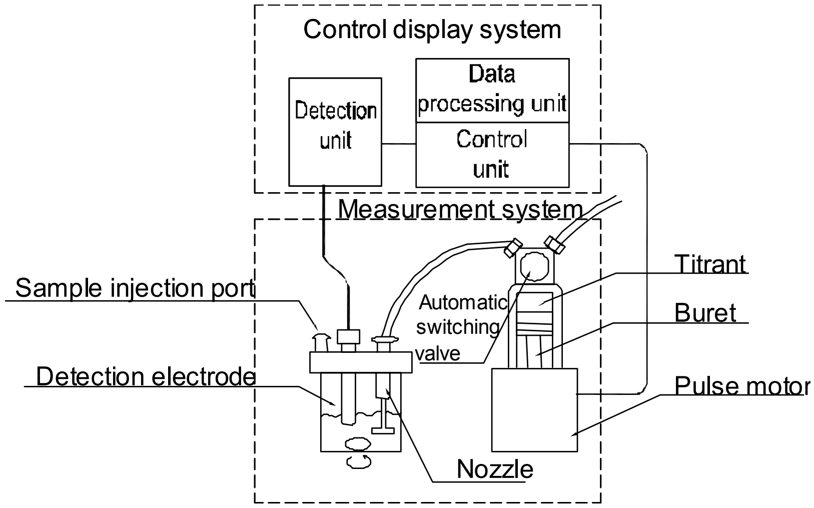

Figure 24: Volumetric Moisture Meter

Coulometric Titration

At coulometric titration the sample is added to an electrolytic solution. Its main constituents are iodine ions, sulfur dioxide, a base, and a solvent, e.g. alcohol. Generator electrodes produce iodine by electrolytic oxidation, resulting in an immediate Karl Fischer reaction. The iodine is produced in proportion to the electrical charge. According to Faraday's law of electrolysis the water content can be determined direct from the charge required for the electrolytic oxidation.

1 mg of water = 10.71 C

Advantages are, that the reagents don’t need assessment, they can be used repeatedly until their reaction capacity is consumed and the low detection limit of some µg of water.

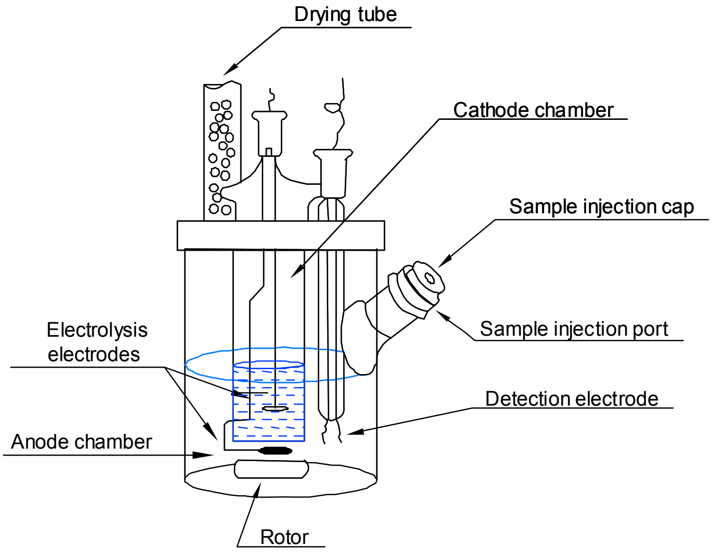

Figure 25: Electrolysis Cell and Heating Chamber for a Coulometric Karl Fischer Titrator

Figure 25 displays the major component parts of a coulometric Karl Fischer titration instrument. Water from the sample could be brought into the reaction vessel by three methods:

Firstly it is possible to inject the material directly into the reaction vessel, e.g. oil through a syringe. This method pollutes the reagent and side reactions of aging products or inhibitors with the reagent are possible. E.g. it is known, that aldehydes and ketones react with the methanol of the reagent to acetales and ketales causing water as a byproduct.

Secondly the water can be dissolved in another medium, e.g. methanol. This is applicable for cellulose samples. The sample will be immersed into methanol to extract the water from the cellulose. Then the methanol-water-solution will be injected into the reaction vessel.

Thirdly the sample (paper, pressboard or oil) can be heated in an external oven and a gas stream with water vapour is lead into the reaction vessel. Advantageously the reaction vessel remains clean of pollutions and aging byproducts, depending on their boiling point. A drawback of this method is the blank value of the gas stream and the heating vessel. It decreases the sensitivity compared to the direct injection method. Obviously the evapourated water depends on the heating temperature of the samples. According to IEC 60814 it should be 130-140 °C. In contrast to this only temperatures of more than 180 °C for pressboard samples lead to results comparable to the methanol extraction method [32].

Accuracy of Karl Fischer Titration

Although KFT is counted as a reliable measurement method, it is effected by the following influences:

- There is always a moisture ingress from the atmosphere during sample preparation and transportation to the laboratory, especially if the samples were taken onsite. Therefore all results have a deviation to higher moisture contents.

- For the heating method the blank value prevents moisture measurements in dry oils (below 10 ppm). Furthermore direct injection and heating method lead to different results for moisture in oil. This might be due to
- the influence of oil additives and aging byproducts such as aldehydes and ketones.
- Water molecules are bound with bonds of different strengths. In Cellulose these are hydrogen and Van Der Waals bounds. In mineral oil containing active contaminants the water molecules may be bound in hydrates by Van Der Waals bounds. The dissolved water reacts readily but the bound water must first become dissolved by thermal energy or stronger chemical bonds. It is however unsure, if all the water is released. Thus heating temperature and reaction time strictly changes the released amount of water.
- Oil laboratories commonly use different proceedings to determine moisture in oil and paper particularly for conditions not covered by standards. Round robin tests of various laboratories revealed essentially different measurement results of moisture in oil and also moisture in cellulose [33].

11.2 Capacitive Probes

Capacitive probes indicate moisture relative to saturation RS. They consist of two electrodes with a hydroscopic dielectric, e.g. polymer, see Figure 26. Water molecules penetrate into the polymer depending on the water activity (relative saturation) of the ambient material. Water penetration *c* then changes the capacity *C* because of the high relative permittivity of water $\varepsilon_r = 80$, see Figure 26. A RC-oscillator measures the change of capacity by a change of frequency, this variance is calibrated to relative saturation.

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d} \quad \text{and} \quad \varepsilon_r = \varepsilon_i + \varepsilon_w \cdot c \qquad (24)$$

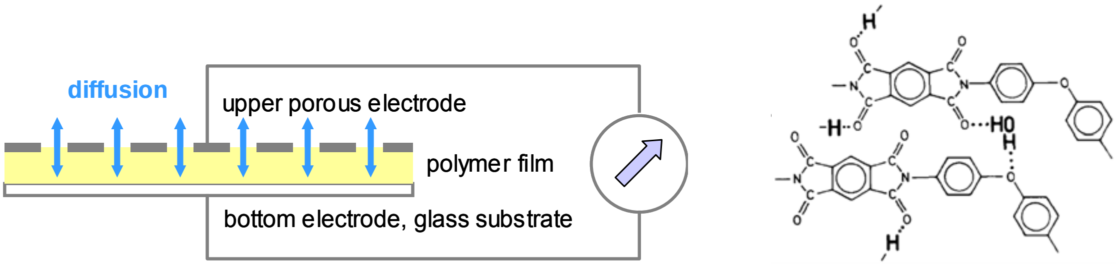

Figure 26: Schematic Drawing of a Polymer Thin Film Probe (left) and Water in the Dielectric Attached to Polyimide Molecules by Hydrogen Bonds (right)

Advantages of capacitive probes are a very easy application even onsite and online, continuous measurements and a high accuracy compared to sampling and transportation to laboratory with subsequent Karl Fischer Titration.

Accuracy of Capacitive Probes

A comprehensive compensation for temperature effects and nonlinearities is necessary, especially for the low humidity range. Beyond this other molecules than water may likewise diffuse into the polymer and thus change the capacity, leading to a measurement error. This influence is considered to be small, since e.g. aging byproducts have a low permittivity compared to water.

Strong acids may corrode the electrodes and thus change the capacity of the arrangement. Therefore a cyclic calibration of capacitive probes is required. Saturated salt solutions provide a well defined relative humidity in the gaseous phase above them ("Greenspan table"). Observing temperature, gas circulation and sufficient time the probe is calibrated in such a head space.

Commercially available sensors differ by their long time stability under stress and the time to achieve a stable measurement value.

Application of Capacitive Probes for Online Monitoring

One advantage of capacitive probes is the ease of application for online monitoring. Although the water content in a transformer is not expected to vary rapidly, the continuous measurement of moisture in oil allows to a large extent resolving the problem of continuous temperature variations in transformers [54].

As mentioned in section 6.2, the equilibrium curves allowing conversion of moisture in oil to moisture in paper are applicable only under stable temperature conditions. In practice most transformers experience daily ambient load and temperature variations. In such conditions, a single sampling of oil may lead to erroneous evaluations of moisture content in solid insulation. With continuous monitoring it is possible to account for diffusion time and to improve significantly the moisture content calculation.

From the relative saturation RS recorded at the sensor, it is possible to calculate the relative saturation of oil in contact with the winding if the winding temperature is known. Equilibrium curves as depicted in Figure 17 can then be used to provide a value for the ultimate moisture content in cellulose that would apply if thermal stability condition would prevail. With continuous monitoring it is possible to apply an averaging function that reflects the adsorption and desorption time delay.

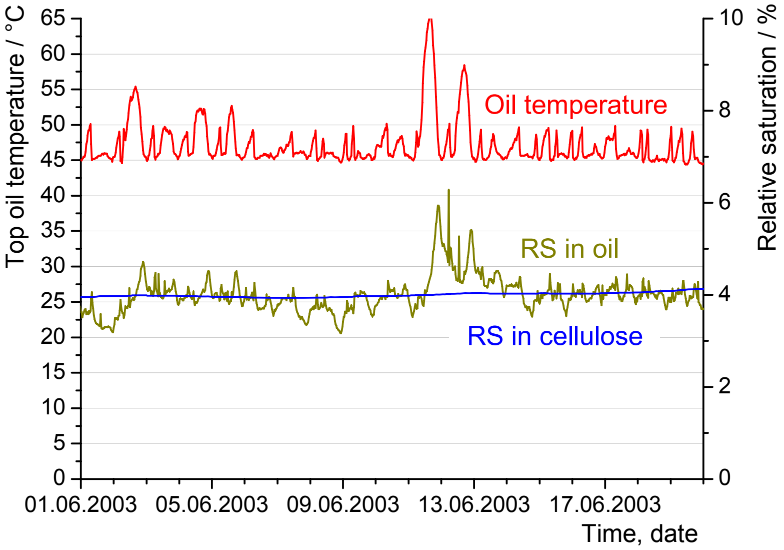

Figure 27: Top Oil Temperature, Relative Saturation in Oil and in Cellulose Measured resp. Calculated by an Online Monitoring System [53]

Figure 27 illustrates the application of water measurements using capacitive probes in a power transformer equipped with an online monitoring system. The load factor influences the top oil temperature, which follows in diffusion processes varying the relative saturation in oil. A long term average equilibrates the relative saturation in oil with the relative saturation in cellulose and comes to $C_{w,rel}$ = 4,1 %. Using an equilibrium diagram (Figure

17) one can derive the moisture by weight in cellulose too, here 2,4 % moisture relative to weight. Obviously this result applies for the cellulose and oil, that are at the same temperature. The obtained results gain in reliability, if the probe is inserted into the hot oil flow before the cooler or as close as possible to the winding.

Since the capacitive probe provide a measurement of the relative saturation RS, the type of oil and the oil condition does not interfere in the calculation. Further development is needed to refine the diffusion and absorption time constant in regard to insulation geometry, temperature and type of insulation.

11.3 Chilled Mirror Dew Point Instruments

These instruments measure the dew point of water vapour in gases. Firstly the sample is equilibrated within the headspace of a sealed chamber. At equilibrium, the relative humidity of the gas in the chamber is the same as the relative saturation of the sample. A thermoelectric cooler chills the mirror until condensation appears, detected by an optical reflectance sensor. A thermocouple attached to the mirror measures the dew-point temperature. The relative saturation of the sample can be calculated from the sample temperature and the dew point temperature.

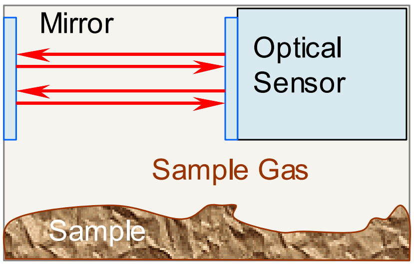

Figure 28: Chilled Mirror Dew Point Instrument

Advantages are, that it provides one of the few truly direct physical measurements of humidity and the accuracy is high (below 1 % of RS). Calibration is not necessary since the measurement is based on temperature determination, but measuring a standard salt solution checks proper functioning of the instrument. Disadvantages consist in the need for an ultra clean mirror that forbid evapourating media, in a slight temperature shift by the transition from the vapour phase to a liquid and in a very long time to achieve a stable reading, depending on the instruments setup.

11.4 Dielectric Response Methods

Dielectric response methods promise to determine the moisture content in the solid insulation of power transformers without opening the transformer or taking an oil sample. Problems with oil sampling, transportation, Karl Fischer Titration and moisture equilibrium become negligible. They can be applied onsite after disconnecting the transformer.

Dielectric response methods measure a superposition of conductivity and polarization phenomena. Moisture in paper/pressboard is obtained by a comparison of measurement data to measurements on oil-paper-insulations with known moisture content [38].

Macroscopic polarization

The main insulation of power transformers consists of multiple layers of paper or pressboard (cellulose) immersed in oil separated by oil ducts. The time depending polarization is caused by electronic, ionic, dipole, space charge and interfacial polarization and is called dielectric response. At measurement times longer than 1 s the polarization by space charge and at boundaries (interfacial polarization) dominate the dielectric response. Interfacial polarization is effective because of the different conductivities of oil ($10^{-13} < \delta < 10^{-10}$ S/m) compared to pressboard/paper ($10^{-16} < \delta < 10^{-13}$ S/m). Thus under an electric field ionic charge carriers in oil will become deposit at interfaces to cellulose and form a charged cloud. The dielectric properties of oil and cellulose and its polarization phenomena depend on aging state and water content. Sophisticated analysis methods can determine the water content of cellulose (paper / pressboard).

Conductivity

Polarisation processes are superimposed by the materials conductivity. It represents the movement of free charge carriers in cellulose and oil. Water and aging products both change conductivity thus it is hard to discriminate between the two effects. However, recent studies suggest, that the effect of water will dominate over conduction effects from aging byproducts like carbonic acids [71].

Polarization and Depolarisation Currents PDC

A DC current measurement will record the charging and discharging currents of an insulation. They are also known as Polarization and Depolarisation Currents (PDC) [34]. Relaxation measurement results are usually presented in a log/log scale with charging and discharging current over time as depicted in Figure 29. According to the common interpretation scheme the first 1-100 seconds are influenced by oil conductivity. The end value of polarization current is determined by the pressboard resistance and therefore by moisture.

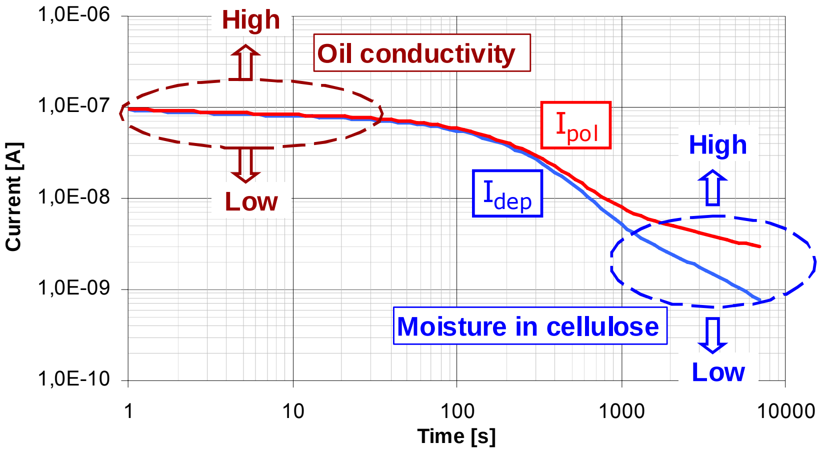

Figure 29: Interpretation of PDC Measurement Data

Frequency Domain Spectroscopy FDS

AC voltage and current measurements could be led back to the old known Tangent Delta measurements. However the frequency range is much enhanced especially to low frequencies (e.g. 0.1 mHz). The derived measurement method is called Frequency Domain Spectroscopy FDS [36]. It is possible to discriminate between the influence of oil conductivity (range from 100-0.1 Hz in figure Figure 30) and the influence of moisture content (above 100 and particularly below 0.1 Hz).

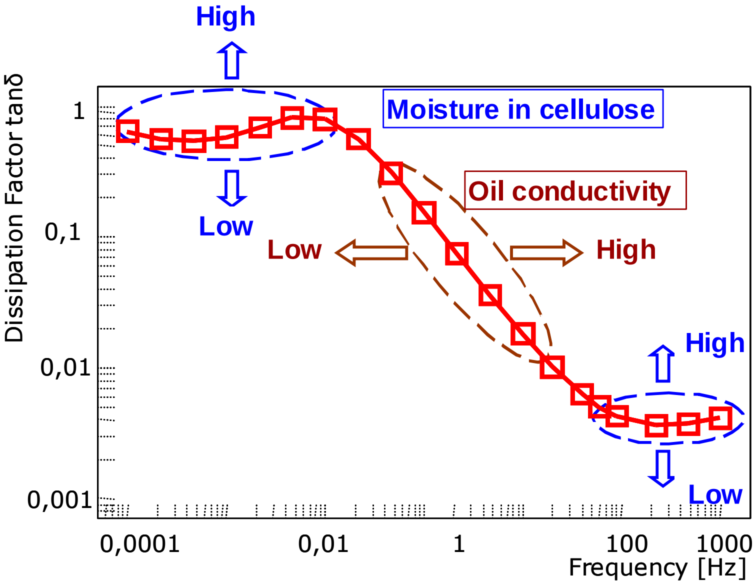

Figure 30: Common Interpretation Scheme for FDS Measurement Data

Reliability of Dielectric Response Methods

Dielectric diagnostic methods as PDC and FDS were rapidly developed during the last years and nowadays provide credible results. Nevertheless they are subject to the following influences:

- Insulation temperature strongly changes the calculated moisture content. The thermometer mounted in the transformer tank displays the oil temperature, not that of the insulation.
- Aging byproducts dissolved in oil and deposited in pressboard and paper increase the conductivity of the whole insulation and therefore pretend the role of water. Aged transformers may appear moister as they really are.
- In some cases an unusual insulation geometry decreases the accuracy of the calculated moisture content.
- The dielectric response is dominated by the barriers and spacers of the oil duct as “cold thin structures”. Thus dielectric response methods indicate the moisture content of the main insulation, not of the insulation paper wrapped around the conductors as “hot thin structures”.

As a matter of principle all measurement methods reflect the same physical phenomena, provided the measurements were done correctly. The point constitutes in the interpretation of the measurement data. Discussions about the reliability of the moisture results calculated by the RV-method [36] induced closer investigations by CIGRÉ TF 15.01.09 and other research groups [38], [39]. The conclusion was: “For the RVM technique, the old interpretation based only on simple relationship between the dominant time constant of the polarization spectrum and the water content in cellulose is not correct.” [38].

The achievable accuracy of the PDC and FDS method in most of the cases comes to better than ± 0.5 % of moisture by weight in the solid insulation [47]. Due to the cost it will probably only be relevant in special cases.

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