

Drying of Transformer Insulation using Zeolite

Key Words: Power transformers, in-service drying procedure, lifetime extension.

Power and distribution transformers are some of the most important components in the power network. Compared to other equipment, they require very little maintenance since they have no continuously moving parts. However, the insulating and other materials in a transformer degrade with time in service. Many of the degradation products are soluble in the insulating liquid and their occurrence is reflected in, for example, the interfacial tension, acid number, and water content of the insulating liquid in a transformer as it ages. During the normal breathing process due to the oil expansion and contraction of a free-breathing transformer, moisture can enter the transformer insulation. Especially in the case of a rapid cooling, during which time the incoming air cannot be sufficiently dried, moisture can contaminate the insulating liquid and thus the solid insulating materials immersed therein.

Excessive adsorption of moisture will saturate the insulation and increase its conductivity. Also, at high temperature, vapor may develop, which may be potential source for partial discharges (PD) and increase the feasibility of breakdown. Water increases electric conductivity and dissipation factor, and worsens electric strength. Moisture also has a great influence on the life expectancy and load capacity of a transformer. Water is not only detrimental to the dielectric properties of the liquid paper insulation system, it also decreases its resistance to aging [1]-[8]. The presence of moisture in a transformer deteriorates the transformer insulation by decreasing both the electrical and mechanical strength of the solid insulation. In general, the mechanical life of the insulation is halved for each doubling in the water content [4]; the rate of thermal deterioration of the paper is proportional to its water content [5].

Since moisture is recognized to be “enemy number one” of liquid-filled transformers [9], it is of great importance to pay attention to the moisture content of composite insulation systems. In order to maintain low dielectric loss, high dielectric breakdown strength, and low rates of degradation of the insulating system in HV equipment, considerable efforts have to be made to maintain low water concentrations.

In a new transformer, the water content of the paper is about 0.5% and will gradually increase during use. It is useful to know

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oil-cellulose equilibrium curves (the so-called “Norris Curves”) under equilibrium conditions [4]. Assuming a transformer is in equilibrium operation, this provides a quick way to examine the moisture content in paper in order to predict failure by measuring the moisture in oil. The condition of a transformer insulation system can be monitored by routine oil sampling and laboratory analysis. The moisture level in the fluid is “an indicator” of the dryness level of the solid insulation as well. Since equilibrium is extremely sensitive to temperature, equilibrium is generally never reached in an operating transformer [7], [9]. The best way to check the condition of the insulation would be to take a sample of the paper from inside the transformer and to measure its water content using the Karl-Fischer titration method. However, as removal of paper samples is not feasible for in-service transformers, it is necessary to find other reliable methods. The need for an on-line moisture sensor for transformers has up to now only led to a sensor for the water content in the oil. New methods based on measurements of the dielectric re-

sponse [10] and recovery voltage measurements (RVM) [11] to measure the water in the solid insulation are still under investigation and discussion.

A drying of the transformer is recommended when the suggested water-saturation limits have been reached. The transformer can either be dried on-site using removable portable drying units for online or offline operation or dried offline at the workshop. Offline procedures will increase costs and cause long outages.

In this article, another approach to the problem, recently proposed as an alternative [12], [13], is presented. With the application of a synthetic hygroscopic mineral (molecular sieve zeolites)—a revolutionary, environmentally friendly, multipurpose mineral—a continuous drying process of the transformer oil during operation without the need for a service interruption is achieved. Some experiments with zeolite 3A and 5A on the aging of transformer insulation have already been performed by H.P. Moser et al. [14], [15], which showed reduced aging in the presence of zeolites especially for mineral oil and cellulose based transformer board. However, there are no published data on the effects of zeolite on the electrical and dielectric behaviour available.

Description of the Synthetic Mineral

Zeolite is a porous material that was originally discovered by a Swedish mineralogist, A.F. Cronstedt, in 1756 [16]-[19]. He found, that the mineral lost water rapidly on heating and thus seemed to boil. The name *zeolite* comes from the Greek word *zeo* (to boil) and *lithos* (stone). Zeolite is a natural volcanic mineral with a number of unique characteristics. It was formed when volcanic ash, deposited in ancient alkaline lakes, interacted with the salts in the lake water and changed into various zeolite minerals.

Zeolites are naturally occurring aluminosilicate minerals with three-dimensional structures based on $[\text{SiO}_4]^-$ and $[\text{AlO}_4]^-$ polyhedra (Figure 1a). The silicon and aluminium atoms are tetrahedrally coordinated with each other through shared oxygen atoms. These polyhedra are linked by their corners to produce an open structural form that has internal cavities in which molecules of various sizes can be trapped. The elements are arranged within the minerals in a manner that gives the crystal a honeycomb framework of channels and cavities. By controlling the ratios of cation exchange and the cation used, it is possible to synthesize zeolite crystalline structures with varying pore size and thus to regulate adsorption selectivity. The internal voids, engineered to have specific opening size ranges, trap and hold a variety of molecules that enter the structural matrix (Figure 1b). The adsorbed molecules can be removed by heating and/or evacuation. Because of their regular and reproducible structure they behave in a predictable manner.

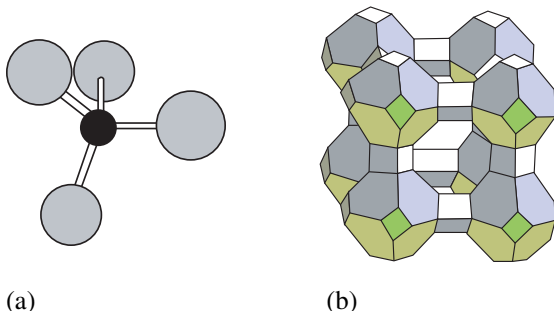
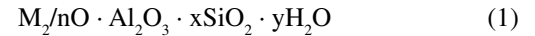


Figure 1. Structure of a polyhedral Zeolite.

One gram of zeolite provides up to several hundred square meters of surface area for chemical reactions to take place. This characteristic of zeolites gives them great adsorbing power. Zeolites are able to adsorb up to 30% of their dry weight in gases such as nitrogen and ammonia, over 70% in water, and up to 90% in certain hydrocarbons [16], [19]. Zeolites are used in many industries for the selective removal of gases from composite gaseous mixtures.

A representative empirical formula of a zeolite is:



where M represents the exchangeable cation of valence n. There are numerous naturally occurring and synthetic zeolites, each with a unique structure. There are over 40 different kinds of natural zeolite found in various parts of the world and over 100 synthetic ones [19]. The pore sizes of commercially available zeolites range from $\sim 3 \text{ \AA}$ to $\sim 30 \text{ \AA}$. The rate of diffusion of a molecule through a zeolite is therefore determined by a combination of the size of the substrate and the type of zeolite used. Not all zeolites have been studied, but extensive studies have been made on type A zeolite due to its use in consumer products [19]. These studies have demonstrated that zeolite A is essentially nontoxic via oral, dermal, ocular, and respiratory routes of exposure; zeolite A was also found to be safe for the environment [18],[19]. The cavities are connected by pores with exactly defined diameters (3, 4, 5, 10 \AA) according to the type of the zeolite, the name of which corresponds to the pore diameter. When the Na^+ ion is exchanged for the larger K^+ ion, the pore diameter is reduced to 3 \AA , so that only very small polar molecules will be adsorbed (zeolite 3A). Depending on the size of the pores, molecules may be rapidly adsorbed, slowly adsorbed, or completely excluded.

Water Molecule Adsorption/Desorption

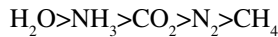
Zeolites possess a high affinity for water and are able to adsorb and desorb it without damage to the crystal structure. This property makes them useful in desiccation as well as in other commercial systems, such as heat storage. In many industrial and commercial applications, zeolites have been found highly effective in controlling moisture levels particularly in low humidity ranges, where other desiccants are less effective [19].

The zeolite structure (Figure 1) can only be penetrated by molecules when the diameter of the micropores is larger than or comparable to the dimensions of the diffusing molecules. Figure 2 shows as an example the correlation between the effective pore sizes of various type A zeolites and the dimensions of molecules penetrating the adsorbent.

Water and nitrogen are two of the smallest molecules that can easily penetrate almost all structures. As can be seen in Figure 2, the only zeolite that can exclude other molecules in liquids is the K type (type 3A), which is a zeolite with most of the naturally occurring smaller sodium cations replaced by larger potassium cations. The dimension of a water molecule is 2.65 \AA [16], [17]. Secondly, besides this geometric effect, the selectivity is determined by the dipole moment of the molecules.

It has been well established that faults in transformers are very often accompanied by gases, which may or may not be dissolved according to the condition of the insulating liquid. Such a feature is

very helpful for the correlation and identification of failure sources in liquid-filled transformers [20]. Safe transformer operation has become very dependent on dissolved gas analysis (DGA) as a diagnostic tool. From the gas components occurring in insulating liquids (e.g., H_2 , CH_4 , C_2H_2 , C_2H_4 , C_2H_6 , C_3H_6 , C_3H_8 , CO , CO_2 , O_2 , H_2O) [20], zeolite 3A can only adsorb H_2O and H_2 as the size of a hydrogen molecule is 2.89 Å [18]. Although water and hydrogen molecules are roughly the same size (Figure 2), water is preferably adsorbed by zeolites due to the higher dipole moment of the water molecule. The following order shows the adsorption preference of different molecules by type A zeolites [20]:



The higher the dipole moment, the higher the adsorption preference. The dipole moment of a water molecule is 1.844 debye, whereas that of ammonia and hydrogen is 1.46 Debye and 0 respectively. Note that 1 debye = $3.336 \times 10^{-30} \text{ C} \cdot \text{cm}$.

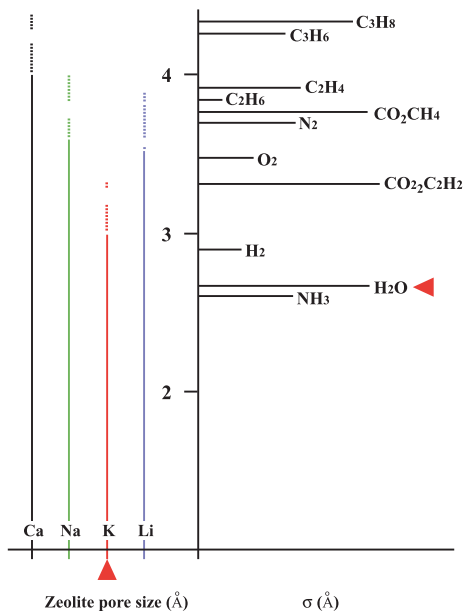


Figure 2. Chart showing a correlation between the effective pore size of various zeolites for adsorption in equilibrium versus the temperatures of 77 to 420 K (range indicated by - - -), with the kinetic diameters of various molecules as determined from L-J potential relation [17], [18].

The impact of zeolites on DGA has been reported by Daemisch [21], who reported the adsorption of acetylene (C_2H_2) by molecular sieves. This is most probably not due to the dipole moment but due to the very nonuniform charge distribution within the molecule. The molecule is of a linear type ($H-C \equiv C-H$), with a triple bond between the two central carbon molecules. The charge distribution thus has a negative maximum at the center, whereas the marginal hydrogen molecules have a more positive character. Due to the linear and reversed left to right composition this does not result in a dipole moment, but in a heterogeneous charge distribution along

the molecule chain, thus being sufficient to make it attractable by zeolites.

Moreover, Figure 2 clearly shows that acetylene (pore size of 3.3 Å) adsorption by zeolite 3A is only possible at high temperatures. The dotted line on this Figure along the ordinate axis (zeolite 3A pore size) gives the pore size dilation in a temperature range varying from 77 to 420 K. Thus, C_2H_2 can be adsorbed by zeolite 3A only at temperatures close to 400 K, which represents a hot spot inside the transformer. In the suggested online-drying procedure described later, the zeolite bed is intended to be installed as a separate unit. Its temperature will depend on the installation site. In order to restrict the temperature rise inside the bed, a cooling unit could be considered to help keep the temperature below 60°C.

The zeolite is therefore expected to capture only water molecules without affecting most of the other dissolved gases. Zeolite 3A was chosen to be the drying agent for the transformer oil, whereas zeolite 4A has been used for comparison, as this material has similar properties but a slightly larger pore size. Regeneration of zeolites 3A and 4A, which should be carried out at a water uptake of a maximum of 20% by weight, takes place in an oven at temperatures between 300 and 350 C, preferably in a vacuum.

Upgrading Mineral Oil

In order to estimate their drying efficiency, specific amounts of type A zeolites were immersed in oil samples, and kept in a sealed vessel to avoid any influence of the environmental conditions. The water content was regularly controlled using the Karl-Fischer Titration method [22]. The samples were dried with 0.1, 0.5, 1, and 10 g/litre of zeolite 3A or 4A, respectively. The results of the investigations are summarized in Figures 3 to 8.

Figures 3 and 4 compare the drying efficiency of zeolites 3A and 4A for different starting humidities of 28 and 47 ppm. At 65°C, zeolite 3A in oil seems to desiccate slightly better than zeolite 4A although its behavior is similar at 23°C. The reason may be found in the thermal activity of the water molecules. With increasing temperature, the mobility of the molecules increases so that water molecules trapped in a zeolite pore can leave their location more easily, if the bonding forces are lower.

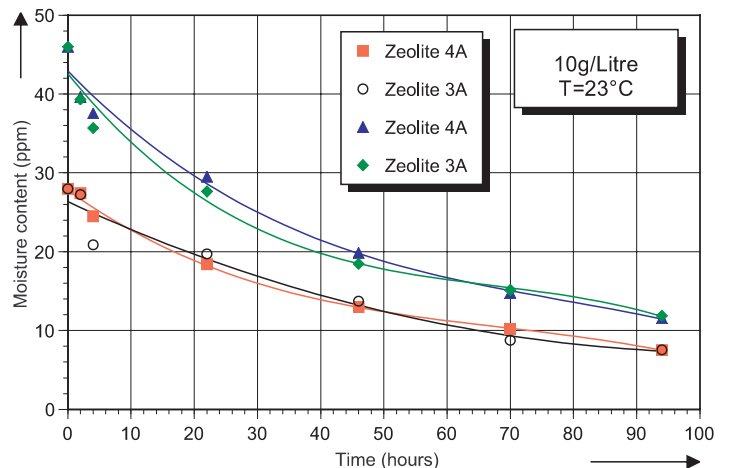


Figure 3. Comparison of oil drying velocities of zeolites 3A and 4A at room temperature for different starting humidities.

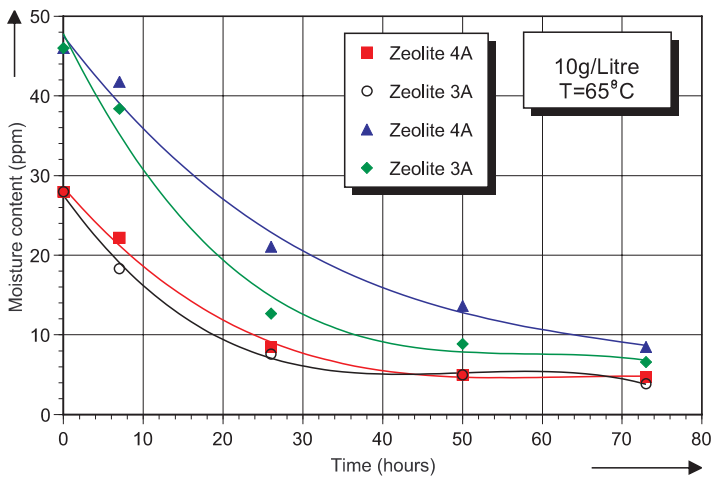


Figure 4. Comparison of the oil drying rates using zeolites 3A and 4A at 65°C for different starting humidities.

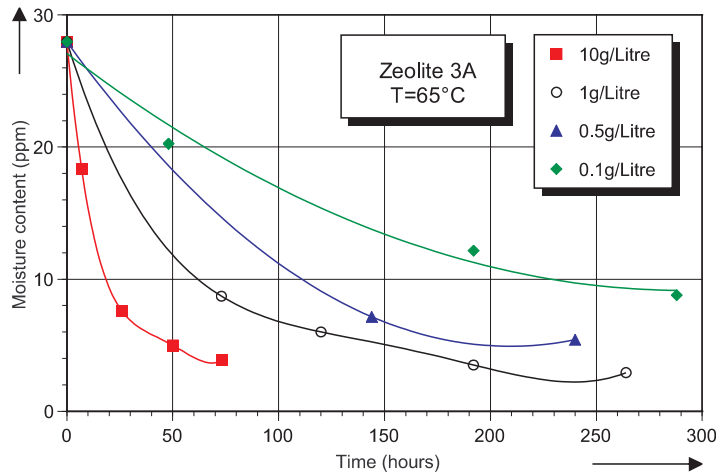


Figure 7. Drying velocity of oil with an initial water content of 28 ppm for different amounts of zeolite at 65°C.

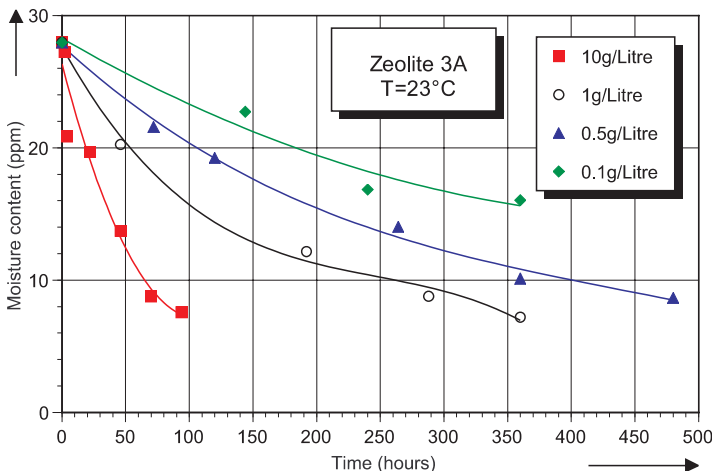


Figure 5. Drying rates of oil with an initial water content of 28 ppm for different amounts of zeolite at 23°C.

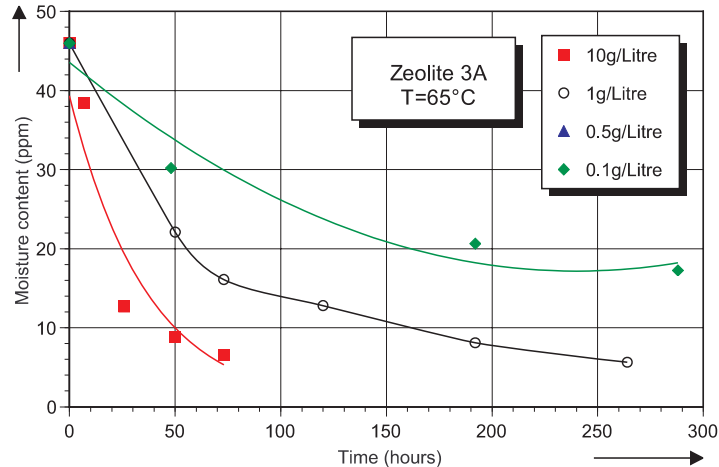


Figure 8. Drying velocity of oil with an initial water content of 46 ppm for different amounts of zeolite at 65°C.

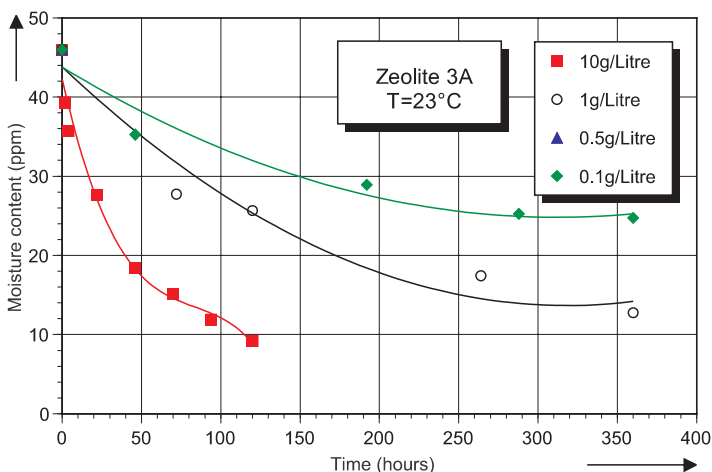


Figure 6. Drying velocity of oil with an initial water content of 46 ppm for different amounts of zeolite 3A at 23°C.

As the size of the zeolite 3A pore is better suited to the size of a water molecule than that of a zeolite 4A pore, the bonding forces are also higher. Seen as a balance of water adsorption and desorption, the zeolite 3A can adhere the water molecules more easily than the zeolite 4A, thus resulting in a faster adsorption. The higher the zeolite amount, the higher the drying rate, as can be seen from Figures 5 to 8. Figure 9 shows data of tests performed on highly moistened mineral oil (90 ppm). The temperature influence on the moisture uptake of zeolite is clearly shown—the higher the temperature, the higher the sieving rate.

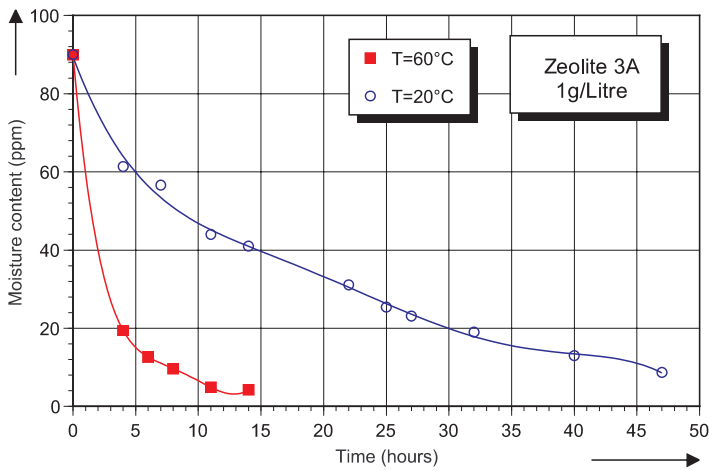


Figure 9. Drying velocity of a highly moistened mineral oil (initial water content of 90 ppm) with 1g/liter of zeolite at 20 and 60°C.

The moisture saturation limit at room temperature for the investigated mineral oil is about 55 ppm. As the moisture content at the start of the experiment exceeds the saturation limit at room temperature, free water precipitated from the oil in suspension or drops is present. Figure 9 shows that the water content of the oil rapidly decreased from 90 to 60 ppm (30 ppm of moisture adsorbed in 4 days) compared to the situation in Figure 6, where 20 ppm was desiccated in 7 days, starting from a moisture content of 47 ppm when using 1 g/liter of zeolite. Undissolved water therefore seems to be rapidly removed by zeolites.

Upgrading an Ester Liquid

Zeolite 3A was also used to dry a highly hygroscopic liquid. Figure 10 shows the results performed on an ester liquid at different temperatures and for different zeolite amounts. With an amount of 30 g/liter and starting with a water content of 633 ppm, the water

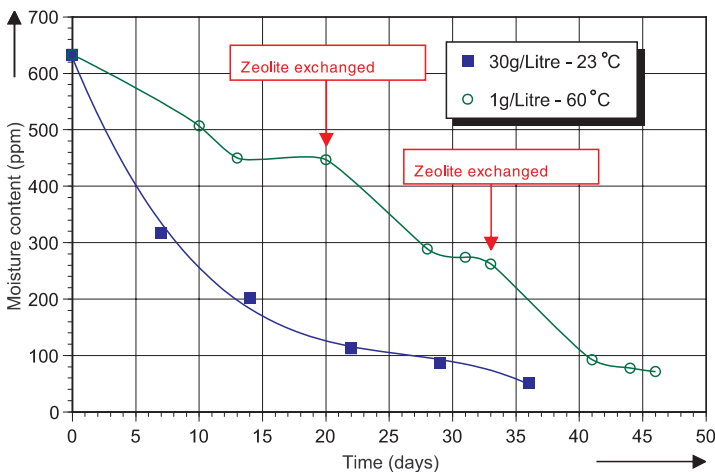


Figure 10. Drying velocity of an ester liquid at an initial water content of 633 ppm with different amounts of zeolite and at 23 and 60°C.

content in the liquid was reduced to 200 ppm after two weeks and to 50 ppm after 36 days. The upgrading of ester liquid using 1g/liter of zeolite requires more time and regeneration or change of the zeolite bed. The first zeolite bed was saturated after about 13 days. The moisture content adsorbed was about 190 ppm, which corresponded to 18.24% in weight of the dried zeolites. This value was close to the saturation limit of 20% obtained for others applications of zeolite 3A [17], [19].

The arrows in Figure 10 indicate the time at which the zeolite bed was changed. These investigations show the capability of zeolite 3A for drying a hygroscopic liquid.

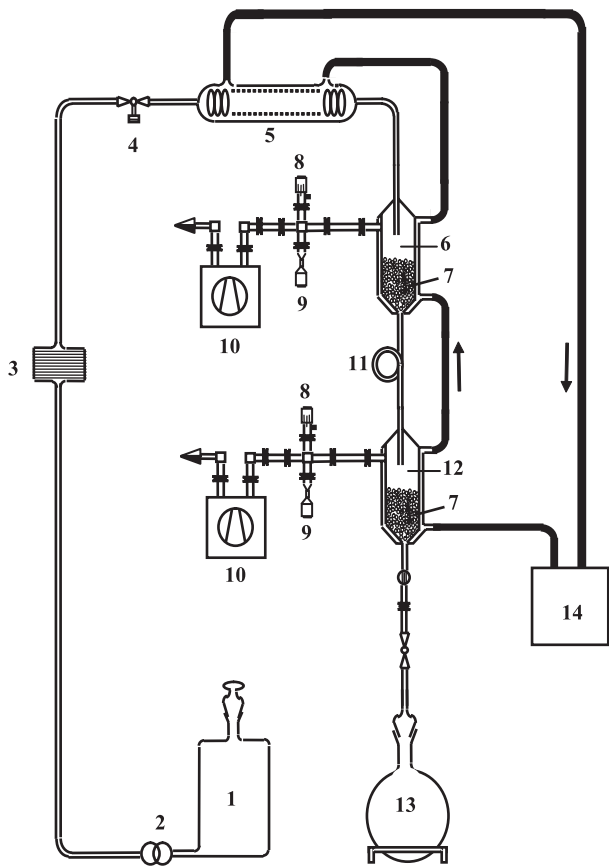
Influence of Zeolite on the Dielectric Properties

To determine the influence of zeolite on the dielectric properties of oil, a specific amount of zeolite was sealed in a filter paper and directly immersed in oil specimens stored in a sealed vessel. The oils were pretreated or dried in order to ensure the same initial conditions for all investigations. The drying took place in two-stage packed columns (Figure 11) [23]. The oil sample flowed successively through a fine filter (3), a one-way valve pressure reducer, (4) a heat exchanger (5) into the first column stage (6). In this stage the oil flowed at a pressure of $P_1 = 1$ mbar and a temperature of $T_1 = 50^\circ\text{C}$ through Rasching rings, was degassed and dried before arriving at the second stage with $P_2 = 0.1$ mbar and $T_2 = 60^\circ\text{C}$. Here the water and gas contents continued to reduce. The drying lowered the water contents for ester liquid from approximately 80-200 ppm and for mineral oil from approximately 15-20 ppm, to <30 ppm for ester liquid and <5 ppm for mineral oil [23]. At the same time the total gas content was reduced to less than 1 percent by volume. For investigations with higher water contents, the insulating liquid samples were stored in a water vapor atmosphere to reach the desired water content. For all investigations, the water content was determined before each series of measurements started.

Note that the zeolite that was used for drying the samples was sealed in a fine filter paper in order to avoid contamination of the oil by the particles. The investigations were performed at various temperatures and at water contents of 10 and 20 ppm.

Relative Permittivity (ϵ_r) and Dissipation Factor ($\tan\delta$)

The measurements were performed with a Schering-Bridge (model Tettex 2801 together with a Wagner Auxiliary Branch model 2900, sensitivity $5 \cdot 10^{-7}$) at 50 Hz. The relative permittivity results are summarized in Figure 12, which shows a comparison between the values obtained for specimens dried by standard methods and those desiccated by zeolite for different temperatures and water contents. The temperature and moisture content dependencies of the dissipation factor of the specimens are summarized in Figure 13. It is evident from Figure 13 that zeolite has a beneficial influence in reducing the dissipation factor, especially at higher temperatures. This may originate from the heating of the oil during conventional drying, thus being associated with deterioration, generation of conductive molecules, and resulting in an increased $\tan\delta$.



- 1 Storage tank
- 2 Pump
- 3 Fine filter
- 4 Pressure reducer
- 5 Heat exchanger
- 6 1st.Column stage
- 7 Rasching rings
- 8 Vacuum measuring tube
- 9 Ventilation valve
- 10 Vacuum pump
- 11 Pressure barrier
- 12 2nd Column stage
- 13 Collecting tank
- 14 Thermostat

Figure 11. Schematic diagram of the fluid processing plant. In the second stage, a final pressure of 5 Pa is achievable. Different water contents can be achieved through variation of the final pressure, temperature, and flow rate.

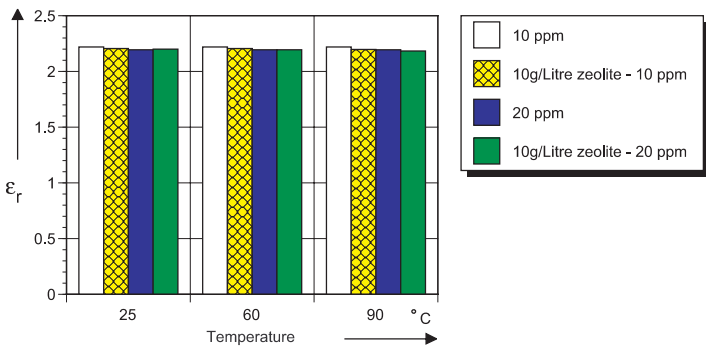


Figure 12. Comparison of the relative permittivity of mineral oil samples dried by a standard method (two-stage processing unit) and samples dried with 10 g/liter of zeolite 3A.

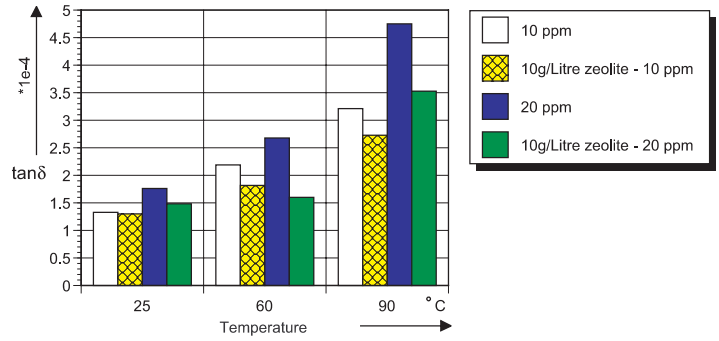


Figure 13. Comparison of the dissipation factor of mineral oil samples dried by a standard method (two-stage processing unit) and samples dried with 10 g/liter of zeolite 3A.

Breakdown Voltage (U_B)

The power frequency electric strength is the most often used parameter to describe the insulating property of a liquid. The measuring procedure, according to IEC 60296 or VDE 0370, has been described previously [24]. The temperature range (0–100°C) used in the investigations was chosen in order to simulate normal operating conditions as well as critical situations in a transformer. The results of the investigations are presented in Figure 14.

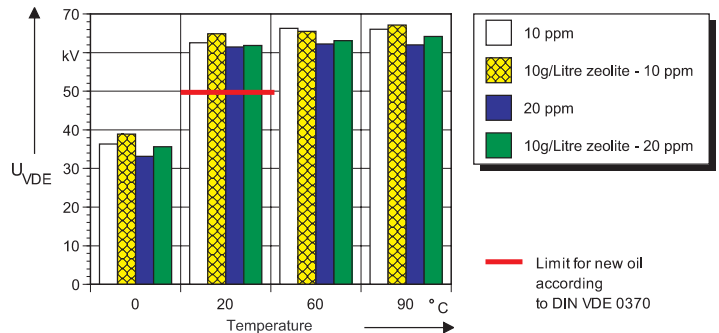


Figure 14. Comparison of the electric strength of mineral oil samples dried by a standard method (two-stage processing unit) and samples dried with 10 g/liter of zeolite 3A.

As for the dissipation factor, zeolite 3A seems to have a small beneficial influence on the electric behavior, as illustrated by the higher breakdown voltage in comparison to conventionally dried samples. It has been generally acknowledged that the life of an oil in service depends primarily on its initial quality, but service conditions also need to be considered.

Influence of Zeolite on Oil Aging Behavior

The evaluation of the aging behavior requires accelerated aging tests. Transformer aging and the rate of aging are described in the industry loading guides (e.g. [1], [2]), in particular, loads beyond the nameplate rating. According to this guide, the main factor influencing the aging and life expectancy is the thermal stress. However, aging is accelerated by contact with oxygen and by the mois-

ture content in the transformer [3], [5], [6], [9], [14]. For this reason, the aging behavior of the mixed insulating fluids was tested at high temperatures in the presence of oxygen. The method consisted of storing oil specimens in opened vessels with the addition of 3 g/L of copper, steel, aluminium and zinc chips, exposed in an oven at a temperature of 110°C for a period of 1000 h. The catalysts, which represented metallic components of the transformer, were sealed inside fine filter papers (pore diameter <2 mm) and added to the oil samples. To appraise the effect of zeolite, different amounts were used (0.1, 1, and 10 g/liter). The zeolites were also sealed in a separate fine filter paper and added to the oil samples, except for one sample where the zeolites were directly added to the oil in order to determine their effects under long term service conditions. Figures 15 to 17 show the results of the investigations performed on the aged samples.

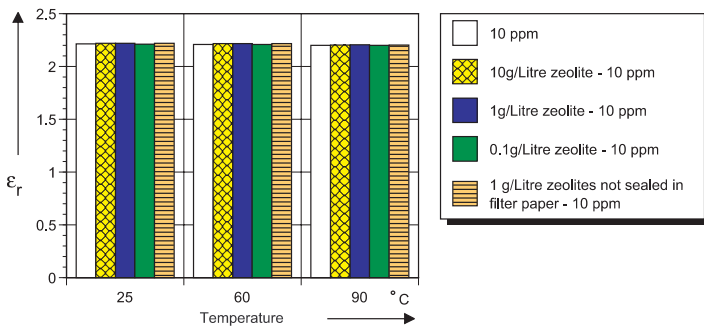


Figure 15. Comparison of the relative permittivity of aged mineral oil samples dried by a standard method (two-stage processing unit) and samples aged with different amounts of zeolite 3A.

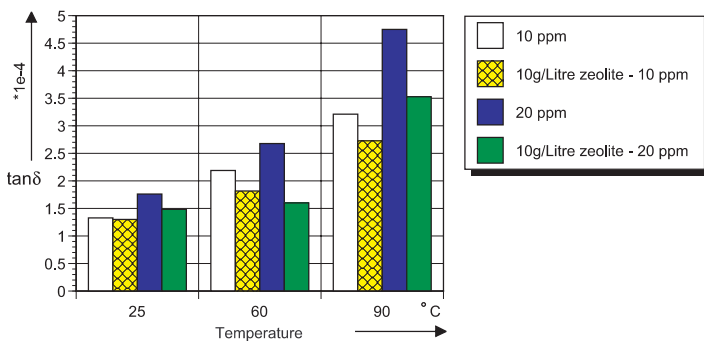


Figure 16. Comparison of the dissipation factor of aged mineral oil samples dried by a standard method (two-stage processing unit) and samples aged with different amounts of zeolite 3A.

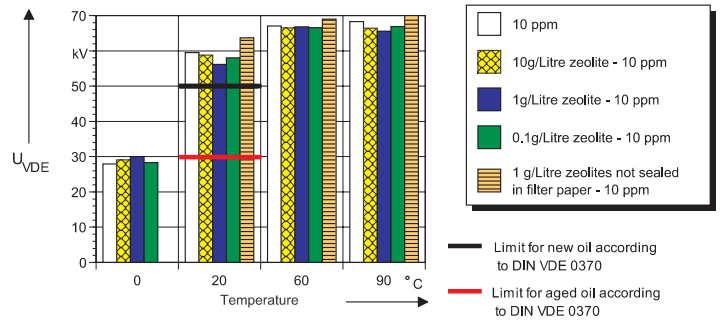


Figure 17. Comparison of the breakdown voltage of aged mineral oil samples dried by a standard method (two-stage processing unit) and samples aged with different amounts of zeolite 3A.

As these Figures show the values (relative permittivity, dissipation factor and breakdown voltage) obtained for samples aged with zeolites, both sealed in fine filter paper and in direct contact with the oil, are not inferior to those of the samples aged without zeolite.

It can be concluded that, from the viewpoint of dielectric properties, zeolites do not have any negative influence on transformer liquids. Zeolites can thus be used for continuously upgrading transformers oils. At present, the majority of the power transformers in operation in Germany have reached an age of 25 years or greater so it is of great interest to investigate the drying capability of zeolite using service-aged oil and thereby to explore the effects of contaminants and impurities. The results for two samples, where the drying has been performed at 60°C, are presented in Figure 18.

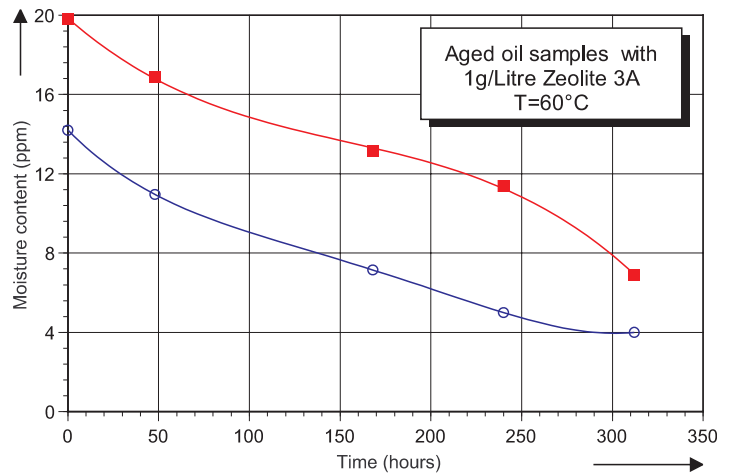


Figure 18. Drying velocity of aged oil using zeolite 3A.

It can be seen that, compared to the samples of Figure 7, the drying velocity is slightly reduced. The reason may be the presence of fine impurities or particles or some other molecules present in the aged oil samples, which have been adsorbed by the zeolites in addition to the water molecules. When designing processes for continually drying transformer oils, it will thus be useful to precede the zeolite beds with a very fine filter, in order to filter insoluble particles out of the liquid before they can enter the zeolite bed.

Proposal for Continually Upgrading Transformer Oils

During the service of liquid-immersed, high-voltage transformers, the oil used as coolant becomes contaminated with water, gases and insoluble particles [3], [5], [6], [9], [14], which adulterate the liquid and lead to an increasingly inefficient operation of the transformer. Thus it is desirable to remove the contaminants either periodically or continuously as required. The dilemma of high-voltage transformer drying is that good drying is a time-consuming and expensive process, and is therefore controversial due to the increasing market demand for shorter transformer outages and reductions in costs. Some transformer drying procedures are presented in [24], [25]. An important step to meet this request was made some years ago with the introduction of vapor-phase technology. Also, a new suggestion for careful vapor-phase drying was presented by Krause et al. [25]. The efficiency of the drying process of high-voltage transformers depends on many parameters, the most important of which are:

- process duration
- environmental impact or outdoor conditions (influence of season, etc.)
- attention paid to the connections between the transformer and the drying units
- voltage rating and power of the transformer
- the capacity of the drying unit, etc.

Current equipment for upgrading transformer oils during service require many moving parts such as pumps and vacuum chambers, which require frequent maintenance and considerable space [25], [26]. Accordingly, there has been a need for more satisfactory means for continually upgrading the dielectric liquids with a minimum of maintenance. With an oil strainer based on zeolite, these requirements may be adequately fulfilled, as shown in Figure 19.

The operating transformer is connected to a zeolite bed via a pump and a fine filter for filtering insoluble particles out of the liquid (Figure 19a). After the zeolite bed, which performs the drying, the insulating liquid is returned to the transformer tank through a second filter. The first filter is expected to prevent fine particles from accessing the zeolite bed, thus avoiding the obstruction of their pores, whereas the second filter is required for preventing particles from the zeolite grains from contaminating the upgraded liquid. The only moving part in such a system would be the pump whereas a regular exchange of the filter cartridge would ensure constant drying capabilities. The schematic representation of the inherent processes is shown in Figure 19b.

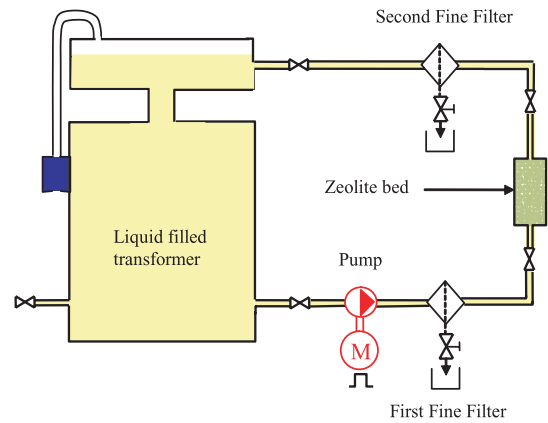


Figure 19a. Online drying procedure for a liquid-immersed transformer.

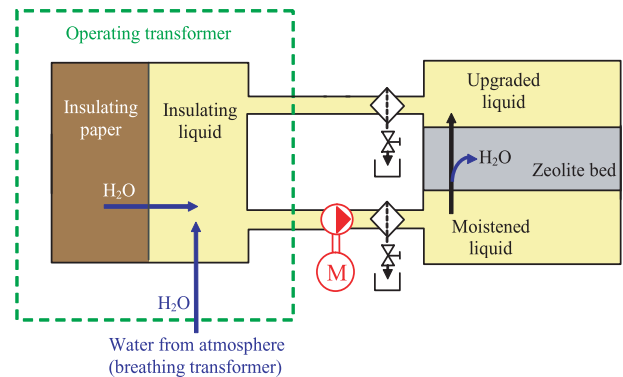


Figure 19b. Schematic representation of the drying process through diffusion and zeolite adsorption.

In an operating transformer, papers can contain much more water than the oil. For example, a 150-MVA, 400-kV transformer with about 7 tons of paper may contain as much as 223 kg of water [4]. The oil volume of about 80,000 L, assuming a 20-ppm moisture concentration, will have a total mass of water of only 2 kg, much less than that in the paper. In order to simulate the applicability of the proposed drying procedure a laboratory based-model has been investigated.

The transformer model consists of a vessel filled with 3.2 L of oil. To keep close to reality, 280 g of cellulose paper was impregnated and immersed in the transformer model. The transformer model, connected to a zeolite bed (an amount of 1g/L was used) via a pump, was then continuously heated at a temperature of 60°C to simulate an operating transformer. To appreciate the drying velocity, oil was sampled at two different points as shown in Figure 20. Figure 21 shows the results obtained for a pump velocity of 10.9 L/hour, the initial water content in the transformer model being 22.2 ppm.

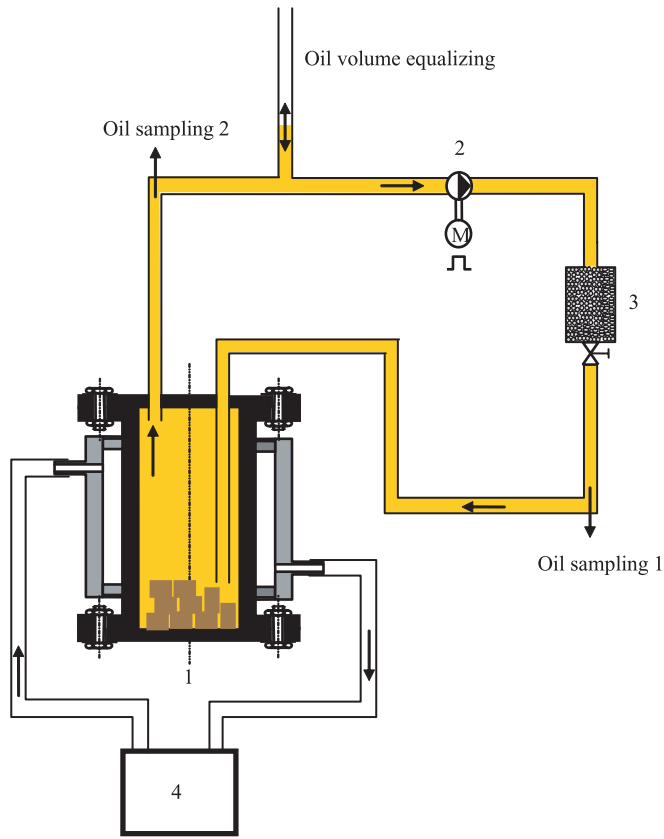


Figure 20. Laboratory simulation for continually upgrading transformer oil—1: transformer model with cellulose papers, 2: pump, 3: zeolite bed, 4: heating apparatus.

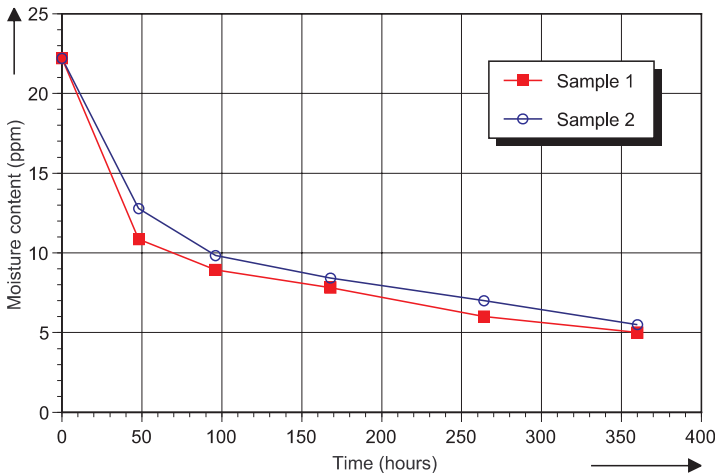


Figure 21. Water content of the oil measured in the transformer model starting from a water content of 22.2 ppm. The velocity of the pump is 10.9 L/h. Note that sample 1 and 2 refer to Figure 20.

Features of a Zeolite Saturation Sensor

The adsorption of water molecules by the dehydrated zeolite structure produces a pronounced change in the electrical conductivity, for example, there is a nonlinear increase in the conductivity

of zeolite A [18]. Since we are only interested in the saturation of the zeolite bed used to upgrade the transformer, we considered this simple idea leading to the development of a saturation sensor filled with the same zeolite as the desiccator. To avoid interpretation errors of the readout, precautions have been taken in order to avoid displacement of the zeolite grain in the sensor.

The sensor was immersed in moistened oil having an initial water content of 80 ppm, contained in a sealed vessel. The change in resistance and capacitance related to the moisture reduction of the zeolite sensor were measured using a RCL impedance-measuring system. Figures 22 and 23 show the experimental results.

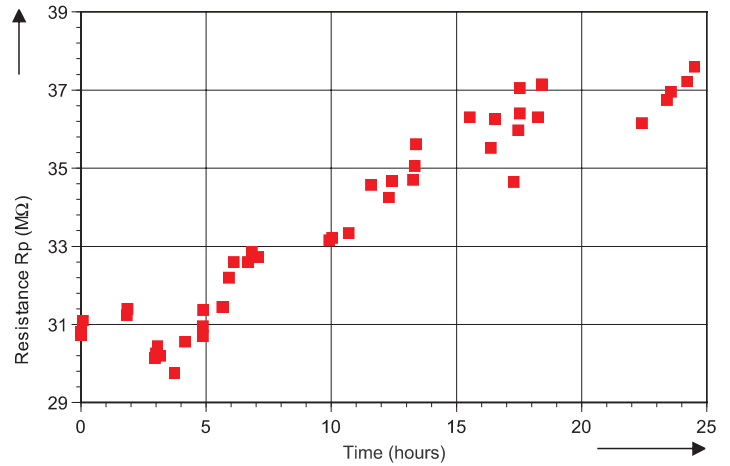


Figure 22. Variation in sensor resistance versus time.

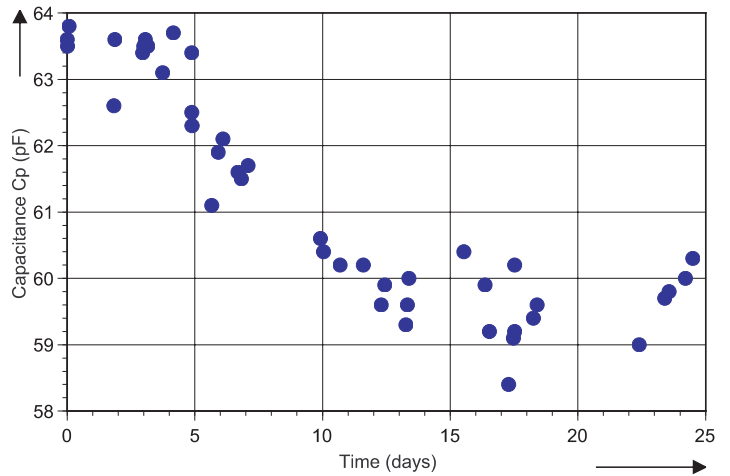


Figure 23. Variation in sensor capacitance versus time.

The investigations show a strong correlation between the resistivity or capacitance (permittivity) of the impregnated zeolite bed and its moisture content. The resistivity of the zeolite sensor changed over the entire humidity range, between roughly 30 MΩ for an initial moisture content in oil at 80 ppm, to 37 MΩ for a final moisture content in oil at 12 ppm—a variation of 27.6% with respect to the dry condition. The zeolite sensor capacitance over the entire humidity varied from 64 to 59 pF—a variation of 7.8% from the dry condition.

The experiments confirmed the feasibility of the method, particularly for the conductivity measurement. More research is needed to refine the methods and to collect more complete data. For example, a non-uniform distribution of the moisture or other aging products can complicate the evaluation of the measurements. Moreover, it is also known that as materials age, their permittivity and conductivity may also change. These difficulties can be overcome, however, with additional experience and knowledge of the service history of the test materials.

Conclusions

We have presented here a transformer insulation upgrading process based on the beneficial effect of a mineral based desiccator (zeolite). Based on the type of the zeolite and its pore size, water can be preferentially removed from the insulating liquid. Long and short term investigations showed that zeolite has no negative influences on the dielectric properties of the insulating liquid. Different amounts of zeolite have been investigated for upgrading transformer insulating liquids and, by combining the drying efficiency and zeolite bed size, it has been shown that 1 g/L of zeolite is suitable for this application. A drying process for on-line operation has been proposed, consisting of a device for dehumidification and filtering insoluble particles out of the liquid, which the fluid can be upgraded and decontaminated in a continuous process.

The advantages of this procedure are its simplicity, low cost and applicability for on-line operation. No additional storage tank or vacuum chamber is required. The procedure also includes the option of using a filter to purify the liquid, thus additionally reducing a possible source for PD or breakdowns.

Contrary to some dehumidifiers like silicagel, zeolites do not show changes in colour when they are saturated, so a simple sensor has been proposed. The investigations showed that this sensor could determine the actual status of the zeolite filter by measuring the variation in conductivity or permittivity of a sensor filled with the same material. Nevertheless more research is needed to gather more data in order to optimize the sensitivity as non-uniform moisture distribution or aging products can affect the measurements. Moreover, it is well known, that as material age, their permittivity and conductivity may also change. These difficulties can be overcome with additional knowledge of the service history of insulation system.

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