Transformer Life Extension - Part 1
Drying of Transformers

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Prof. Dr. Hossein Borsie since 1986 academic director of the University of Hannover, Institute of Hochspannungstchnik. He is a member of VDE, DKE and various Cigré Task Forces and national and international working groups for standards.

Prof. Dr. Hossein Borsie studied and received his PhD in electrical engineering at the Technical University of Hanover. He habilitated with the Venia Legendi „High Voltage Measurement". In 1979 he was appointed to the University of Ferdowsi Mashhad in Iran for the field Enegietechnik. He was from 1980 to 1982 and dean per dean of engineering. In the period 1981 to 1985, he was also Scientific Advisor to the Minister of Energy Inranischen.

The transformer factory „Reza Trans factory" was founded in 1982. Prof. Borsi took over from 1982 to 1985 the technical directorate. He is the author of more than 350 national and international publications. He has 25 national and international patents and is the author and co-author of several books. The focus of his previous research activities are high-voltage measurement technique, solid and liquid insulation, monitoring and diagnosis of vari-

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Life Extension of POWER TRANSFORMERS by Drying

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PRESENTATION OVERVIEW

Including among others:

- **Water in the transformer !?**
- **Physics of drying**
- **Different drying techniques**
- **Online drying of transformers**

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Influencing variables

Electrical characteristics of an insulating liquid are strongly affected by water content (humidity) and gas content

Concentration of water and gas in the liquid is proportional to the partial pressure of water vapor and gas in the area above the liquid

Characterization of the water and gas absorption capabilities through the absorption coefficient

Solubility

$$c_F = m_G/V_F = K(T)\, p_G$$

(Henry´s law)

- c_F = Concentration of the dissolved gas in the liquid
- m_G = Mass of the dissolved gas
- V_F = Liquid volume
- $K(T)$ = temperature-dependent constant
- p_G = Partial pressure of the gas

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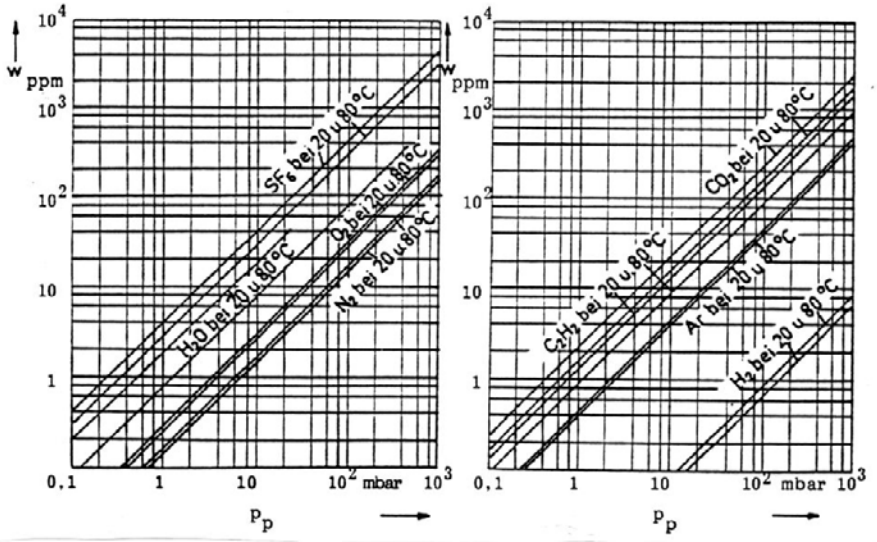
Absorption of gas vapor and water vapor



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Dissolution capabilities

Water and gas absorption of liquids

$$w = K\, e^{-H/T}$$

H, K => constants

T => temperature

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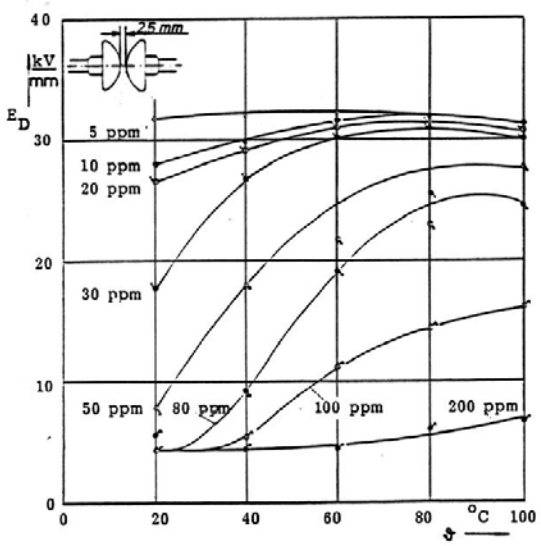
Influence of the humidity on the breakdown voltage



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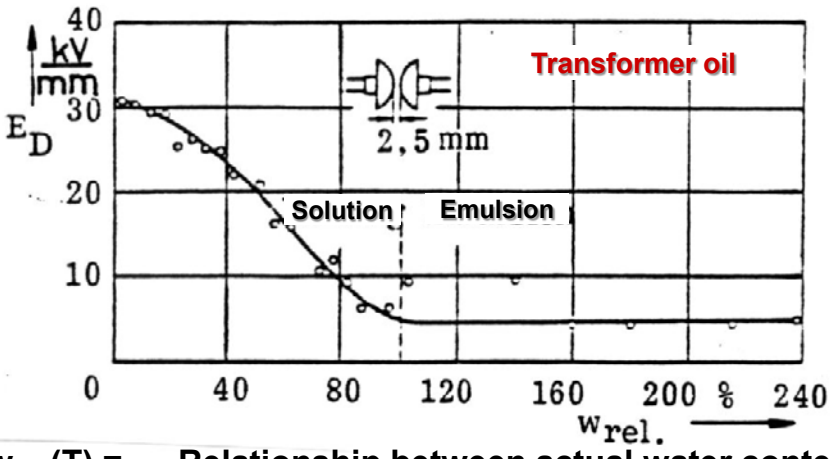
Influence of the humidity on the Breakdown field strength



w_{rel} (T) = Relationship between actual water content and saturation water content (T)

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A temperature increase of 6 - 8°C is doubling the depolymerisation speed

A moisture increase of 1% is also doubling the depolymerisation speed

4% moisture at 50°C leads to a moisture content in the oil of 50 ppm. Is the oil quickly cooled down (power failure during winter), is it possible to have free water already at 20 °C

With a too high moisture content, there is the risk of bubble formation in the insulation at much lower hot spot temperatures as 140°C as with dry insulation

Water in oil paper insulations:

- Reduces the breakdown voltage of oil
- Can lead to bubbling at hot spots
- Accellerates the aging of paper

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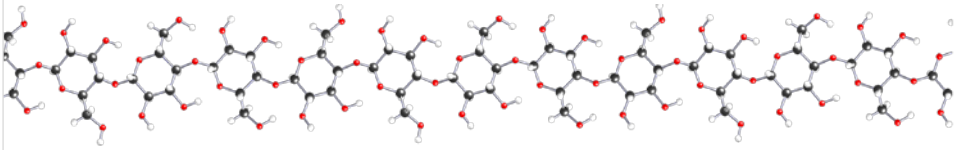
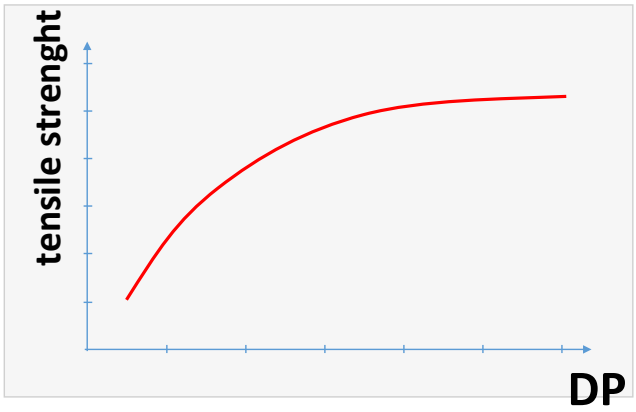
- Cellulose: Built of glucose chains



- Degree of polimerization (DP): Average number of glucose rings in a chain
  - New paper: DP: ~ 1200
  - End of life: DP: ~ 200
- Water splits the chains (Hydrolysis)
- Water is a byproduct of the hydrolysis
  - ➢ Self-accellerating process
  - ➢ The higher the water content, the faster the aging

- Problem: Mech. strenght is reduced with decreased DP



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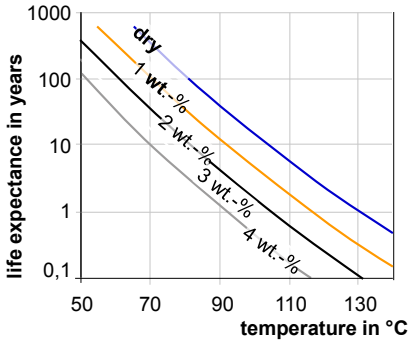
Temperature accellerates aging

Water accellerates aging

„Rule of thumb“:
- Each 8 K ↑: half life expectance
- Each 1 wt.% ↑: half life expectance



Source: L. E. Lundgaard, “Aging of oil-impregnated paper in power transformers”, IEEE Transactions on Power Delivery, Jan. 2004

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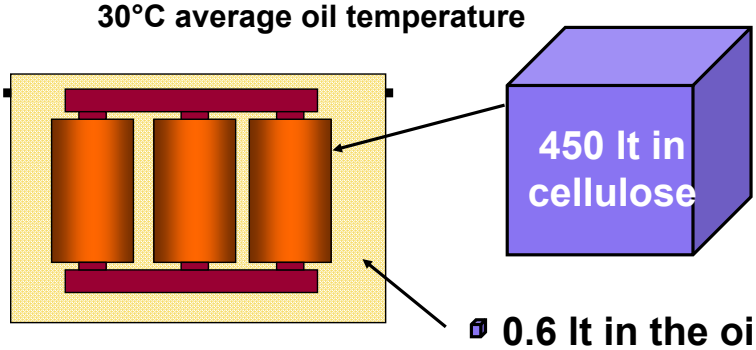
MOISTURE DISTRIBUTION PAPER/OIL

Example: 400 MVA Transformer with 15 Tonnes cellulose insulation and 60 Tonnes oil
3% average moisture in cellulose
30°C average oil temperature



Over 99 % of the moisture is collected in the cellulose!

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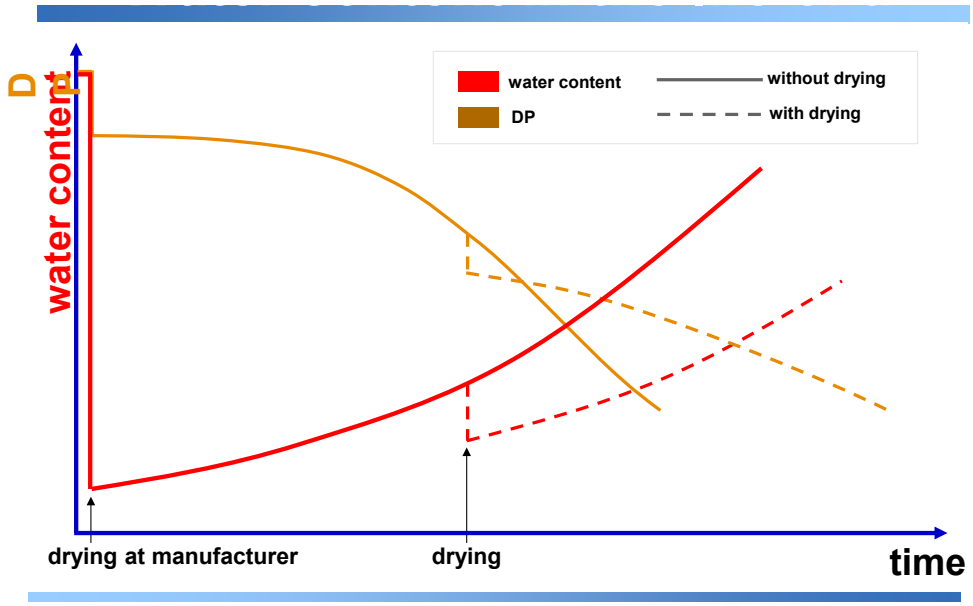

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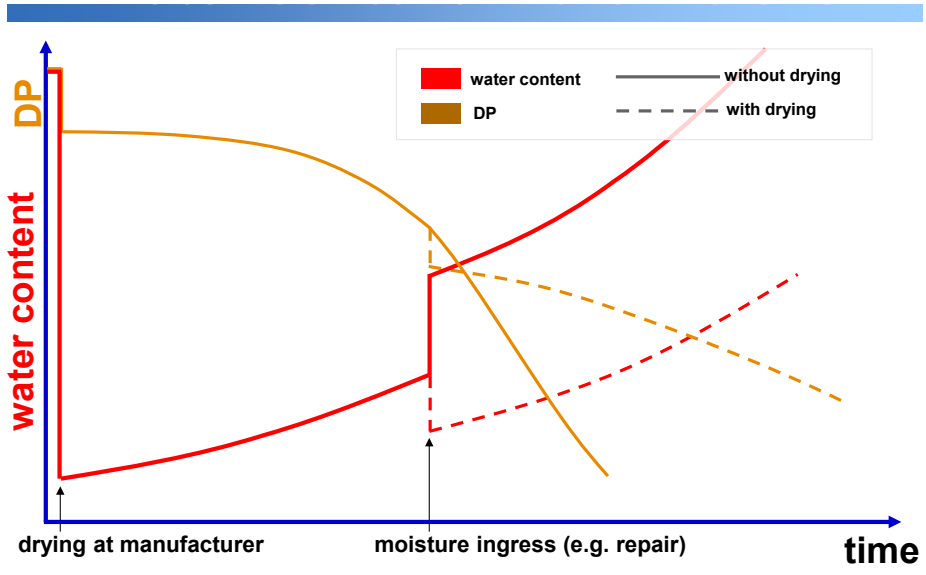

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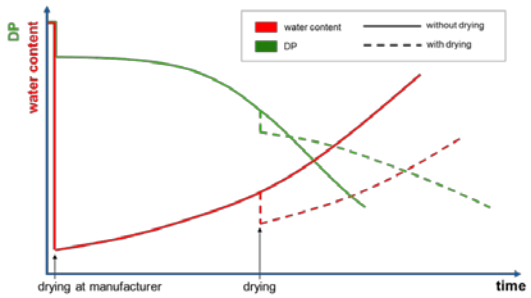
Drying of Transformers

- The water content increases steadily with the life of a transformer
- Time is dependent on temperature (↔ load)
- Drying slows down the aging but can‘t reverse the aging
- Knowing the water content can tell you if drying is neccessary



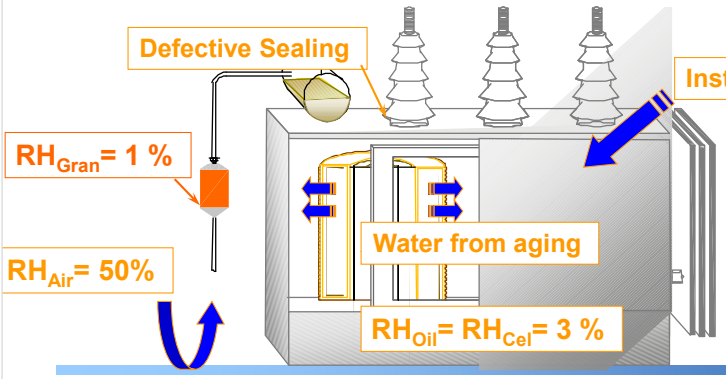
Moisture Equilibrium and Diffusion

Moisture equilibrium

- Water potential even in the whole system
- **Diffusion:** Difference in RH as a function of temperature, pressure, absorption capacity

$$C_{W,rel} = a_W \cdot 100\,\%$$

$$C_{W,rel,Pb} = C_{W,rel,Oil} = C_{W,rel,Air}$$



Contamination rate:

	RH	WC_{Cell}
New	1-2	0,5
Fair	5-10	1,5-2
Wet	10-15	3-4,5

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Drying of Transformers

Moisture Distribution and Aging

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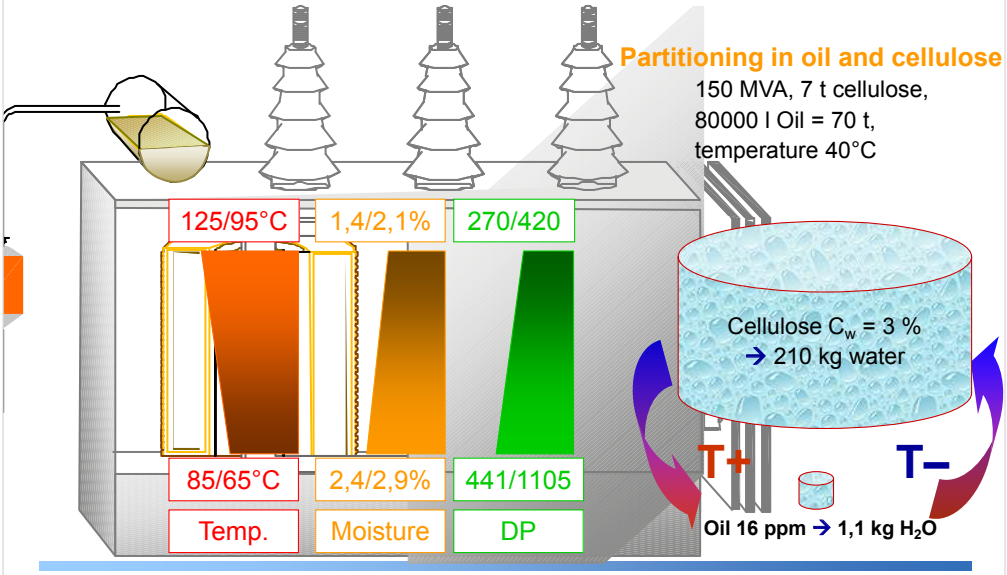

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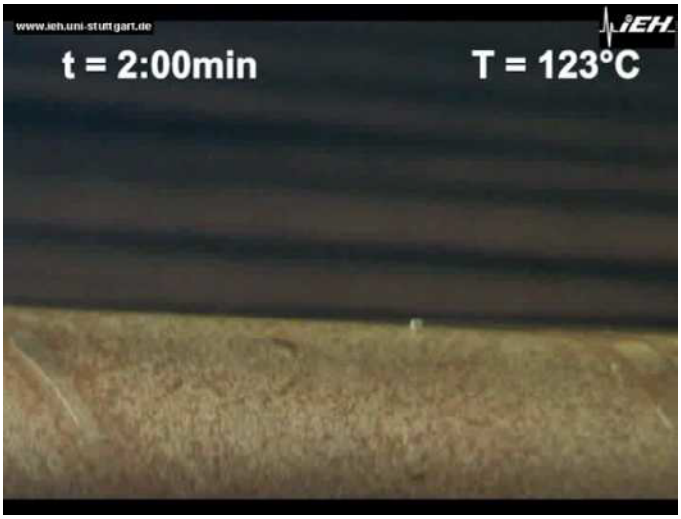
Bubbling in Oil



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Drying of Transformers

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PHYSICS OF DRYING

Diffusion / Drying speed is influenced by:

- **Temperature**
- **Humidity**
- **Pressure difference on the diffusion path**
- **Material properties**

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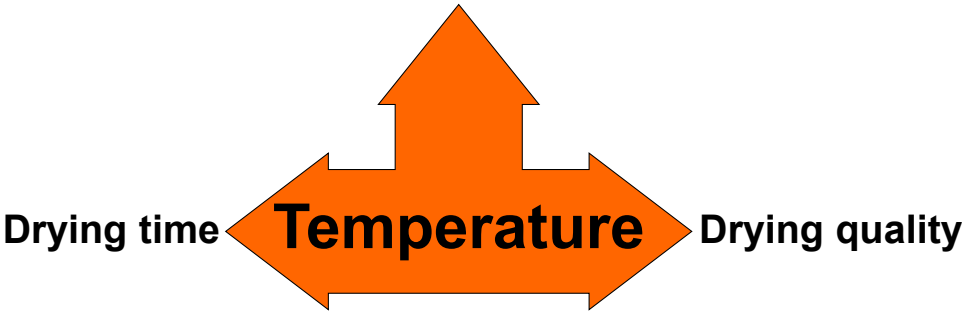
PHYSICS OF DRYING

Depolymerisation



Temperature is the key parameter in any drying process

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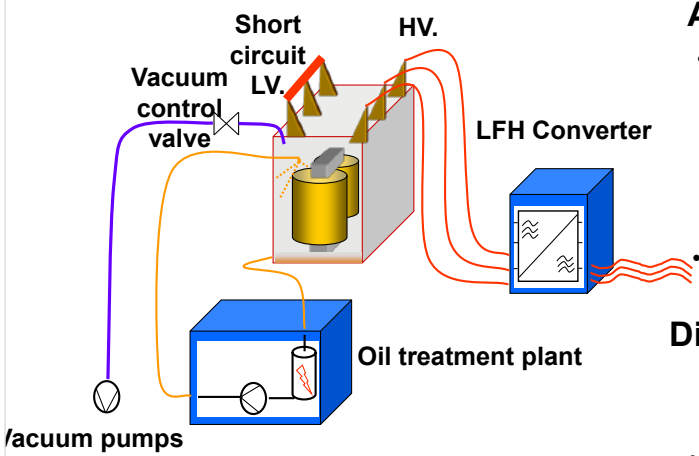
Drying of Transformers

- **Drying too short**
  - → Moisture content too high
    - → Accelerated aging
      - → Reduced lifetime
- **Drying too long**
  - → Energy costs, production speed
  - → Paper too long at hot temperature
    - → additional Loss of DP
      - → Reduced lifetime

➡ **Optimal drying time is essential**

➡ **Monitoring of moisture content necessary**

LFH AND HOT OIL SPRAY



Advantages:

- constant heat feeding under vacuum
- Heat from inside and outside
- Short drying time
- Excelent drying results

Disadvantages:

- larger invesment
- only reasonable for larger transformers

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THE WORKING PRINCIPLE

Why low frequency current drying

Heating up of coils from the inside by applying 20 – 50% of nominal current

Using the lowest possible voltage to avoid flash over (considering the Paschen law)

Perfectly controllable temperature inside the transformer

"No" temperature limit

Short drying time

Best drying results

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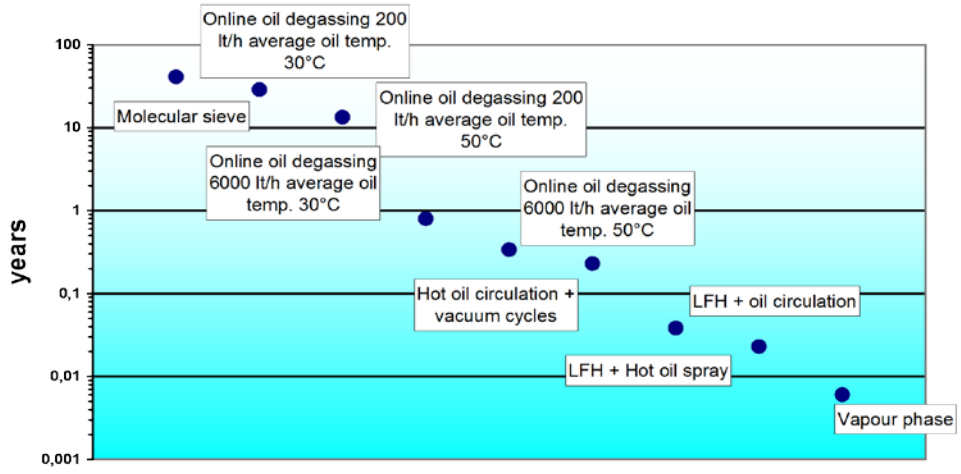
PROCESS COMPARISON (TIME)

Drying time to dry a 400 MVA transformer with 14 tonn insulation from 3% down to 1,5 % average humidity



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Drying of Transformers

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Drying by vapor phase method

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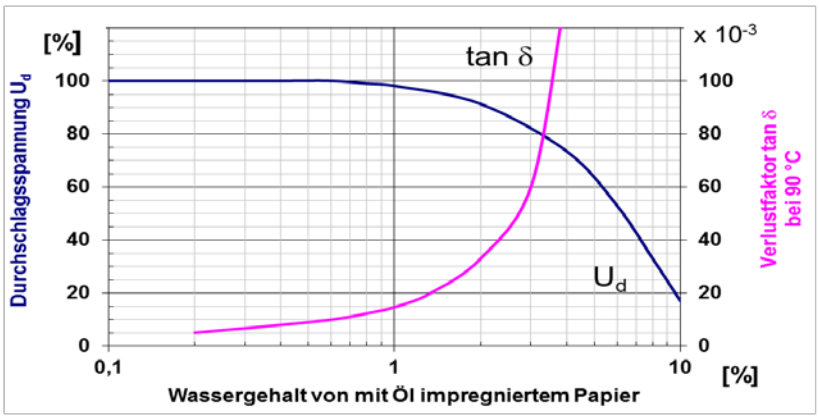
Decrease of the electrical properties

- Decrease in the breakdown voltage
- Increase in the loss factor



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Drying of Transformers

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Requirements for an ideal drying process

- Uniform heating
- Average moisture content of the insulation of <0.3%
- Reduced depolymerization
  (Absence of oxygen during the drying process)
- Removing residues from transformer oil (repair transformers)
- "Short" drying times

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The technology of the vapor phase drying

The most efficient process for drying active parts of new power transformers - State-of-the-Art Technology

- Introduced about 50 years ago - long experience
- Operating under vacuum to reduce the depolymerization process

Principle

1. Solvent is evaporated
2. The solvent vapor condenses on the colder parts of the active part
3. Uniform heating of the transformer
4. The water evaporates and is extracted from the transformer

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Drying of Transformers

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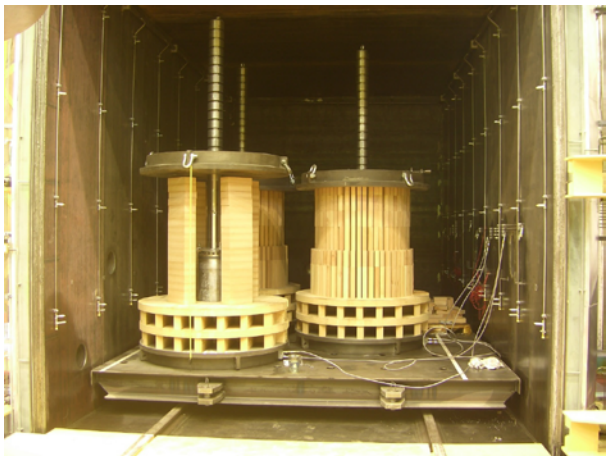
Drying and pressing windings



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Technologies for transformer drying

Drying at the workshop:

After the insulating liquid has been removed, heat and vacuum extract water from the solid insulation.

- **Transformer operation has to be interrupted.**
- **Transformer has to be transported to the workshop.**
- **Time consuming procedure >>> high loss of use**

Drying on site:

Heat and vacuum are applied on the transformers´operation site.

- **Transformer operation has to be interrupted.**
- **Insulating liquid has to be drained and stored.**
- **Transformer tank has to be tight for the vacuum.**
- **Efficiency of the drying is equivocal:**

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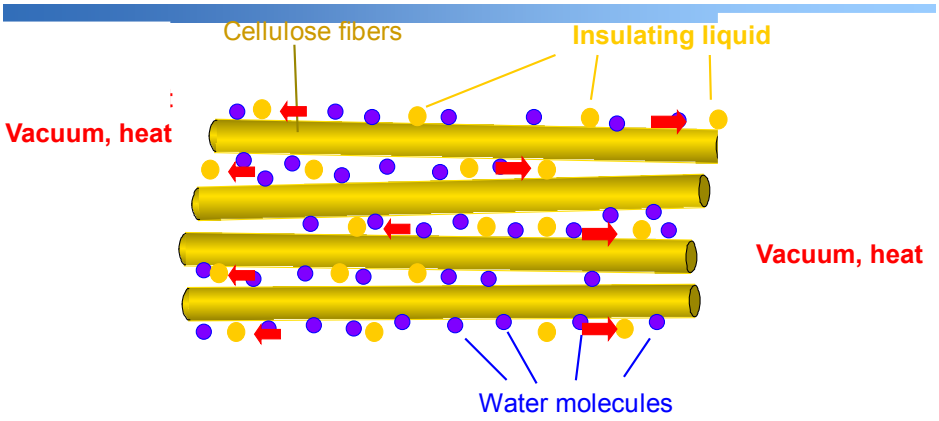
Drying of Transformers

Technologies for transformer drying



Drying potentially endangers the solid insulation as the winding coil usually is not re-fastened after drying (>>> stability in case of shorts?)

Technologies for transformer drying

Drying as a continuous procedure:

The liquid insulation is continuously dried during transformer operation.

Through the drying of the liquid insulation the solid components are dried as well.

Such systems are advantageous for already impregnated transformers with moderate water strain. The drying is performed during regular transformer operation, thus no outage is required.

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Technologies for transformer drying

Drying as a continuous procedure:

One of the most important advantages of continuous drying procedures in comparison to other on site drying procedures is the considerate treatment of the insulation

Caution: It should be looked out that the system does not influence the amount of failioure gases as the failiour gases are important for protection and diagnosis purposes in a transformer

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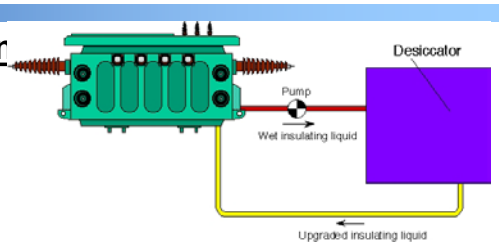
Continuous transformer insulation drying

Applicable techr



Vacuum and heat

Hygroscopic materials (molecular sieves, Zeolites)

Interfering the Dissolved Gas Analysis

Use of the water equilibrium at different temperatures

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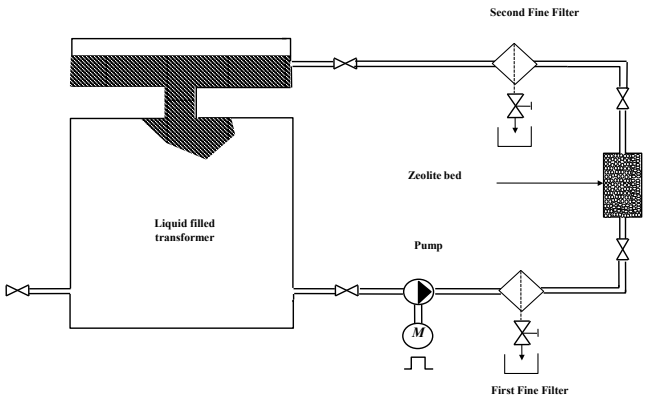
Continuous transformer insulation drying with Zeolite

Continuous drying with Zeolite

- Zeolites can absorb up to 30% of their weight in gases and over 70% of water
- There are different kinds of Zeolites
- For drying purposes Zeolite A3 is suitable, as it absorbs beside water oxygen molecules
- Both water and oxygen are important for the ageing of the insulation
- Wet Zeolite can be dried easily

Realization

Online drying procedure for liquid immersed transformer with Zeolite as drying element



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Continuous transformer insulation drying with Cellulose

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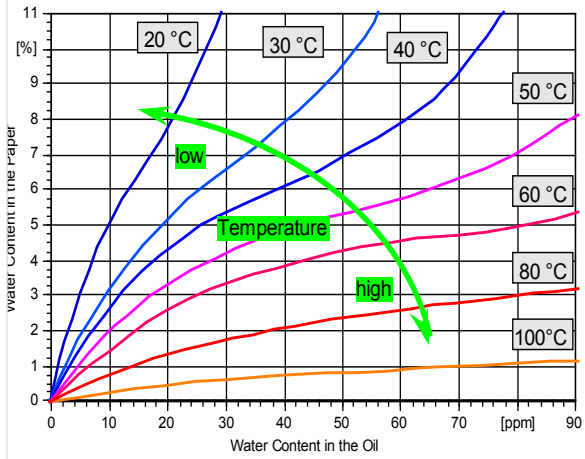

- Solid insulation dispenses water to insulating liquid at high temperatures
- Solid insulation incorporates water at low temperatures

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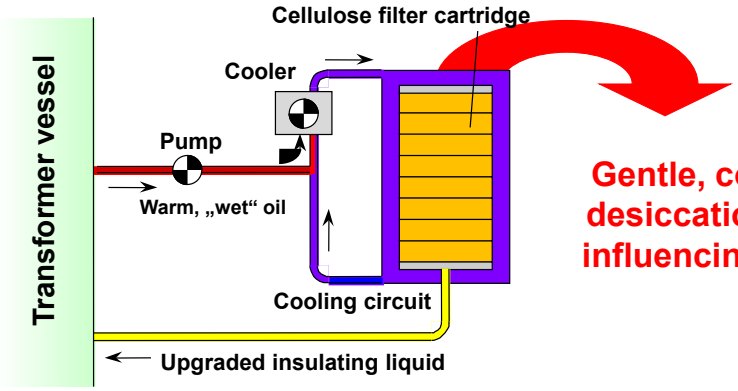
Realization



Gentle, continuous desiccation without influencing the DGA

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Enhancing the Extraction Rate

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The rate of extracted water is limited by the water solubility of the insulating liquid.

Liquids with higher hygroscopicity like ester liquids thus enhance the drying velocity.

The electrical properties of ester liquids are comparable to mineral insulating oil while their hygroscopicity is about 30 times higher.

As mineral insulating oil and ester liquid are completely miscible the retrofilling of a previously with mineral oil insulated transformer is possible without the risk for emulgations, which potentially reduce the electrical strength of the mixture.

Enhancing the Extraction Rate

45/x

For transformers with high amount of humidity in the insulation it is recommended to use a system with a combination of Zeolite and Cellulose drying procedure