

# Q&A

## POWER TRANSFORMER DRYING: VAISALA

TRANSFORMER  
TECHNOLOGY  
Q&A WITH PAUL  
KOESTINGER,  
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# VAISALA

Transformers are critical components in electrical transmission systems. However, moisture can degrade transformers and reduce their lifetime. In this Q&A article with transformer drying experts [Paul Koestinger](#), owner of Retranol GmbH, and [Senja Leivo](#), Senior Industry Expert at Vaisala, we will explore common questions about moisture in transformers, its effects and key drying methods to remove moisture and extend transformer life.

### What is the purpose of drying a power transformer — and why do it?

Concerning drying power transformers, there are three main points:

- 1. Life expectancy:** The moisture in the transformer governs the degradation of the paper. The more moisture you accumulate in the paper, the shorter the lifetime of the transformer. Keeping average paper moisture content to 1% or below optimizes insulation life. But normal levels of around 2% still allow decades of safe operation before the end of life.
- 2. Dielectric breakdown:** When a transformer cools down, cold oil can contain less moisture than hot oil, which may result in free water in the oil and in the transformer in the dielectric field, which can lead to a cascading flashover and insulation failure.
- 3. Overload capability:** Overloaded transformers can create bubbles due to the evaporation of moisture in the transformer. The higher the moisture content, the lower the temperature where these bubbles form. Since bubbles immediately precipitate dielectric failure, the overload capacity is reduced with high moisture.

Temperature dictates paper degradation. The higher the transformer's temperature, the faster the paper degradation. Moisture also has a significant influence on the speed of degradation. The more moisture in a transformer, the quicker the paper will degrade.

Once a power transformer's insulation paper becomes brittle, the transformer approaches the end of its lifetime. Degraded paper does not mean the transformer will fail immediately, but a short circuit in the grid will result in significant movement on the windings. If the insulation paper around the copper winding starts breaking off, the transformer can short circuit.



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### What are the primary sources of moisture in power transformers?

Moisture can make its way into transformers through several routes, even in units that should theoretically operate moisture-free:

- **Breathing:** As transformers operate, the bulk oil expands and contracts with temperature fluctuations. This causes the tank to breathe, with the oil level rising and falling in the conservator. To replace the volume, the space is designed to breathe through a silica gel breather that dries the incoming air. However, the gel cannot dry air down to the deficient moisture levels inside the tank. Slow ingress still occurs over decades of breathing, especially in industrial transformers with frequent load cycling and oil movement.
- **Broken gaskets:** Any external oil leaks around gaskets, valves or seals allow moisture to migrate into the tank while oil leaks out. The concentration gradient in power transformers drives moisture into the paper insulation. Even tiny leaks allow moisture accumulation over months or years of operation.
- **Paper degradation:** Over decades of continuous operation, the cellulosic paper insulation slowly degrades through thermal aging, oxidation and hydrolysis from small amounts of accumulated moisture. This degradation process produces water as a byproduct, gradually increasing the overall moisture content within the transformer over its lifetime.

Another crucial topic when discussing drying is moisture distribution in a transformer. While small amounts of water vapor and droplets dissolve or suspend within the insulating mineral oil, the vast majority of moisture in a transformer migrates into the solid cellulose-based insulation around windings.

Over 99.8% of the total moisture content within a transformer resides in the cellulose paper insulation, not the bulk oil.

For example, consider a 400 MVA transformer containing 15 tons (33,000 lbs.) of cellulosic insulation and 60 tons (132,000 lbs.) of mineral oil. An average insulation moisture content of 3% would contain approximately 450 liters (120 gallons) of moisture bound in the solid insulation and only 0.6 liters (0.16 gallons) dissolved in the oil (at 30°C). The moisture distribution is not entirely even throughout. Thicker blocks and barriers are less accessible and absorb less over time. About 50% of the total cellulose interacts more actively with the oil, exchanging moisture.

Ester fluids can contain roughly 20 times more moisture than mineral oil before becoming saturated. But even with esters, over 97% of total moisture remains concentrated in the paper insulation.

Moisture can infiltrate transformers from several sources over decades of operation.

### When does moisture accumulation warrant drying a unit?

While no moisture should be present in new transformers, ambient humidity, leaks and degradation gradually increase moisture.

Three common scenarios call for a complete transformer drying process:

1. The first and the most common is following any major internal maintenance or repairs. After exposing the core and windings to ambient air and moisture, a drying process helps remove any moisture. The longer the exposure period with oil removed, the more critical a complete drying becomes. A few days of exposure introduces minimal moisture, while repairs taking weeks or months cause severe moisture increases.
2. When sampling and testing indicate high moisture content in oil and insulation, general guidelines — like the IEC standard 60422 — suggest drying is beneficial above 20 PPM moisture in mineral oil. Online monitoring provides the best trend data to identify increasing moisture over time.

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When it comes to drying itself, the main factor is the diffusion speed. The more moisture we remove in one hour, the better the drying efficiency. This diffusion speed or drying speed is influenced mainly by temperature. The hotter you heat some material, the easier it is to remove moisture.

And because humidity is a significant factor, drying a transformer from 4% to 3% is much easier than from 2% to 1%. The lower the moisture content, the harder removing moisture from the transformer becomes. When extracting moisture from a material, we have to create a pressure difference between the inside of the material and the outside. Applying vacuum is always an excellent idea whenever you want to dry transformers. Also, the material properties are fundamental to understand because drying thin paper around the copper winding is much easier than the thick blocks on the material. Speaking of drying in the field, the issue of oil impregnation exists. Understanding your material is essential because when you dry it in the factory, there is no oil on the paper. In the field, you always have oil-impregnated material that blocks the moisture going in but also prevents the moisture from coming out. So, more powerful systems are necessary to remove the same amount of moisture as in the factory.

Consequently, vacuum is a critical issue in the drying process. A perfect drying situation demands higher temperatures and vacuum simultaneously.

Reaching a specific temperature is vital. The higher the temperature in the drying process, the faster it is. So, your drying time will be shorter, but you also have temperature-dependent paper degradation. You cannot heat a transformer to 200 degrees and finish within one day. You must have an equilibrium between perfect temperature and what kind of degradation you have in the process.

**Determining when to proactively dry transformers depends on various factors, but what practical methods can be applied once drying is deemed necessary, and which is the most efficient?**

Transformer drying techniques range from relatively simple processes to highly engineered solutions for large units.

**Factory vapor phase drying:** Considered the gold standard for the lowest moisture content, vapor-phase drying heats the transformer active part to 130° using vaporized solvents without oxygen. This facilitates deep drying over three to five days. Factory systems use sealed chambers and hydrocarbon vapor, achieving residual moisture levels below 0.5% in insulation. New large units are all dried this way, but bringing vapor-phase ovens into the field is not due to explosion risks.

**On-site vacuum drying:** Mild heat is applied through hot oil circulation and then pulling a strong vacuum on the tank. This removes moisture directly from the windings and paper by vaporization. As energy is consumed by evaporating moisture, the process cools down over time. Depending on the transformer size, multiple vacuum cycles with heating phases may be required to reach target moisture levels.

**Hot oil spray technique:** Hot oil is sprayed directly onto windings while vacuum is held. This way evaporation of moisture can happen at the same time as heating the insulation. This approach is often used in shell-type transformer designs.



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**Low-frequency drying:** A low-frequency power source runs a current directly through transformer windings to generate internal heating from 20-50% of a nominal current. With no oxygen present, high temperatures safely dry paper. This process is often combined with hot oil spray and presents the most powerful drying technique on site.

**Online oil drying/degassing:** Continuously circulate a side stream of oil through an external vacuum dehydration unit and return degassed oil to the tank. Although very slow, the gradient between dry oil and wet windings during this process allows gradual moisture removal over months or years and keeps the oil clean.

**Molecular sieve dryers:** Install temporary molecular sieve filters that continuously circulate a portion of the oil volume, slowly reducing moisture levels in the circulating oil. Gradual paper drying occurs over months or years.

#### What technique is the most efficient?

That depends on transformer size and your needs. Let's compare the different methods with our example unit, the 400-MVA transformer, with 3% moisture.

Drying this transformer in the factory, its vapor phase will take some days. This transformer needs a week to dry if we use the low-frequency technique. In the method with hot oil and vacuum, that's a month of drying time. If we go to oil circulations, even with high temperatures, consider a year or much more with small drying machines with minimal oil circulation. So, with a smaller transformer, consider more straightforward techniques. With big transformers, adopt a more advanced approach.

Numerous drying techniques can be applied in the field to remove moisture from transformer insulation and oil.

#### After completing an on-site drying process, how can utilities confirm that the drying process was successful?

Controlling the drying process is a complex task. However, controlling the moisture extraction rate helps provide the most valuable data to guide drying process control and determine when satisfactory dryness has been achieved.

##### Measure hourly moisture extraction rate

By installing dew-point sensors on vacuum lines or measuring moisture at the exhaust of the vacuum pump, the moisture extraction rate can be calculated in grams per hour or ton of insulation.

Target 5-20 g/hr-ton initially in factory vapor. Expect substantially lower extraction rates in the field due to oil impregnation effects and lower process temperatures. But higher rates indicate the presence of higher levels of moisture.

##### Monitor vacuum level evolution

The magnitude of vacuum pull provides the driving force to remove moisture from insulation by vaporization. As moisture decreases over time, vapor pressure drops and vacuum increases. When the vacuum level flattens out, the air ingress and the suction capacity are equalized.

##### Check measurements after oil filling

Final dryness validation relies on methods like Dielectric Frequency Response (DFR, DIRANA, PDC). However, these are not useful during the actual heating process. To get a good understanding through a moisture in oil sample will take months.

Extraction rate and vacuum trends are the best real-time guides for controlling on-site drying processes.

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#### What special considerations apply when drying ester-filled transformers?

Ester fluids can absorb and dissolve far higher quantities of moisture than traditional mineral oils. This increased solubility allows faster surface moisture removal on wet insulation and more effective drying by circulating oil through a dehydrator.

Despite the liquid's high moisture capacity, most moisture remains trapped within the cellulose paper insulation, not the bulk fluid. Simply changing the liquid without internal drying does not dry the transformer.

The difficulty with esters, especially natural esters, is that they tend to polymerize when they are exposed to heat and oxygen at the same time. This needs to be considered when selecting the drying technique. Hermetic sealing systems are far more critical with ester fluids since external leaks allow much faster moisture ingress compared to mineral oil.

Ester-based fluids present unique drying considerations compared to traditional mineral oil-filled transformers. However, another critical transformer design factor also warrants attention during drying — the compression force clamping windings and core steel.

#### How critical is monitoring winding clamping pressure changes during drying?

Removing moisture from paper insulation can lead to some loss of clamping pressure on transformer windings.

Normal operation leads to gradual loss of the original clamping force over decades of thermal cycling, material degradation and mechanical vibrations. Limiting the target residual moisture minimizes drying-related clamping loss based on field experience. Re-clamping before drying showed to be sufficient in most cases on old units.

Moisture accumulation presents a vexing challenge in maintaining power transformers. While drying requires care and expertise, moisture reduction will extend the safe operating lifetime of these critical assets. When faced with moisture issues, transformer owners can leverage established drying methods to return transformers to optimal dryness, managing transformer life cycles for decades of safe operation.

Download the definitive [Vaisala eBook on Moisture in Transformers](#). This companion to our [renowned webinar series](#) is full of the latest practical and scientific advice on measuring moisture in power transformers.

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