Moisture in Transformer Insulation

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EXPERTS GRAPPLE NOT SO MUCH ON THE DESIRABLE MOISTURE LEVELS FOR THE SOLID INSULATION, BUT RATHER WITH THE EXACTNESS OF ESTIMATING THE WETNESS OF IN-SERVICE UNITS.

Intuitively it is agreeable to all that moisture in transformers is not desirable. This article has as its goal to offer a very practical and experience-based profile that addresses several commonly asked questions with answers and opinions from both our industry and experience with having dried more than 500 transformers with moisture issues.

What are some of the most commonly asked questions?

1. What are the different moisture levels to be aware of and how is a transformer evaluated as slightly, moderately or extremely wet?
2. Is the moisture that shows up in the oil a reliable indicator of the condition of the solid insulation?
3. What are the accepted methods of drying insulation? Conversely, what has shown to be ineffective in drying a transformer?
4. How does moisture affect aging and reliability?
5. What can be said for the economic effects of moisture on a transformer and the costs for restoration to reliability?

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Bob Rasor PE has over 40 years of service in this industry. He has been active in IEEE and recent chair of the 2015 revision to C57.106, an IEEE Guide for Acceptance and Maintenance of Insulating Mineral Oil in Electrical Equipment. He is also currently serving on several Working Groups including a new moisture guide where he is chairing one of the task forces. Bob is the Technical Director for SDMyers LLC.

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What are the different moisture levels to be aware of and how is a transformer evaluated as slightly, moderately or extremely wet?

Experts grapple not so much on the desirable moisture levels for the solid insulation, but rather with the exactness of estimating the wetness of in-service units. Again, if the question is what is considered dry insulation, there are few disputes.

A new, dry transformer with under 0.5% moisture in the insulation is the norm. How much of the total moisture is in the paper insulation and how much is in the oil? Only about 1%, or even less of this water is in the oil. An interesting way to show this involves considering a 1,000-gallon transformer with an estimated 1,100 or so pounds of porous/paper insulation. If one-half percent of this weight is moisture, and if completely in the oil, it would be just over 5 pounds of water dissolved in 1,000 gallons (7,500 pounds) of oil. This would mean a perfectly dry transformer would have 780 ppm of moisture in the oil! But we can see how it is the reverse, as depending upon the temperature, often under 10 ppm, but, no more than 10 to 25 ppm of water is the typical expected water content in a dry transformer.

What about a transformer starting to show signs of moisture issues? How wet is too wet? And first of all, how did it get wet? There are three basic ways a transformer can become wet:

1. The unit somehow came from the factory improperly dried. This is not all that common. With factory testing including an Insulation Power Factor test before shipping, a value around 0.5% indicates dryness. Lesser Basic Insulation Limits (BIL) can tolerate 1%, and some distribution units reportedly allow 2%. In a general sense, the Insulation Power Factor values at lower levels like these align well the % Moisture by Dry Weight in the solid insulation (%MBDW).

2. The next cause of moisture in a transformer comes from aging of both the oil and the paper insulation, because moisture is a by-product of the chemical reaction of both oil and paper with oxygen, heat and even minute levels of moisture. Copper is also a catalyst for oil oxidation, making the control of moisture, heat and oxygen even more desirable. If there are no rising acid levels, no indication of the creation of furans (a chemical byproduct of the breakdown of the paper insulation) and a good D1816 dielectric strength, this cause becomes less likely.

3. Lastly, and most commonly, moisture enters transformers by ingress. The oil level in a transformer will rise and fall due to changes in temperature based on changes in load and ambient. With these changes, the oil may vary in volume as much as 4-5% a day. If a unit is not sealed properly, the oil preservation system will allow moisture to be drawn in as the oil cools and decreases in volume. Once in, it dissolves and does not reverse migrate.

Once a unit is showing elevated moisture levels in the oil, the paper insulation is also affected. Figure 1 shows the variation experienced due to temperature and the migration of water from the insulation to the oil, and vice-versa. This transformer was dry for about 10 years and sampled twice a year – once in the summer and once in the colder months. The warmer the oil, the more the moisture migrates. At year 10 or so, the unit developed a leak and moisture levels became unacceptable. More on this in the next section.

Figure 1. Moisture and field dry-out - 138 kV transformer 8,400 gallons [1]

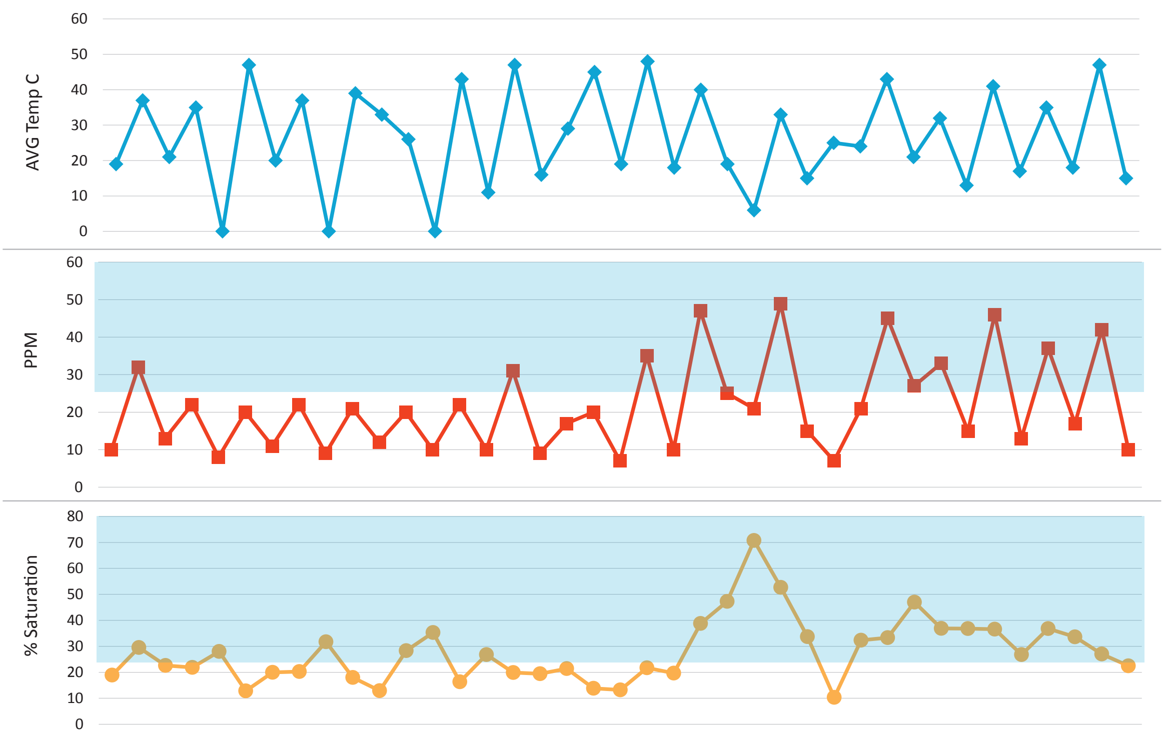
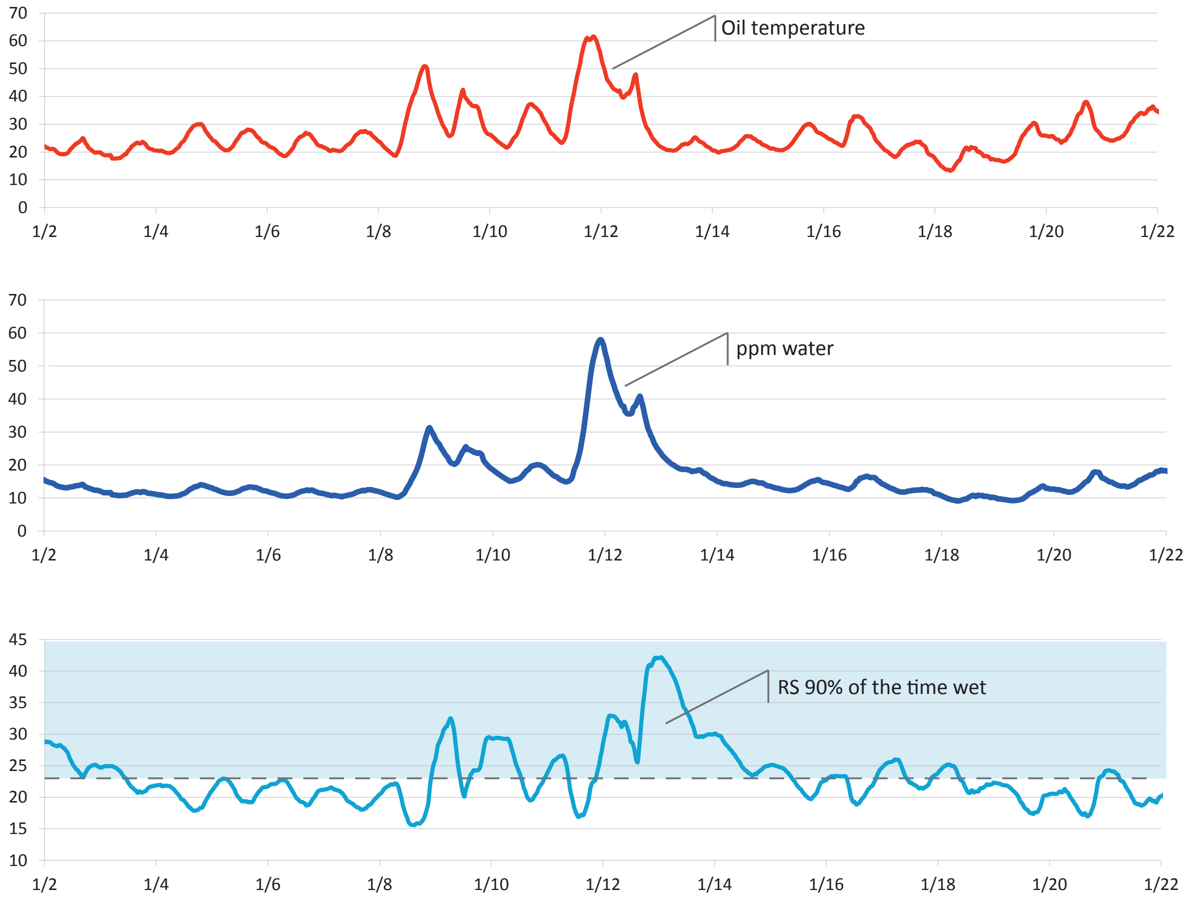


Figure 2. Migration of moisture in and out of the oil in a transformer with changes in temperature [2]



Is the moisture that shows up in the oil a reliable indicator of the condition of the insulation?

It was stated earlier that most of the moisture in a transformer is NOT in the oil. However, the water in the oil is still a reliable indicator of moisture in a transformer.

How wet does the oil become if the biggest "holder" of the moisture is the porous insulation? There are several methods that have been developed to relate moisture levels in the oil to the moisture in the solid insulation. They have some variation, but most involve having some measurement of temperature and a graphical or numerical relationship between the ppm of moisture in the oil and the % Moisture in the paper insulation. The results of these methods are used as estimates. In studying the different methods, even though they vary and can have differing results, they can all identify a wet transformer. And the useful aspect of % Saturation is that it stays elevated even if the moisture retreats back out of the oil and into the insulation when temperatures drop.

In Figure 2, from IEEE and EPRI studies, a transformer studied in Australia shows the dramatic migration of moisture in and out of the oil in a transformer, with changes in temperature.

If only a Parts per Million (PPM) reading is used, it will vary to where even a wet transformer can give an apparent dry PPM result if the oil is cool enough. In both figures, where the current IEEE Guide C57.106 [3] has a 25 PPM limit for a 138 kV class transformer, readings varied from 15 to 50 ppm in Figure 1 and 10 to 60 ppm in Figure 2, solely based on the oil temperature. The same charts show that the % Saturation was elevated independent of temperature.

Opinions vary on where the limits are set to determine wet versus not-so-wet versus dry. Based on our experiencing these opinions first-hand, at 30% Saturation most would agree the transformer is becoming a concern.

There is also another factor that can affect how representative an oil sample can be to judge the wetness of the insulation. Most oil samples are drawn from the bottom valve of the electrical equipment. These valves are known to collect moisture that can be higher than the water content of the oil in the main tank. Several articles have been written on this, and other oil service companies have determined that this happens. The valve, sticking out into the cooler ambient air, tends to have moisture condense inside the valve, and then it gets trapped in the valve since most are globe valves and do not have a straight, open path into the main tank. SDMyers profiled over 500 samples that tested high in moisture. When resampled with extra flushing, only 70% of them were actually wet. It should be routine to verify first-time high moisture levels with a sample that has at least one gallon of oil flushed for every inch of valve size.

What are the accepted methods of drying insulation? Conversely, what has shown to be ineffective in drying a transformer?

This portion of the paper has the least amount of controversial opinions. IEEE C57.140 Guide for Evaluation and Reconditioning of Liquid Immersed Power Transformers [4] has in several revisions expanded upon only a few methods for drying wet insulation.

1. **Factory drying** is perhaps the most effective, but the least practical for owners – and most costly. Once taken out of service and shipped to a repair facility, there are at least three methods for drying, with most including untanking the core and coil assembly. Baking, vacuum drying, or a process known as Vapor Phase Drying are the ways repair shops can remove moisture from the insulation. Typically, electrical testing is a follow-up means to verify a good outcome.

2. Next in terms of cost, are the field **vacuum dry-out methods**, of which there are several. This procedure will require a vacuum rated transformer and an outage for one to two weeks, as well as around the clock vacuum drying, usually with a cold trap and then a dew point check before filling – also costly. From basic physics, when vacuum is applied to wet paper insulation, once the vapor pressures are satisfied for vaporization, a transformer can be dried. There are field details to this in as much as many wet units that are vacuum rated have thousands of gallons of oil and coils needing to be heated with sometimes hundreds of thousands of pounds of mass. If the oil is the means to heat the core, it can be heated in bulk and then quickly drained or hot-oil-sprayed.

Alternatively, the windings can be heated by DC current or new magnetic induction methods, but regardless, the vacuum from a field processor flashes off the moisture and it can be trapped and measured or electrically tested to confirm an endpoint. There are indeed several ways to help confirm a field dryout endpoint:

The Piper Chart
Once the dryout is completed, and the transformer is still empty, vacuum is applied at a known winding temperature, and the Piper Chart is read for an estimation of dryness. The Piper Chart, shown in Figure 3, from IEEE C57.93 Guide for Installation and Maintenance of Liquid Immersed Power Transformers [5], has lines of %MBDW with respect to temperature on the x-axis and vacuum on the y-axis. During a vacuum dry-out, it is important to know the temperature of the insulation.

Cold Trap Measurement
If drying by attaining a heated core and coil, and then pulling vacuum with a cold trap, IEEE guides point out that collecting diminishing moisture and then only 2 ounces of moisture per hour in a cold trap is an indication of the completion of moisture removal (provided there is at least 40°C in core temperature). Some cold traps use very efficient refrigerants and a fast cycle defrost. It is still not uncommon for liquid nitrogen or even dry ice and acetone to be used to attain the minus 80°C temperatures ideal to sublime moisture to a frozen state.

Dew Point Test
After drying, with the drained transformer, dry air or nitrogen is applied to the transformer at minus 60°C dewpoint or dryer, and to a pressure of 2 psi. After 24 hours, the slightly pressurized dry gas is relieved through a dew point meter. If the transformer is dry, the dew point of the gas will have stayed around minus 50°C. Charts like the one shown in Figure 4 have been developed and used by Original Equipment Manufacturers for decades to estimate a dry transformer. Again, as with most moisture related metrics, temperature plays an important role.

Electrical Testing
Lastly, after filling, confirmation of dryness can be estimated by electrical testing. The insulation power/dissipation factor is used, or newer to the industry, a test called Dielectric Frequency Response.

One additional noteworthy discussion comes from the notion that a wet transformer can be efficiently dried by dehydration "passes" of hot, dry oil in the transformer. While a hot oil circulation treatment will indeed dry the oil, the migration of the other 99% of the moisture into the oil is much too slow to achieve complete moisture reduction in the windings.

There are many case studies where the oil is dried (even with up to 10 circulation passes) with great final oil results, only to realize the leach-back effects of 99% of the water, having the oil again show high readings of moisture, because the paper insulation is still wet. Only surface moisture from the insulation is believed to be removed with hot oil circulations. Also, IEEE C57.140 [4] limits this processing to only surface moisture for the insulation, stating the following:

7.1. Off-line de-energized processing methods. For non-vacuum rated transformers:
b) Hot liquid method consists of heating the entire volume of liquid in the transformer and passing it through a vacuum degasifier/dehydrator to remove the moisture from the liquid and reheating the liquid as it is returned to the transformer. The hot dry liquid will pick up moisture from the surface of the active parts of the transformer and that moisture is removed from the liquid using the vacuum dehydrator/degasifier. This is also a slow process because moisture deep within the active part must migrate to the surface areas to be removed by the hot liquid.*

ON-LINE DRYERS USE A SLOW CIRCULATION METHOD WITH DRYING MEDIA TO REMOVE THE MOISTURE AS THE TRANSFORMER WINDING RELEASES IT.

Photo: SDMyers

3. **On-line (energized) Transformer Drying** is another method that has been shown to be successful. This method is especially useful for field moisture reduction for non-vacuum rated transformers. IEEE C57.140 [4] states the following:

> **7.2. On-line energized liquid dry-out method**
> On-line transformer moisture removal systems have become increasingly popular to extend the operating period of a transformer that has had an increase in moisture level or may be gassing and needs to remain in service until a scheduled outage can occur.*

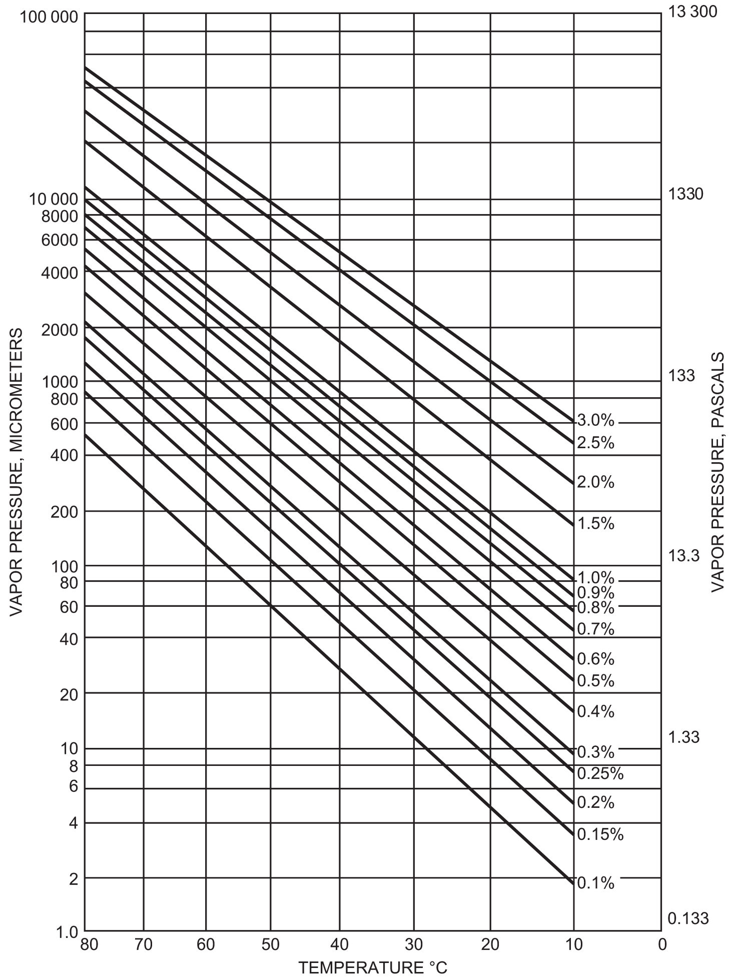
On-line dryers use a slow circulation method with drying media to remove the moisture as the transformer winding releases it. Temperature again plays a role as the increased solubility of the oil will allow moisture to migrate out of the insulation where the dryer can remove it. This process can take upwards of a year in some cases, while other smaller transformers may dry somewhat faster.

In Figure 5, a dryer was equipped with moisture sensors, and a transmitter and posts data for viewing and recommendations.

As the moisture leaves the paper and other porous materials, the transformer slowly dries. In this example, as the transformer

Figure 3. Moisture equilibrium chart Piper [5]

IEEE Std C57.93-2019
IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers



NOTE—This chart was prepared using information from a Piper Chart, which was extrapolated and interpolated from published data on cotton paper. Piper gave a multiplication factor of 1.7 to use for Kraft paper (non-thermally upgraded). This chart incorporates the 1.7 factor, and the values obtained need to be corrected. It should be noted that equilibrium moisture content of cellulose is dependent on whether equilibrium is approached by absorption or desorption, since there is a hysteresis effect.

Figure B.2—Moisture equilibrium chart (with moisture content in percent of dry weight of insulation) Piper [B23]

ELEVATED MOISTURE LEVELS, BEING MORE PROBLEMATIC IN LARGER TRANSFORMERS, HAVE A COMPONENT OF SERVICE COST VERSUS OUTAGE COST TO CONSIDER.

* IEEE C57.140-2017 – Adapted and reprinted with permission from IEEE.

Figure 4. Dew point chart

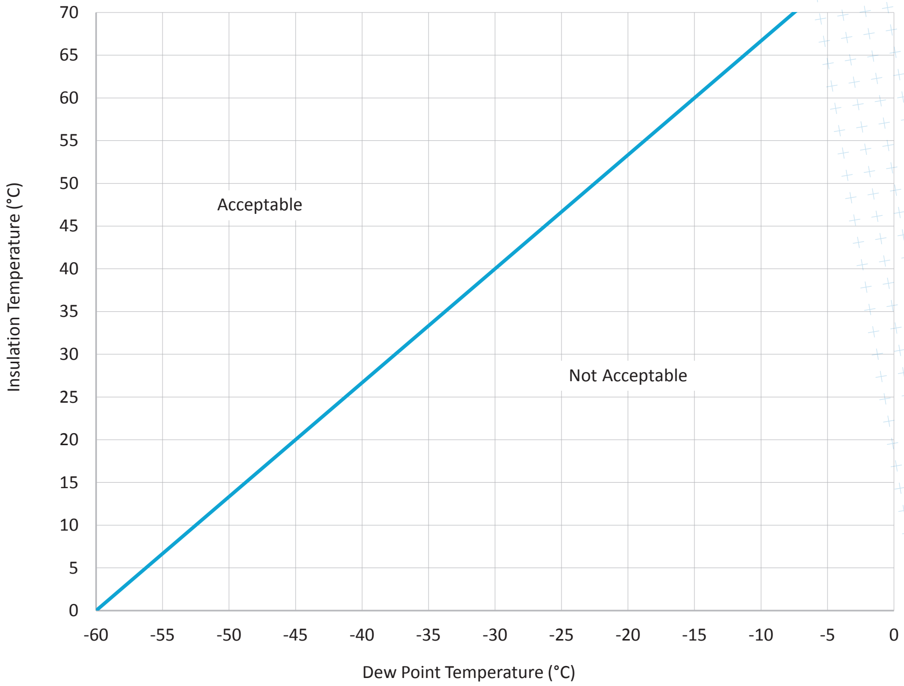


Figure 5. Transformer dry-out with on-line dryer

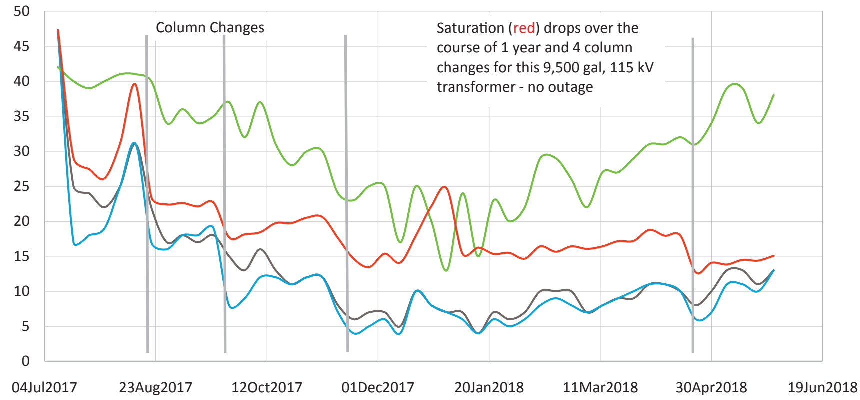


Figure 6. Mineral oil saturation curve

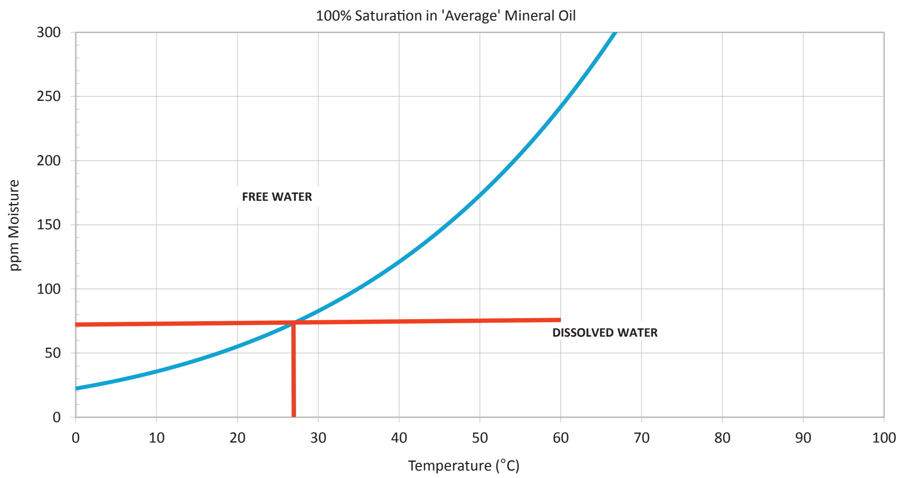


Photo: SDMyers

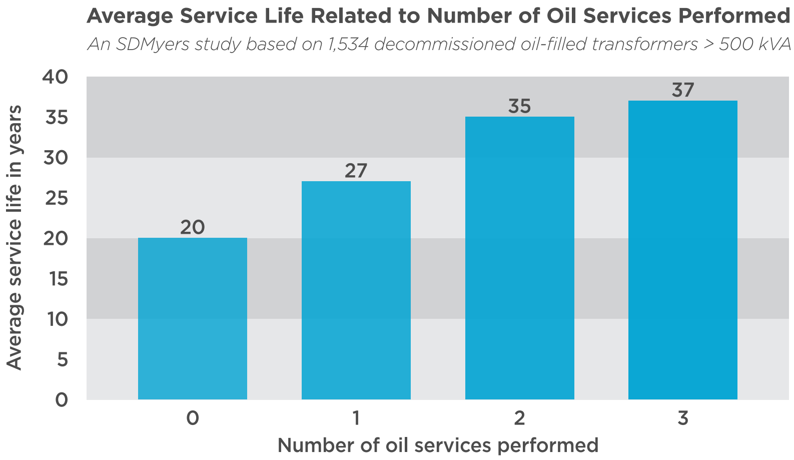
insulation dries, the moisture in the oil is first lowered, and then remains under 10 ppm. Profiles like this are common, although the time frame varies by the severity of the moisture levels and the size of the transformer. By transmitting data, the condition of the filters is monitored and aid in the efficiency and time frame for the dry-out.

How does moisture affect reliability and aging?

There are three or more potential modes of attack that moisture poses for a transformer – two are acute, and one more chronic. First the acute concerns:

1. **Free water**. Normally from a leak, this condition has an effect on the dielectric integrity of the oil, i.e. there is a possibility of dielectric failure. A variation of this issue arises for transformers with a higher % Saturation with varying loads, especially in the winter. For example, a transformer with 30% saturation at 60°C would become oversaturated if the temperature suddenly dropped to 27°C, Figure 6. The oil in the radiators can oversaturate and cause the formation of water droplets, potentially leading to failure.
2. Another acute failure concern is when a transformer has a **very high moisture content at elevated temperatures**. At 4.5% moisture in the paper insulation and 90°C, reports indicate the moisture can vaporize at the hot spot and cause localized dielectric failure [6].
3. **A third concern is accelerated aging**. It has been known for many decades that the aging rate of paper insulation is proportional to its moisture content. In other words, the paper aging rate is doubled when the moisture in the paper is doubled. Conversely, the paper aging rate is cut in half when the moisture in the paper is cut in half. Further, if the paper aging rate is cut in half with half the moisture, then the remaining life of the paper is doubled. So, the moisture content has a profound effect on the life of the paper insulation, and thus on the life of the transformer.

Figure 7. Average service life related to number of oil services performed. A study based on 1,534 decommissioned oil-filled transformers >500 kVA [7]



References

[1] B. Rasor, "IEEE TF Moisture in Oil", Fall 2012, Milwaukee, Wisconsin

[2] O. Roizman, "IEEE TF Moisture in Oil", Fall 2010, Toronto, Ontario

[3] C57.106-2015 - IEEE Guide for Acceptance and Maintenance of Insulating Mineral Oil in Electrical Equipment

[4] IEEE C57.140-2017 – Adapted and reprinted with permission from IEEE. Copyright IEEE 2017. All rights reserved.

[5] C57.93-2019 - IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers

[6] A. Stannett, *The Problems of Water in Transformers*, 1965

[7] R. Rasor, D. Roberts, A. Shkolnik, "Transformer Reliability – A Statistical Look," in *Proceedings of 2014 CIGRE Canada Conf.*

What can be said for the economic effects of moisture on a transformer and the costs for restoration to reliability?

The most economical way to keep moisture and its effects at bay is by prevention. Regular fluid testing and visual inspections for leaks are the key. Although less common these days, units with desiccant dryers must also stay well maintained. Moreover, elevated moisture levels, being more problematic in larger transformers, have a component of service cost versus outage cost to consider. A 50 MVA transformer could be dried in just two weeks with a field vacuum dry-out. This same unit may take over a year to dry with an on-line dryer, but there is no service interruption. The cost of a field vacuum dry-out is estimated at double the cost of service with or purchase of an on-line dryer.

Additional consideration needs to be given to oil qualities. Whether a vacuum dry-out or an on-line dryer, there are oil conditions that should be corrected with either method of dehydration. Hot Oil Cleaning of the oil and paper insulation help maintain reliability and restore life. A study of 1,500 transformers with issues of moisture, elevated acid number, or with the need for replenishment of oxidation inhibitor showed that units that received the needed service had on average almost six additional years of life per service performed, Figure 7.

Conclusion

Moisture in transformers has become much more understood over the past ten years. Moisture mitigation solutions in addition to the traditional vacuum processes allow for economical field restoration to a more reliable condition. The effects of allowing elevated moisture levels in transformers range from acute to chronic. Moisture levels can be field-corrected, along with their cause – often the result of aging gaskets. By correcting the source of the moisture and then removing the moisture from the paper insulation, the reliability and remaining life of the transformer can be significantly improved.