



Best Practices for Transformer Testing and Maintenance

by **Jason Dennison**
and **Bob Rasor**

A well-maintained transformer can last more than 50 years. If you catch a fault condition early, there are corrective actions you can take to prevent further damage to the transformer and avoid costly downtime from catastrophic failure.

Why do transformers hum?

Because they don't know the lyrics.

Most of the time the transformer "just sits there and hums like it always does" behind a fence, out of sight, out of mind, which can give a false sense of security of just how much risk resides in the transformer should things goes awry and in terms of business expense and production loss.



Sampling and Inspection

Liquid sampling and visual inspections are crucial parts of any effective transformer maintenance program. It's most efficient to schedule inspections at the same time as liquid sampling because the person pulling the sample is already on site. After taking a fluid sample, the technician can inspect and record the vital pieces of information about the transformer, such as:

- **Gauge readings** – Record temperature and liquid levels.
- **Preservation system** – Check gas pressure, desiccant condition, and pressure relief devices.
- **Radiators** – Check for corrosion, fan operation, and pumps.
- **Surfaces** – Check for corrosion, assess the condition of the paint, and check the seals.
- **Bushings** – Check for corrosion and issues with connections and coatings.
- **General area condition** – Observe and record vegetation control, check for pests, and assess the condition of the substation fence.

A thorough inspection should also include infrared (IR) scanning of key areas such as the bushings, connections, radiators, cables, the transformer tank, and the preservation system to look for inconsistencies in the thermal profile of the unit. Infrared scanning is not as cost prohibitive as it once was. The cost of IR equipment has dropped dramatically over the past several years, and there are many service companies that provide IR scanning as a service, with some also offering diagnostic information.

When pulling the liquid sample, it is crucial to do so in a manner that ensures the sample is representative of the entire volume of liquid in the transformer. This is key to ensuring the quality of the liquid analysis. ASTM D923 provides basic instruction on proper sampling practices, and most labs will provide sampling instructions on how to draw accurate samples.



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Typically, the sampling process starts at the sample valve, located near the bottom of most transformers. The first step is to flush liquid through the valve in order to clear out stagnant liquid in the valve body that may not be representative of the rest of the liquid inside the transformer. This liquid is waste and must be handled according to regulations from bodies such as the EPA, and according to your organization's spill containment plan.

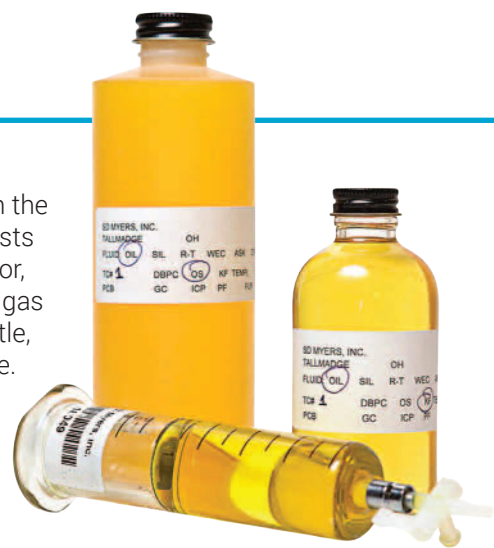
Transformer oil sampling

Did you know? Convective and conductive forces inside the transformer play a key role in homogenizing the liquid and its characteristics inside the tank of the transformer. This homogenous liquid is what you want to send as a representative sample to an analytical lab.



Transformer oil testing lab

Sample containers vary based on the test performed. Containers for tests such as liquid screen, power factor, moisture analysis, and dissolved gas analysis will include a plastic bottle, a glass bottle, and a glass syringe. It is considered best practice to fill the containers in the order of the sensitivity of the analysis. The container for DGA testing, for example, should be filled last, because it allows as much liquid to flow through the sample valve as possible to get the most representative sample of the liquid inside the transformer. All sample containers should also be clearly labeled to pair the sample with the transformer from which it came.



Oil sampling containers

Accurate data alone is not enough to keep an electric power system viable. You need to be able to make good decisions based on that data.



Transformer oil testing lab

Liquid Testing

There are a great number of tests that can be performed on dielectric liquids that can help assess the health of a transformer. The most common tests are indicators of general aging and contamination, moisture incursion, and incipient faults. These tests are:

- **Liquid Screen** – A group of tests that looks for premature aging of the dielectric fluid. A liquid screen can also point to contamination from internal issues such as coking or sludge, or external issues such as contamination from other liquids.
- **Karl Fischer** – This test determines the presence of moisture in the dielectric liquid, and the liquid temperature determines the percent saturation of water. This is an important test because moisture in dielectric liquids can lead to oxidation and formation of acids that degrade the solid insulation.
- **Dissolved Gas Analysis (DGA)** – A DGA detects the presence of key gases that can identify incipient faults from low- to high-energy events and can point towards issues with the solid insulation.

This group of tests is the foundation for assessing the health of a transformer. Depending on the criticality of a transformer—the estimated impact of potential loss—further testing may be required.

These tests can be performed during routine testing or when diagnostics suggest that an issue is present.

Some of these tests include:

- **Power Factor** – This test can indicate liquid breakdown, contamination, and, in some cases, moisture.
- **Inhibitor** – Transformer oil typically includes an inhibitor to help prevent oxidation, which can lead to premature aging of the liquid. The weight percentage can be determined by this test.
- **Furan Analysis** – A byproduct of paper degradation is the formation of certain compounds, called furans, which can be correlated to the tensile strength of the solid insulation in the transformer.
- **Metals in Oil** – By burning off organics in the liquid, this test can determine very low quantities of metals such as aluminum, copper, and iron.

Other specialized tests exist to determine certain impurities or to confirm physical properties of the liquid, such as Corrosive Sulfur, Flash and Fire Point, Particle Counts, and Filming Compounds.

This is not an exhaustive list of tests available, and there are other tests that may be useful too. These tests are typically ordered based upon the results from regularly scheduled testing.

Ultimately, which tests to perform at what interval is a decision that asset owners should make through the lens of maximizing the reliable life of the transformer.

A transformer powering the light in the parking lot, for example, would be considered less critical than a transformer that powers a data center or operating room. It's also important to view the power system as a whole. Performing an impact assessment across the power system can identify opportunities to shore up the reliability in any operation.

Diagnostics

DATA»INFORMATION»KNOWLEDGE»WISDOM

Accurate data alone is not enough to keep an electric power system viable. **You don't need just the data; you need to be able to make good decisions based on that data.** Translating data into insights requires expertise.

While industry organizations like NFPA have standards on manual sampling, and ASTM has standards on sampling liquids and performing tests, many standards are available that can assist in diagnosing the condition of a transformer. IEEE guides such as C57.106 and C57.104, and IEC guides such as 60567 and 60599, pertain to acceptance criteria and result interpretation.

The key to useful diagnostics is in **understanding the actual transformer** so that the guides, standards, and practical experience can be used in concert to assess its health. For example, without practical knowledge of the transformer, the recommendations in the guides might state that the level of acetylene in a DGA of a new oil-filled cabinet transformer is a concern, and recommendations range from "test it again" to "purchase a DGA monitor" to "shut it down immediately." But it is possible that the acetylene inside the new cabinet transformer

is left over from the welding process during manufacturing. Pairing the guide recommendations with practical knowledge, it is possible to make an informed decision on whether to perform ongoing DGA to be sure that the result is not indicative of a fault and to establish a baseline for future analysis.

Diagnostics should be action oriented. It is common for experts to see early warning indications of problems in test data, and for them to recommend further action. Often, however, these warnings are ignored. Many failures could have been avoided if they had been addressed earlier.

There are thousands of transformers in our database that are more than 50-years-old. Achieving this length of service depends on the people responsible for maintenance having a reliability mindset and the capability to address warning signs as early as possible. Some issues can be fixed without an outage, though many issues do require planning a shutdown. While inconvenient, a planned outage is much more cost-effective and manageable than an unplanned event that could severely disrupt operations for an undetermined period of time.

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Monitoring

The field of remote transformer monitoring devices and services has been developing for many years. However, as our industry better understands the capabilities and as communication technologies become more cost effective, the field is gaining traction. System security is improving but will continue to be a key issue for the advancement of monitoring devices that require connectivity, particularly as more of what is traditionally "Operations work" leans more heavily on IT infrastructure and support.

It is common to test a transformer via laboratory analysis one to four times per year at routine intervals.



DGA monitoring

Laboratory testing and continuous monitoring are both here for the long haul. The best reliability plans will exhibit the flexibility to capitalize on both types of data.



The advent of continuous monitoring changes the landscape on the quantity of data available by orders of magnitude. This volume of data can be a powerful asset for understanding the ongoing condition of a transformer. It does, of course, change some of the skillsets required to care for critical assets. The job market for business and data analysts is exploding as companies come on board with data-rich applications. It is no longer enough to just acquire data; you must also be able to make it understandable and actionable.

Laboratory testing and continuous monitoring are both here for the long haul. Traditional laboratory analysis generates high quality, high integrity data from systems and processes that have been honed over decades against methods that are defined by standards bodies such as ASTM. Continuous monitoring as an emerging technology is going to play an increasingly larger role in helping asset owners make faster maintenance decisions, and the volume of the data can be used for trending and for more sophisticated

analysis. The best reliability plans will exhibit the flexibility to capitalize on both types of data; the pairing of all that data with in-depth knowledge will drive an organization toward more intelligent decision-making.

Oxidation, Aging and Reliability

The paper insulation is what gives the transformer its mechanical strength. This remains the most prominent factor in the reliable life of your transformer. The term “reliable life” refers to the transformer’s ability to take on expected stresses—load variations, surges, lightning, and temperature variations—and maintain servicing levels and frequency.

How Does the Insulation Weaken?

Short answer: **oxidation and moisture degradation**. Strength is measured by the Degree of Polymerization (DP). DP is a measurement of the average length of the cellulose molecule chains that make up the paper and is directly

related to its tensile strength. Shorter cellulose molecular chains mean lower tensile strength and weaker paper.

Oxidation and moisture degradation weaken the paper insulation. Acids are created in transformers due to oxidation and will weaken/age the insulation. Since the insulation strength (DP) is based on the cellulose molecular chain length, damage from acids (created during oxidation) to the chain results in lowered tensile strength for the transformer’s eventual inability to withstand original design stresses. The damage is irreversible.

The paper insulation exists in a mineral oil environment. If the oil stays in acceptable condition, the paper has an optimal environment to maximize its life and reliability. However, oil is a hydrocarbon and subject to the chemical laws governing it. Heat, moisture, and oxygen are present in transformers and cause oxidation where acid is formed, as well as other destructive oxidation byproducts, including more moisture.

These acid compounds are polar and are attracted to the paper and absorbed by it — even as they are created. The acid builds up and weakens the paper by breaking bonds and shortening the cellulose chains (lowering DP), meaning the tensile strength lowers. As noted, moisture is also destructive to paper, so keeping moisture levels in acceptable ranges is also important (see IEEE Field Reconditioning Guide C57.140, Section 7.2).



Acid—an oxidation byproduct—deteriorates the paper insulation

What Are Aging Indicators?

Regular intervals of fluid testing are economical and also still the most commonly used means to monitor transformer reliability. **Aging indicators** include elevated acid, lowered IFT, elevated moisture and Liquid Power Factor along with the creation and presence of furanic compounds. When cellulose paper degrades, furans are liberated. Furans are created from the paper and found in the oil. They are measured in parts per billion. Additionally, there are more chronic aging dissolved gases present, such as carbon monoxide (CO). Electrical testing and the strength of the insulation also correlate to Insulation Power Factor.

Typically, the age of a transformer does not necessarily affect its performance—unless there is a fault condition. Severely overheated transformers can degrade rapidly. It is important to make sure cooling packages are working properly and levels are maintained. If fluid levels drop below the cooling ports, severe damage can happen quickly. Visual inspections of all the mechanical aspects of a transformer must be a part of all sampling and services.

Can the Damage from Acids Be Limited?

Yes, at first. But as time goes on and corrective action is deferred, the acids and other oxidation products eventually form sludge, which leads to localized overheating. Heat is one of the necessary conditions for oxidation. Therefore, additional heat further intensifies the oxidation, and again, results in more water that further intensifies oxidation. Servicing the still reliable paper insulation early will limit damage. The acid, being polar, is quickly absorbed into the paper and leads to detrimental effects, namely small and larger amounts of acid that will eventually cause damage and can be corrected. There are widely accepted stages to this aging process:

1. Acid is usually first generated in the oil by oxidation from the presence of heat, oxygen, and moisture. It is

true, however, that the paper can also oxidize independently of the oil.

2. Initial small amounts of this acid are first absorbed by the paper insulation. Oil levels remain in the “acceptable” range. At this point, keeping oxidation inhibitor at the proper levels will continue to retard oxidation.
3. The “questionable” range is when to take action with oil processing. Keeping the acid below the damaging range will avoid loss of the paper insulation’s strength.
4. Once the acid has reached 0.1 mg KOH/g, damage has begun, and action is vital. Stop further damage with Hot Oil Cleaning. Despite the name, Hot Oil Cleaning cleans the insulation, not just the oil, by ridding the insulation of destructive acids and sludges. At this stage, furans can be rising and may be 500 ppb or greater.
5. Once furans are over 1,000 ppb, the paper will show significant damage. Any action taken can slow further damage but will not recover what has been lost.

How is the acid in the transformer corrected? Hot Oil Cleaning and absorptive clay treatments can create a solvent-like action to dissolve and remove the acid and sludge. As the oil is heated and cleaned, it also cleans the paper insulation when done with the proper treatment recipes. The controlling factors for effectiveness are heat, dwell time, and adsorbent clay in a vacuum oil purifier.

How can you slow or prevent oxidation? Processing services exist to prevent, slow, or even stop oxidation. Here are a few common approaches in our industry:

1. Control the moisture. **Moisture reduction is key** to slowing and stopping oxidation. As much as 75 percent of transformers with oxidation issues in our database have an accompanying moisture presence. It can be a little confusing as to which came first, since moisture not only causes oxidation, but is also a byproduct of oxidation.
2. Dry and cool the oil. Where oxygen from the air is present in

a transformer, moisture and heat can be reduced. Passive dryers work, but if load and ambient are driving up temperatures, additional auxiliary cooling may also be needed to reduce these components to oxidation.

3. Apply **Oxidation Inhibitor** to the oil. Inhibitor is a primary way to combat oxidation and is supported by IEEE C57.106. As the oil produces free radicals, the oxidation inhibitor will react with and stabilize them, thus stopping the oxidation chain reaction in its earliest stages. Ideally, **oxidation inhibitor levels should be kept at 0.3 percent** or greater.

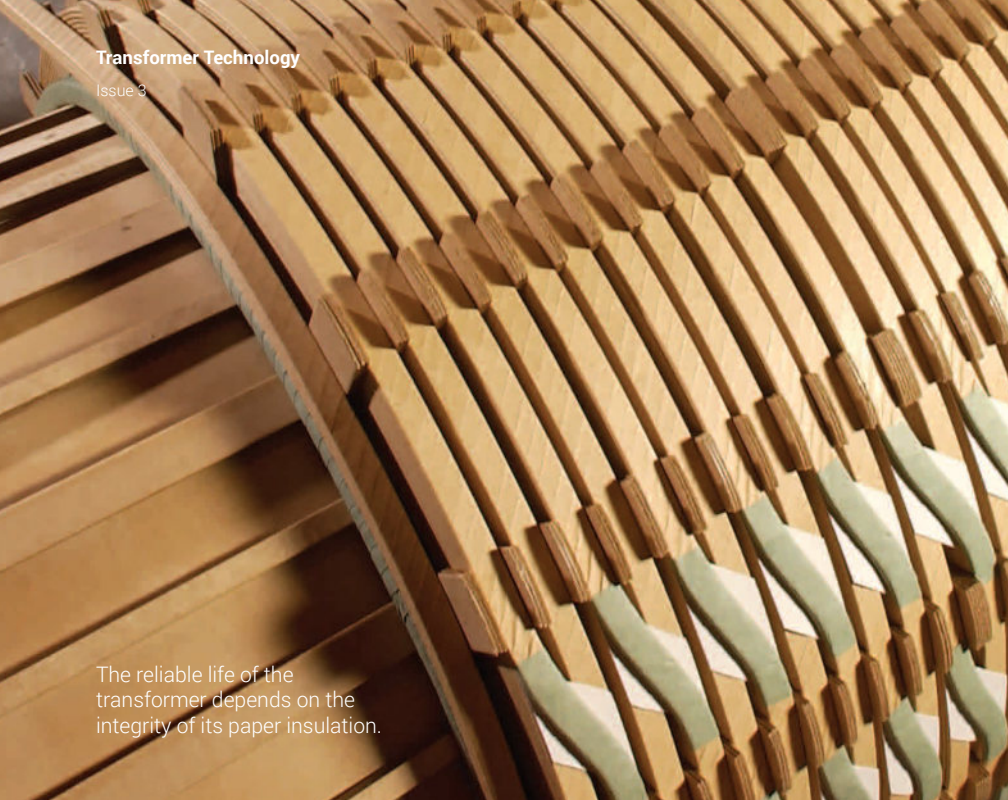
What about damage already done?

Once the cellulose is damaged, insulation life cannot be restored. The damage is irreversible. Here are some points to consider:

- Hot Oil Cleaning improves the condition of the insulation. The smaller the amount of acid in the insulation, the lower and slower is its destructive effect.
- There is a point whereby, looking at the condition of the insulation, the oil, and results from other important indicators such as IR and electrical testing, the best course of action is to replace the transformer.
- Consider the past furan and DP levels prior to oil reclamation. Most oil processing with clay filtration such as Hot Oil Cleaning will strip furans from the oil.

Consider the time and temperatures needed for proper and complete cleaning. Oil can be cleaned in just a few passes in lower temperatures. It takes more passes at a higher heat to provide adequate cleaning of the paper. If the oil only is cleaned and the paper left untreated, within months the acids will come back out of the paper and oil qualities will again move away from the “acceptable” range.

Healthy insulation is promoted by controlling the harmful byproducts of oil oxidation. This optimizes the strength of the paper insulation which is the reliable life of the transformer.



The reliable life of the transformer depends on the integrity of its paper insulation.

As the oil is heated and cleaned, it also cleans the paper insulation when done with the proper treatment recipes. The controlling factors for effectiveness are heat, dwell time, and adsorbent clay in a vacuum oil purifier.

Combustible Gas Issues

Combustible gas levels are an indicator of an abnormal condition in a transformer. They are created by excessive localized or general overheating. Extreme temperatures and arcing are identified by a key gas: acetylene. These conditions are typically acute and must be dealt with immediately. The following are typical steps taken to correct them:

1. Retest to confirm the condition.
2. Arrange an immediate inspection and include electrical testing, depending upon the severity. Many issues can be field-corrected. Untanking is rarely done in the field, so there are repairs that require taking the unit out of service and shipping it to a repair facility.
3. Drain and perform an internal inspection.
4. Make repairs in the field, when possible.
5. Refill the transformer. Care must be taken to fill with the proper procedures. Vacuum rated transformers must be vacuum filled if the core has been exposed. UHV units require a complete drain and fill any time the oil is lowered.

If refilling a lower voltage unit, cleaning can be performed with a cartridge filter. Consult with OEM requirements. In this case, the oil will still contain combustible gases and it must be degassed with a vacuum oil purifier. This will reset the gas levels.

Some leach back is expected for the first several months.

Staying ahead of leaks and maintaining the correct level is another important aspect of reliability in transformers. The regular visual inspection assures this. It is recommended to perform a visual inspection no fewer than four times a year. The following are some of the aspects of the inspection:

- **Level in the transformer.** Keep in mind, some training is required to interpret the level gauge with respect to the temperature of the oil. Oil expands 1 percent for every 10 degrees Celsius. A 25-degree Celsius measurement is “normal” or “low” if the oil temperature is significantly higher than 25 degrees Celsius.
- **Leak inspections.**
- **Gauge information.** A consistent “zero” psi on a pressure vacuum gauge often indicates a leak, as the transformer is not holding pressure or vacuum. A transformer with a leak is “breathing” ambient air and, therefore, humidity in and out of the transformer. The moisture is however typically only “in” as the oil and insulation have a high affinity for moisture.
- **Paint and rust condition.**
- **Bushing and insulator surface condition.**
- **Overgrown vegetation in the substation** that could lead to a flashover.

Best Practices

Whether you're conducting oil processing, doing transformer repair, or electrical testing, there are best practices that are important to follow for safety and reliability.

It is helpful to define procedures and equipment to optimize the services rendered. For instance, in oil processing, it is important to not just filter oil, but also to address **cleaning the paper insulation**. When oil processing, require pumping records to assure the temperature and passes will achieve the required results. Reaching 70 degrees Celsius is optimal to allow the oil to reach the aniline point where it can dissolve oil generated sludge and acid

Additionally, moisture cannot be corrected by "pumping" on a transformer, as there is approximately 100 times more moisture in the paper insulation than there is in the oil. Instead, use either **vacuum dryout techniques or online moisture dryers**, as defined by the Field Guide of IEEE, C57.140.7. Online dryers are effective in moisture reduction.

Selecting and Working with a Contractor

It is always important to contract with an experienced provider with a proven safety record and a well-documented training program. There are a number of contractor-related criteria to be included in the scope of the project. Always create a written, clear scope of work for any bidding purposes. This will help avoid short cuts and define expectations.

As mentioned, you should require pumping records to achieve the required results when oil processing. When electrical testing, make sure it is defined as who is disconnecting and grounding. When hiring a contractor, you should:

- Define work hours and how to handle changes that are discovered while on site. At a minimum, have the provider control and monitor moisture and the acidity of the oil.
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handle changes discovered while on site.

- Ask that the provider have an equipment reliability program to assure excellence in the equipment being sent including safety gear inspection and key calibration records.
- Refer to C57.106, the "Oil Guide," which can be used for oil quality requirements.
- Follow IEEE C57.93 and C57.140 for field drying and vacuum filling. Be aware of the required set times after filling before energizing when the core is exposed.
- Ask that the provider have an equipment reliability program to assure excellence in the equipment being sent, including safety gear inspection (PPE) and key calibration records.

Environmental Considerations

- Be sure the provider has Field SPCC (Spill Prevention Control and Countermeasures) training, including the use of spill berms, and that they have a spill kit on site.
- Process units from lowest to highest so as to never add to the PCB content of the next transformers. If you have PCBs, expect some surcharges—there are legitimate costs to do it right.
- Be aware of the advantages of the new Ester liquids. These are popular for a reason as they hold up well. They are fire resistant (Fire Point of 300 degrees Celsius) and they are eco-friendly. Ester fluids can be processed in most equipment with a pre- and post-flushing adder. Getting some esters in oil is not much of an issue, but too much oil (>6 percent) will lower the flash point.
- Use a filtering clay when oil processing equipment that improves acid. There are environmentally friendly solutions for regeneration that avoid landfill or incineration of the oily waste. In general, you can expect a drum of waste for every 3,000 pumping gallons of oil.

Reliability Outcomes

Data supports the principles and action-related reliability steps in this paper. In a paper published by CIGRE and the IEEE, which considered 1,500 transformers, the transformers with services to combat oxidation and moisture showed more than six years of extended life per service rendering. This doubled the life of the average transformer, which was reported in many studies to be under 20 years.

Additionally, by maintaining frequent visual inspections and regular fluid and electrical testing, the probability of a surprise lapse in reliability is very small. As indicators trend toward aging, plans for contingency and an acceptable timetable for a planned outage will negate further concerns for a lapse in power provision.

There are transformers backed up by spares or double-ended subs. We refer to these more important units as being **system critical**. Units that shut down operations, or huge segments of your operation, are considered **mission critical**. This reality takes the units with the mission-critical rank and looks at condition or monitoring and moves them to the top of the priority list. Meanwhile, a system-critical unit in bad shape will also be



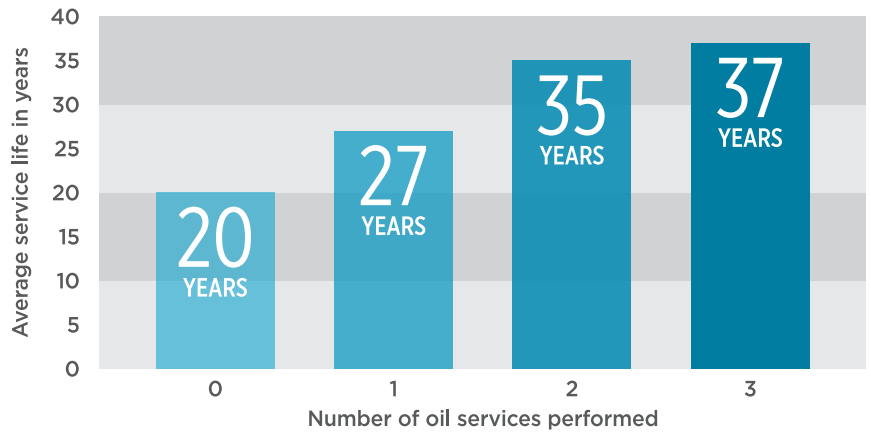
a top priority and warrant a spare or double-ended sub.

When power and people's lives are at stake, a backup electric source might be in order, as well as a backup generator and reliable fuel source. Hospitals and mines are good at this. There are product and service providers who have designed levels of commitment based on non-critical and system or mission-critical transformers.

Even reliable transformers need **contingency plans**. On mission-critical units, the need and timeliness for the required power restoration leads to double-ended subs, spares, and generators — all components of contingency plans. Some main transformers are supported by the power supplier with spares or mobile substations to restore power in four to eight hours. Some operations cannot live with any power interruptions and need a generator and an adequate fuel supply. Production, engineering and finance departments play roles in determining the best fit for a reliability program and the contingency programs for each power system.

Average Service Life Related to Number of Oil Services Performed

An SDM study based on 1,534 decommissioned oil-filled transformers > 500 kVA



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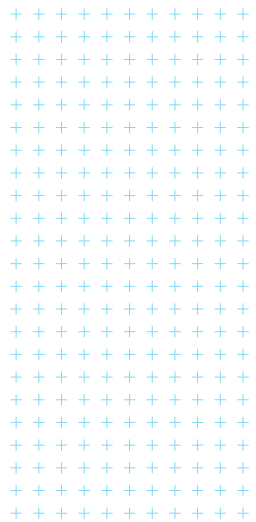


Photo: SDMMyers