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# A PARADIGM SHIFT IN GAS TURBINE LUBRICANT MAINTENANCE

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## Abstract

While gas turbine oil maintenance is recognized as being essential, many programs lack the basic tools to maintain their lubricants within specification. Existing lubricant maintenance is typically reactive in scope, uses filtration technology from the 1970s and does not target the root cause of many lubricant and mechanical failures: varnish.

This paper discusses a modern approach to lubricant maintenance that offers technical advantages to gas turbine owners. This approach maintains lubricant quality in ideal condition on a consistent basis, improving performance and eliminating common issues. Furthermore, this approach can eliminate the cause of lubricant failures, extending the fluid's operating life to 20 years or more.

## 1. Introduction

All lubricants degrade from the day that they are manufactured. This process accelerates once they are put into service. Oxidation creates dissolved breakdown products. Over time, these accumulate in the oil, eventually reaching a saturation point. Beyond this point, they convert into solids and form varnish deposits (Figure 1) which impair lubricant performance [1]. Because this saturation point varies with temperature, oil breakdown products are normally dissolved under operating conditions and convert into varnish deposits during shutdown periods when the oil cools [2].

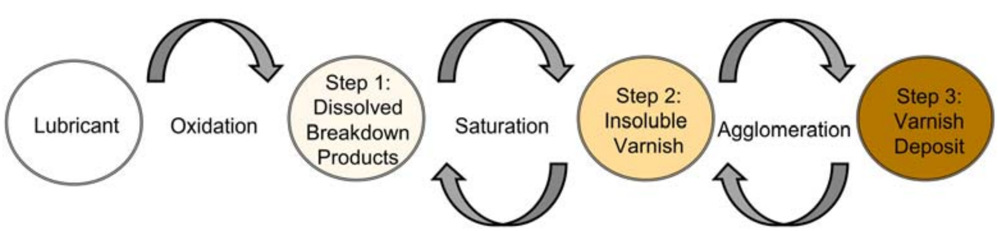


**Figure 1:** Breakdown Pathway Leading to the Formation of Varnish Deposits.

Lubricant varnishing does not have to occur but routinely causes fail-to-start conditions and unit trips, impacting operating performance, company results and, even, employee bonuses. Varnishing impacts gas turbines, steam turbines, hydraulic systems and other critical industrial equipment [3]. This article will explore the reasons why many users struggle with the issue, current developments and offer recommendations. This will allow users to be better prepared to navigate the barrage of marketing and products available.

Key players in the field include oil analysis labs, lubricant suppliers, third party additive manufacturers and filter companies. With each group working independently on the varnishing issue, many different approaches are available. Oil analysis labs are relied upon to identify varnish before it causes problems on-site. Lubricant suppliers have reformulated their oils and improved versions are now being sold as "low-varnish" or even "varnish-free" fluids. Third parties also offer aftermarket additives intended to mitigate varnishing and extend oil operating lifetimes. Lastly, filter companies offer different varnish-removal systems. With such a broad range of approaches, it is not surprising that the average user struggles to decipher the best solution for their application.

## 2. Varnish Measurement as an Effective Maintenance Tool

An effective lubricant maintenance program is only as good as the lab which provides their analytical results. In this regard, reliable data is key to informed decision making. Lab data can, however, become compromised by poor sampling on-site or poor laboratory practices at the testing facilities.

Because it is difficult to simultaneously measure the many varnish-promoting contaminants in an oil, membrane patch colorimetry (MPC) is now widely used to provide an indicator of varnishing potential [4]. Small MPC ΔE values (< 15) indicate that the lubricant possesses low levels of accumulated breakdown products and, therefore, has capacity to hold additional degradation products in solution. A high MPC ΔE value (> 15), on the other hand, indicates a significant accumulation of varnish precursors with limited or no remaining capacity to hold breakdown products in solution (Figure 2). Oils with high ΔE values are, therefore, prone to varnishing.

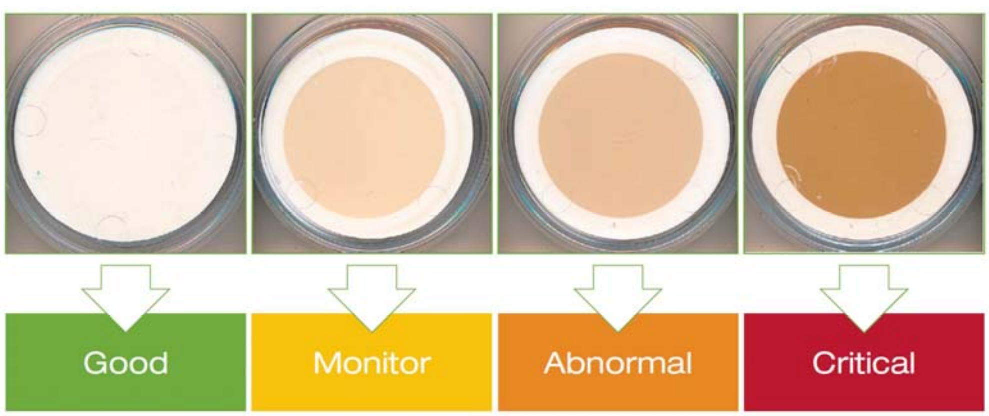


**Figure 2:** MPC Varnish Potential Test Results.

Many users base their decision making on MPC results provided by third party oil analysis labs. These users often fail to recognize that oil samples continue to breakdown after they've been drawn. Indeed, samples often remain idle for extended periods before being sent for analysis. All too often, regular samples are collected but remain on-site for weeks or months. Once many samples have accumulated, they are then sent to the lab in bulk allowing for reduced shipping costs. When critical equipment is involved, this approach may be penny-wise but it is most certainly pound-foolish. As the older samples await testing, they degrade and unreliable MPC measurements may result [5]. The usefulness of regular sampling is also lessened when months' worth of results arrive simultaneously. What good is pulling a monthly sample if decision makers only look at results on a semi-annual basis?

In an effort to correct for potential errors that may result from extended sample storage/shipping times, the MPC test method has recently been modified. The current method requires that samples are heated for 24 hours at 60°C and then aged for 68 – 76 hours at room temperature so they can be effectively "reset" to a condition similar to that which was present at the time of sampling. The MPC test method further requires that labs report this hold period. Labs without specialization in turbine oil applications often neglect this key step. It is, therefore, prudent to check that this hold time is reported as confirmation that your lab is following the correct test method. The updated MPC method also requires that oil sample containers be light-resistant and that MPC heating and aging periods be carried out without exposure to light. These improvements aim to prevent post-sampling breakdown from being misinterpreted as in-service breakdown and offer better consistency between labs. Your oil analysis lab should, therefore, provide dark/opaque bottles which prevent light from reaching samples. If the lab provides clear containers, it is unlikely that they are performing the MPC test in a manner which will yield reliable data.

Finally, the same oil analysis lab should be used consistently. Different labs employ different instruments, different methods and different analysts. It is, therefore, unreasonable to expect distinct labs to provide the same results. Even when a test is performed by the same operator using the same method/instrument at the same lab, there is an uncertainty associated with the result. This is often referred to as experimental error or repeatability. Although a lab may report 2 different values, these are, essentially, the same if they differ by less than the test method's repeatability. Users, therefore, need not be concerned about deterioration of oil properties that fall within this range. It is important to work with a trusted lab to better understand test repeatability and the impact that it should have on maintenance decision making.

Failure to follow these procedures (on the part of the sampler or the oil analysis lab) often results in meaningless values being reported, compromising the effectiveness of on-site maintenance practices.

## 3. The Impact of Oil Formulation on Varnishing

An oil's formulation has an obvious impact upon its varnishing tendencies. Indeed, oil formulations are constantly evolving as suppliers work to minimize their lubricants' propensities towards forming harmful varnish deposits. Additization and base oil composition are the most prominent tools available to formulators in this regard.

Most of the additives used in turbine and compressor oils are antioxidants. These additives are sacrificial and are intended to react with oxidants before they can degrade the base oil. Typical antioxidant additive packages include an amine and a phenol. Amines are generally the more important antioxidant under operating conditions and the phenol can generally be regarded as a support system for the amine [6]. Years ago, the main turbine/compressor oil brands possessed widely varied antioxidant packages. Some had amines only. Some had phenols only. Others possessed both. Today, most common turbine lubricants use both amine and phenol additives. Presumably, oil formulators have concluded that this approach yields the best oxidative stability.

While additives have an important impact on lubricant stability, most varnish is ultimately comprised of base oil breakdown products. It is also the base oil that is largely responsible for a lubricant's breakdown product-holding capacity. Traditional turbine oils were made with Group 1 base stocks. These solvent-refined oils had limited oxidative resistance but had higher capacities to hold oxidation products. Performance and environmental requirements ultimately led to the more common use of Group 2 and 3 base oils in rotating equipment. Group 2 and 3 oils are made from hydrotreating and severe hydro-cracking processes, respectively. Both techniques remove the most readily oxidized species from these base oils, making them less susceptible to breakdown than Group I base fluids. Users often look at Group 2 and 3 base oils as being problematic from a varnish perspective, however, this is not typically the case [7]. These base oils may hold less varnish in solution but they also produce much less varnish in the first place. Some formulations now include a small amount of Group 1 oil or other polar additive to improve the solubility characteristics of their Group 2/3 base oil. These are frequently marketed as "low-varnish" formulations, however, the addition of oxidatively-prone species to an otherwise stable oil may create more varnish problems than it solves.

Base oils made from natural gas are currently being marketed aggressively. Despite the recent changes with regard to their marketing, these fluids are not new. Indeed, they are often Group 4 synthetics which have been used in lubricant applications since the 1930s [8]. These mainly polyalphaolefin (PAO)-based oils are extremely pure lubricants with high inherent resistance to oxidation. They are, however, extremely non-polar with limited capacity to hold polar breakdown products or contaminants which accumulate during service. Since varnish is generally created from base oil and not from base oil impurities, the high purity of Group 4 oils provides little benefit over that of highly refined, Group 2 and 3 products which are already very pure. In addition, static generation can become more pronounced when extremely non-conductive Group 4 oils are used.

Group 5 synthetic polyalkylene glycol (PAG)-based oils have also been marketed more aggressively in recent years. Indeed, these oils are advertised as "varnish-free" alternatives to conventional lubricants [9]. When used in specialized applications with high duty cycles, PAGs can offer advantages. PAG density is slightly higher, which allows engineers to remove more heat from bearing surfaces. The question that end users should ask is: do you have a bearing temperature issue? Journal bearings already have infinite life if you can eliminate wear [10] so what is the technical benefit of being able to lower temperature in an application that does not have temperature issues? For the average user in a journal bearing application, PAGs are unnecessary and should not be purchased on the basis that they don't form varnish or require maintenance. Indeed, oxidative breakdown testing of PAG turbine oils demonstrates that these marketing claims are false: PAGs degrade like any other fluid and, when they do, extremely high MPC values, high acid levels and a tendency towards forming sludgy deposits results (Figure 3) [11]. Better alternatives exist and their established track record offers users a lower technical risk. Some quality Group 2 products even provide superior breakdown testing results, eliminating any logical argument for PAGs in normal turbine applications.

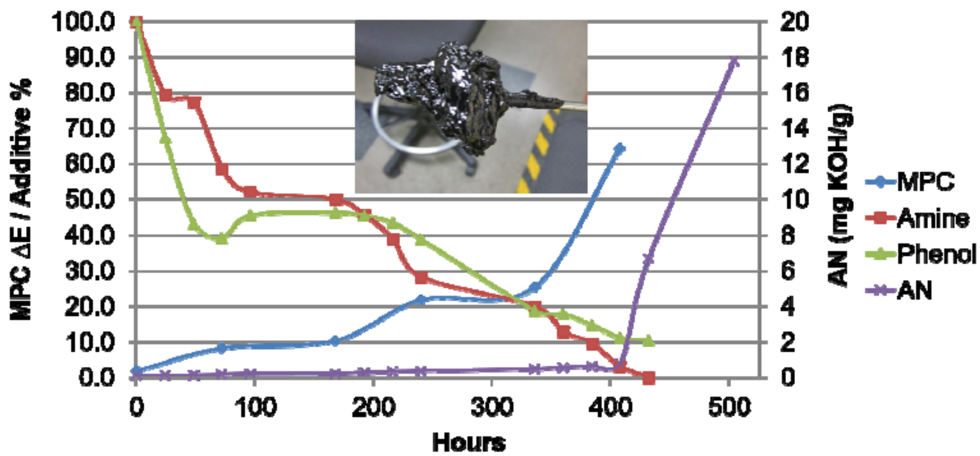


**Figure 3:** Group 5 PAG-Based Turbine Oil Breakdown to Produce a Sludgy Deposit (Inset).

Both Group 4 and Group 5 synthetics are also priced as premium products. They may offer technical advantages over refined products but users should be certain that their application actually requires these advantages prior to committing to their purchase.

In summary, lubricant suppliers have provided users with many, many choices when it comes to oil selection. When selecting a lubricant, key considerations should include base stock quality, antioxidant type and quantity, brand reputation, cost and supplier support. Specialized testing is also recommended to assess a lubricant's actual resistance to varnishing. Established test methods (ASTM D943 and D7873 etc.) provide useful breakdown conditions but tend to only focus on one aspect of an oil's breakdown profile (acids, sludge formation etc.). Non-routine breakdown testing, therefore, offers users more insight since larger sample sizes can be used so that additional lubricant properties (oxidation, acid number, varnish potential, additive levels etc.) can be monitored. This type of rigorous breakdown testing can allow end users to make informed decisions when it comes to selecting the best lubricant for their application.

## 4. Aftermarket Additives

Aftermarket oil additives have been popular in automotive applications for many years and are becoming more so in turbine applications. Indeed, increased user awareness surrounding turbine oil varnish problems has led a number of companies to develop additives that are claimed to solve varnish problems. Users should note that these additives are not generally recommended or approved by lubricant manufacturers as they change the oil's formulation. Lubricants are carefully formulated to meet application requirements and blended in a proper facility engineered for this task. Once an aftermarket additive is added, the lubricant's formulation is irreparably altered. The addition of a foreign additive complicates oil chemistry, creating new, difficult to foresee breakdown pathways. This introduces unnecessary technical risks and eliminates technical assurances from the lubricant supplier (who would normally be responsible for their oil).

It is also important for users to understand that aftermarket varnish-reducing additives don't remove varnish or its precursors. These additives generally increase the oil's saturation point, allowing it to hold more contamination. This strategy masks varnish problems rather than actually addressing them. Since the oil now contains more varnishing species, the risk of sludge and deposit formation may actually increase following additive use. At best, aftermarket additives move the ball down the field so that varnish problems can be delayed.

## 5. Oil Treatment and Filtration Systems

Most turbine oil purification systems can be classified as being particulate removal-based (electrostatic, agglomeration, depth media etc.) or ion exchange resin-based [12]. Particulate removal technologies offer no varnish protection or reduction when the oil is at operating temperature and warm. These systems remove insolubles but they cannot address the dissolved breakdown products which lead to varnishing. These soluble contaminants pass through particulate-removal systems and remain free to deposit out of the oil elsewhere. To deal with this weakness, oil coolers are often installed upstream of particulate removal technology in an effort to force the varnish-forming material out of the oil and into a filterable form. Essentially, these filters must make the varnish that they then remove! This process is energy-intensive and inefficient since coolers will not force all of the dissolved contamination into a filterable form.

To ensure the performance and reliability of critical equipment, oil conditioning systems, therefore, need to remove varnish and its precursors under operating conditions. Resin-based systems offer this advantage since they remove dissolved oil contamination, making it impossible for varnish precursors to deposit out elsewhere. Moreover, resin-based systems are normally packaged with high efficiency filters, so they combine the best performance at all oil temperatures and operating conditions.

In addition to removing dissolved varnish precursors, ion exchange-based systems provide users with other benefits. By removing accumulated degradation products, the lubricant can be maintained in a highly unsaturated condition. If the unsaturated oil comes into contact with previously deposited varnish, it may, therefore, re-dissolve it. Once this varnish has been dissolved back into the fluid, it can be removed by the ion exchange resin (Figure 4).

A second benefit to ion exchange use is a decreased rate of antioxidant consumption. This occurs since the resin removes contaminants which undergo secondary reactions that lead to additive depletion. When these additive-consuming pathways are eliminated, the oil's antioxidants are better able to protect the base fluid with from oxidation. Results to date have demonstrated that annual amine consumption can be reduced to levels as low as 3%. At this depletion rate, and with breakdown products being removed by resin as they form, a 33 year gas turbine oil life cycle is, theoretically, possible. In the absence of ion exchange, 12 – 20% rates of annual amine consumption are more typical. These translate to 5 – 8 year oil lifetimes which are quite common in this application. The combination of ion exchange-based conditioning and an annual 5% top-up with the oil currently in-use can, further, be used to maintain antioxidant levels and turbine oil condition over the asset's lifetime.

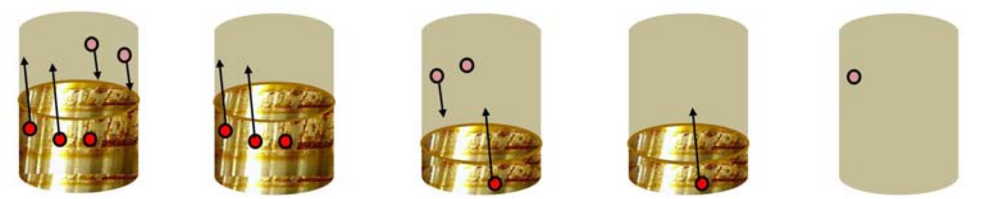


**Figure 4:** Complete Removal of Dissolved and Deposited Varnish by Ion Exchange Treatment.

As a result of their favourable impact on performance and reliability, many turbine manufacturers already recommend the use conditioning skids during turbine operation. To maximize equipment reliability and the return on conditioning skid investment, ion exchange-based systems should be installed as early as possible in a turbine oil's life cycle. By doing so, end users can extend the lifetime of their lubricant to match that of their turbine. This oil life extension eliminates the need for costly flushing and oil replacement every 5 – 8 years, providing a significant return on investment. More importantly, maintaining good oil condition over the fluid's entire life cycle eliminates the risk of costly varnish-related failures.

Table 1 presents the relative costs and savings associated with the use of a conditioning skid on both small and large industrial gas turbines. For the purpose of this paper, a 17.5 MW Solar Titan 130 unit was considered as the small turbine while a 171 MW GE Frame 7FA unit was used as an example of a large industrial gas turbine. Costs for both units were calculated over their entire 25-year lifespan. The requirement for 5% annual oil make up was assumed. As outlined above, the oils in-service in these systems were assumed to be usable for the assets' entire 25-year lifespans when conditioning skids were used. Without conditioning, we assumed that the oils would provide 8-years of service, requiring 2 flushes and 2 oil changes over the turbines' 25-year lifetimes. Finally, 100% generating availability was assumed when a conditioning skid was installed while an assumption of 99.7% availability (only 24 hours downtime/year) was made in the case where no conditioning was present.

As the values in Table 1 demonstrate, resin-based conditioning skids provided immediate 149% and 316% returns on investment for the small and large gas turbines, respectively. These returns are largely the result of savings realized through turbine oil life extension and demonstrate that resin-based systems need not prevent a single failure to be deemed prudent investments. When one considers the impact that conditioning has on turbine reliability, however, the ROI becomes even more staggering. Indeed, if a resin-based conditioning system eliminates one 24-hour-period of downtime per year, remarkable ROI values of 738% and 3196% are achieved for the small and large generating units, respectively.

Table 1 also demonstrates significant ROI gains if even a single failure is avoided over the 25-year life of either turbine. Alternately, one can see that the conditioning system's capex will be recovered so long as it prevents 22 hours downtime over the smaller turbine's 25-year operating life (219,000 hours). For the larger system, the resin skid's capex recovery only requires that it prevent a single 5-hour failure over the 7FA's entire 25-year lifespan. In addition to being best-practice, resin-based conditioning is also, clearly, an extremely prudent investment in this application.

**Table 1:** Relative Costs, Savings and Return on Investment Associated with the use of a Resin-Based Conditioning System on Small and Large Industrial Gas Turbines.

| TURBINE | TITAN 130 | | 7FA | |
|---|---|---|---|---|
| CAPACITY | 17.5 MW | | 171 MW | |
| REVENUE/MW | $40 | | $40 | |
| OIL VOLUME | 5125 L | | 22800 L | |
| OIL PRICE/L | $7.53 | | $7.53 | |
| ANNUAL OIL MAKE UP | 5% | | 5% | |
| ONE-TIME FLUSHING COST | $50,000 | | $125,000 | |
| TURBINE LIFE | 25 YEARS | | 25 YEARS | |
| CONDITIONING SYSTEM | NO | YES | NO | YES |
| OIL LIFE | 8 YEARS | 25 YEARS | 8 YEARS | 25 YEARS |
| # OIL REPLACEMENTS | 3 | 1 | 3 | 1 |
| FLUSHES REQUIRED | 2 | 0 | 2 | 0 |
| CONDITIONING SYSTEM CAPEX | $0 | $15,000 | $0 | $30,000 |
| CONDITIONING CONSUMMABLES/YEAR | $0 | $2,250 | $0 | $4,500 |
| LIFETIME CONSUMMABLES COSTS | $0 | $56,250 | $0 | $112,500 |
| LIFETIME FILL COSTS | $115,774 | $38,591 | $515,052 | $171,684 |
| LIFETIME MAKE UP COSTS | $48,239 | $48,239 | $214,605 | $214,605 |
| LIFETIME FLUSH COSTS | $100,000 | $0 | $250,000 | $0 |
| TOTAL LIFETIME OIL-COSTS | $264,013 | $158,080 | $979,657 | $528,789 |
| LOST PRODUCTION HOURS/YEAR | 24 | 0 | 24 | 0 |
| ANNUAL PRODUCTION LOSSES | $16,800 | $0 | $164,160 | $0 |
| TOTAL LIFETIME PRODUCTION LOSSES | $420,000 | $0 | $4,104,000 | $0 |
| SAVINGS (EXCLUDING PRODUCTION LOSSES) | N/A | $105,933 | N/A | $450,868 |
| SAVINGS (INCLUDING PRODUCTION LOSSES) | N/A | $525,933 | N/A | $4,554,868 |
| INVESTMENT COSTS | $0 | $71,250 | $0 | $142,500 |
| **ROI (EXCLUDING PRODUCTION LOSSES)** | **N/A** | **149%** | **N/A** | **316%** |
| **ROI (INCLUDING ONE SINGLE 24 HOUR PRODUCTION LOSS)** | **N/A** | **172%** | **N/A** | **432%** |
| **ROI (INCLUDING ANNUAL 24 HOUR PRODUCTION LOSSES)** | **N/A** | **738%** | **N/A** | **3196%** |

## 6. Conclusion: A Paradigm Shift in Lubricant Maintenance

Varnish is an extremely common problem in critical industrial applications. As end users become more aware of the risks associated with lubricant varnishing, oil analysis labs, lubricant formulators, additive manufacturers and filtration companies have each marketed their own competing solutions to the same problem. With so many options at their disposal, users understandably struggle to determine which varnish solution is best for their application.

Ultimately, the solution to lubricant varnish requires a paradigm shift in the way that all key players think about oil maintenance and varnish mitigation. The distinct solutions provided by each should not be viewed as competing but, rather, as pieces to a more holistic puzzle.

The selection of a trustworthy oil analysis lab is an important part of oil maintenance since decisions are often based on data that the lab provides. To this end, labs with expertise in turbine oil analysis should be used. These labs will understand the importance of the heating/hold periods required by the varnish potential test method. They will also provide light-resistant sample bottles. Finally, end users should take care to ensure that their sampling procedures are consistent with best practices and do not introduce unnecessary delays which promote additional degradation. Even the best oil analysis lab is only as good as the sample provided.

More important still, is the selection of a quality lubricant from a well-known and reputable oil manufacturer/supplier. End users should seek suppliers that can provide lubricants to meet all (or most) of their facility's needs and offer a high level of technical and customer support. This support can include detailed data outlining how the supplier's oil breaks down and how this compares to competing products. There are advantages to using synthetic fluids, however, these literally come at a cost; before paying for a premium product, users should, therefore, work with suppliers to ensure that it is actually needed in their application. In the vast majority of turbine applications, oils made from highly refined Group 2 or 3 base stocks provide excellent short and long-term performance. These generally work best when they include amine and phenol antioxidants. These fluids have hundreds of millions of operating hours in rotating equipment applications. There is, therefore, no technical risk or uncertainty associated with their use when they are maintained properly.

Regardless of the lab or lubricant employed, breakdown will occur. Despite marketing claims to the contrary, there is no such thing as a "varnish-free" or maintenance-free oil. The fact that degradation can't be avoided does not, however, mean that varnish can't be eliminated. Varnish problems are the end result of unmanaged breakdown. Full-time oil conditioning systems can prevent varnishing and consistently maintain low contamination levels. This is in contrast to aftermarket additives that temporarily mask varnish problems. Ideal oil conditioning systems employ ion exchange resins since these work under all turbine operating conditions. These systems are generally combined with mechanical filtration to provide complete conditioning solutions. Particulate-removal systems are useful but fail to efficiently remove the contaminants actually responsible for varnish formation. By removing dissolved breakdown products and insolubles as they accumulate, ion exchange-based conditioning systems effectively mitigate the risks associated with varnishing.

Oil conditioning systems should be installed as early as possible in the lubricant's life cycle so that optimal oil quality is maintained. Maintaining oil is far easier and less-costly than restoring or replacing a degraded lubricant. In this regard, 5% annual oil top-up can also be used to maintain antioxidant levels. Most importantly, this maintenance ensures that critical equipment is never at risk of varnish-related failure. Indeed, the cost of purchasing, installing and operating a full-time oil conditioning system is far less than the cost of a single failure over the life of that turbine.

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