The unvarnished truth

Nothing good can come of this hard lacquer-like material once it invades lubrication systems. But there is hope for mitigation as well as prevention.

**KEY CONCEPTS**

- Surprisingly, varnish can form even when base stock and additives are relatively new, uncontaminated and thermally stable.
- Varnish will eventually obstruct the flow of lubricant and wreak havoc with mechanics.
- One of the primary contributing factors to varnish is electrostatic discharge.
According to an ExxonMobil Lubricants & Specialties survey of 192 U.S. power plants with a total of 626 gas turbines, approximately 40% of those generating facilities reported current or past varnish issues within six years of oil service life. Electric-power industry sources estimate today’s cost of a utility trip or no-start to be as high as $100,000 per event. In refineries, the economic impact of a turbine trip or no-start can be measured in millions of dollars per event.¹

So why is varnish such a hot topic right now? For starters, the operating conditions for gas turbine oil are getting progressively harsher. Much of this is due to the fact that newer turbines are designed to reduce both operating and capital costs; this means tighter tolerances, 24/7 operation and—most important—the use of a common oil reservoir for the bearing and control oil. So the same turbine oil designed to service the bearings by flowing around 200 micron bearing clearances also must flow through three micron servo valves (see Figure 1). Given this, it’s easy to see why overheating (which leads to varnish) is an issue.

Potential problems caused by varnish in turbine systems include:
• Accelerated component wear
• Interference with mechanical part movement
• Plugged oil inlets and strainers
• Reduced filter efficacy and eventual plugging
• Wholesale deterioration of the lubricant.

Varnish forms deposits and contaminates the oil stream. In some cases deposits form on equipment surfaces where the oil has degraded. In other cases the oil degrades and the insoluble decay floats through the stream—forming deposits along the way. One of the many surprising things about varnish is that it can form even when base stock and additives are relatively new, uncontaminated and thermally stable.

Whether these deposits will cure into an enamel-like coating or stay gummy and greasy depends on a number of factors including the temperature of the fluid. Either way, varnish will eventually obstruct the flow of lubricant and wreak havoc with mechanics.

Dr. John Duchowski, STLE Fellow (CLS, OMA I & II) and director of technology development, Hydac International, with U.S. headquarters in Bethlehem, Pa., and world (and R&D) headquarters in Sulzbach (Saar),

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¹ The varnish in lubricating systems is about the same consistency as varnish used to protect wood. This varnish is a hard, lacquer-like oil-insoluble substance that is difficult to remove—great for wood, not so much for machinery. Sludge—often a varnish precursor—is a soft, pliable residue that’s less tenacious. They are both products of lubricant degradation, so the term varnish often refers collectively to sludge and varnish and most often in the context of gas turbines.
Avoiding Varnish and III oils.

the continuing shift toward Group II higher temperatures, in smaller spaces
longer than Group I base stock, at
devitably stable. These oils can be used
or III base stock, which are more oxi-
makes frequent start and stop of
which means frequent start and stop of
and the resulting frequent
accelerates the formation of
deposits. This is supported by user
testimonials and also by published lit-
erature on the subject.”

One of the ways to offset the stress
on the lubricant caused by gas turbine
design changes is to shift to a higher
quality lubricant—typically a Group II
or III base stock, which are more oxi-
datively stable. These oils can be used
longer than Group I base stock, at
higher temperatures, in smaller spaces
and have the ability to withstand a wide
range of contaminants—all reasons for
the continuing shift toward Group II
and III oils.

There are five American Petroleum
Institute (API) base stock classifications—three for the purposes of this
discussion:1

- **Group I solvent dewaxed base stock** is
  the least refined—usually a mix of
different hydrocarbon chains. These
oils are generally used in applica-
tions without high performance de-
mands but have significant advan-
tages when it comes to additives,
especially in terms of solubility.
Because of remaining impurities,
Group I oils are more polar in na-
ture. This polarity leads to a higher
solubility than other mineral oil base
stocks (see Figure 2).

- **Group II hydrosprocessing and refining base stock** performs acceptably in
terms of volatility, oxidative stabil-
ity and flash/fire points but not as
well in terms of cold start viscosity,
Extreme pressure durability and
pour point. Greater purity means
that the base stock and additives in
the finished product will last much
longer. Fully formulated Group II
lubricants have superior antioxi-
dant properties since nearly all hy-
drocarbon molecules are saturated.

- **Group III hydrosprocessing and refini-
ing base stock** is the most refined
of all mineral oil base stock. It per-
forms well in many regards and is
highly stable. Group III base stock
is manufactured using the same hy-
droprocessing techniques as Group
II base stock. The difference is the
processes are more advanced in or-
der to yield a higher VI. They also

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**WHY VARNISH IS A BIGGER ISSUE NOW**

Kal Farooq, principal engineer for the
Pall Corp. in Port Washington, N.Y.,
says, “Based on field experience and
talking to turbine users, two primary
reasons for the widespread occurrence
of varnish formation in turbine lube
oil systems in recent years are (1.)
more plants are operating as peakers,
which means frequent start and stop of
the turbines and (2.) the widespread
use of highly refined Group II and III
base stock oils that have lower solubil-
ity for the varnish-forming material.

Peaking service puts higher stress
on the oil and the resulting frequent
heat/cooling accelerates the formation
of deposits. This is supported by user
testimonials and also by published lit-
erature on the subject.”

As the trend toward the ever-increasing market share occupied by the newly formu-
lated Group II and III oils continues, it will become increasingly likely that even existing
systems will eventually be filled with oils of this type. It should well serve as a reminder
that these new oil formulations often exhibit electrical conductivities well below their
Group I predecessors, this especially being true of the ashless formulations typically
employed in gas turbine applications.

The ESD issue becomes all the more important because oil conductivity values have not
yet made their regular appearance in any major American or European turbine lubricating
oil specifications, regardless of whether intended for fresh or in-service applications. Yet,
given the fact that nearly all the new oil formulations exhibit conductivities well below
the critical value of 500 pS-m established on the basis of empirical observations—in fact,
often well into the single digit range—conditions amenable to the occurrence of ESD at
normal operating conditions already do exist in a wide variety of applications.

In view of these developments, it would be highly advisable to take the oil electrical
conductivity into consideration when specifying filter elements for both hydraulic and
lubricating systems where such oils are to be employed.

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**DR. JOHN DUCHOWSKI’S ADVICE FOR AVOIDING VARNISH**

Dr. John Duchowski has the following advice for avoiding varnish in the first place.

The best way to eliminate occurrence of varnish in a new system with fresh fill is to
eliminate all potential mechanisms or sources leading to its formation. This may indeed
sound easier said than done, especially because not all the causes of varnish forma-
tion have been positively identified. Secondly, some weighing factors are likely to be
involved as well. In terms of very simple recommendations, definitely the employment
of filter elements that prevent the onset of electrostatic discharge within the system is
easily and readily doable and achievable. The availability of this simple yet highly
effective solution to the electrostatic discharge (ESD) issue should be of considerable
appeal to both OEMs as well as the operators, as it requires little invasive intervention
in order to alleviate the problem. In fact, even existing systems can be relatively easily
outfitted with cartridges of suitable construction.

As the trend toward the ever-increasing market share occupied by the newly formu-
lated Group II and III oils continues, it will become increasingly likely that even existing
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conductivity into consideration when specifying filter elements for both hydraulic and
lubricating systems where such oils are to be employed.

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Germany, says, “The exact chemical
composition of varnish has not been
categorized in detail. It is generally
assumed that these sludgy residues
consist of oil base stock and/or additive
degradation products. Thus, although
the term varnish itself may suggest a
product of some well-defined compo-
sition or origin, in practice many dif-
fent forms of varnish exist and have
been observed. For example, in paper
machine oils, varnish forms predomi-
nantly as a result of additive hydroly-
sis rather than oxidative breakdown.
In contrast, in turbine lubricating
systems, it is the thermal oxidative
degradation that is almost exclusively
responsible for both the additive and
oil breakdown that lead to varnish for-
mation (see Dr. Duchowski’s Advice for
Avoiding Varnish).”

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are extremely pure (hence non-polar) and may require the addition of an ester or aromatic compound to increase solvency so that they can hold additives in solution.

Herein lies the problem: Lubricants with Group II and III base stocks offer much more protection for gas turbines than Group I in many important respects. But when the additives needed to increase solvency deplete, the other additives begin to separate and form varnish. This isn’t just a problem for gas turbines; it’s just more of a problem for gas turbines.

“In particular, the greater degree of refinement typically employed for modern lubricating oils reduces the content of unsaturated hydrocarbons and sulfur-containing species,” Duchowski says. “In turn, the lower content of these polar materials significantly reduces their solvency toward the oxidative degradation products, which are often likewise polar. One consequence of these poorer solvency characteristics is the inability of the fluid to dissolve its own degradation products, which manifests itself in the appearance and accumulation of varnish in hydraulic and/or lubricating systems.”

In addition to the solvency issue with Group II and III base stocks, there also is a significant decrease in electrical conductivity—which introduces the problem of electrostatic discharge.

**VARNISH FORMATION**

Joe Z. Zhou, senior research chemist for Chevron Lubricants in Richmond, Calif., says, “The primary cause of varnish is degenerated lubricant oil species, which are primarily oxidized hydrocarbon molecules. These species go through surface aggregation and further surface reaction processes to form varnish.”

The typical route of varnish formation begins with thermal degradation and progresses to oxidation, which produces contaminants that result in sludge and varnish.

- **Thermal degradation.** Thermal degradation happens at temperatures above 299 C (570 F) and leads to oxidation. There are four potential sources of heat:
  1. **Full spark discharge.** With flash, it will generate nanosecond temperatures from 10,000 C (18,032 F) to 20,000 C (36,032 F).
  2. **Dark stream spark discharge.** With no flash of light, temperatures between 5,000 C (9,032 F) and 10,000 C (18,032 F) can be generated.
  3. **Friction.** The combination of oil against the metal surfaces in the system, as well as metal parts rubbing together, can generate temperatures between 180 C (356 F) and 450 C (842 F).
  4. **Adiabatic compression.** This can generate temperatures between 600 C (1,112 F) and 900 C (1,652 F).³

- **Oxidation.** Oxidation is accelerated by exposure to temperatures of 249 C (480 F) and above. Elevated temperatures accelerate the oxidation process; for every 10 C (50 F) increase in operating temperature, the rate of oxidation doubles.⁴ The presence of aeration, water and metals accelerates oxidation. Once underway, oxidation byproducts develop into insoluble contaminants.

- **Contamination.** Although contaminants come from a variety of sources, internal contamination is most often submicron oxidized oil that agglomerates to leave deposits. Certain oil additives can create more varnish than others—including some rust inhibitors. These contaminants agglomerate into sludge and varnish (see Figure 3).
Duchowski says, “Field experience based on several years of empirical observations as well as ample experimental evidence strongly suggest that one of the primary contributing factors to accelerated oil and additive degradation is the oxidative breakdown caused by the electrostatic charging of filter elements employed in the turbine lubricating system. Awareness of the occurrence of electrostatic discharge (ESD) in hydraulic and lubricating systems has persisted now for well over a decade, yet relatively few steps have been implemented by equipment manufacturers or operators in order to avert ESD or even to minimize its impact on system performance.”

**ELECTROSTATIC DISCHARGE**

ESD is produced by friction that results when two surfaces move in relation to each other—this usually means they must come in contact with each other, but not always. When it comes to liquids like lubricants, the charge occurs on the molecular level at the place where the materials meet. The positive or negative charge that is generated by the moving fluid will migrate from the fluid to the surface it comes in contact with. Common causes of electrostatic charge in a system include one or more of the following:

- Fluid flowing through narrow passages
- Fluids passing through filters
- Fluids that travel through systems at high speeds and/or are highly agitated
- Fluids that are kept at lower temperatures
- Fluids that become aerated.

Streaming current occurs when the fluid carries the charge downstream of the source. As the charged fluid flows, it deposits current along the route. If the surfaces it encounters can conduct electricity and are not grounded, then a charge (opposite the charge of the fluid) deposits on the walls. If the surfaces are either not capable of conducting electricity or grounded, the charge will build up and discharge as static. These discharges can generate sparks with temperatures greater than 10,000 C (18,032 F)—depleting antioxidants and seriously degrading the oil.

According to extensive research by Duchowski and others, ESD leads to the formation of free radicals within the oil, which leads to uncontrolled polymerization that culminates in the buildup of insolubles like varnish and sludge.

**FILTRATION AND STATIC**

The transition to synthetic and glass filters with tighter pores coupled with higher filter flow rates has created a perfect storm for ESD. A high flow rate creates high voltages that result in more powerful and frequent spark discharges. If the filter is made of nonconductive materials like these, the charge will not be able to dissipate into the filtration system. Then the filter will charge until...
the voltage reaches a certain point and discharge to conductive parts such as
the metal components of the filter housing—causing significant damage. While
grounding the filter system will prevent sparking, it will not prevent either the
filter or fluid passing through it from charging and causing damage.

Past attempts to reduce the potential of ESD accumulation have included:

- **Adding an antistatic additive to the fluid.** The additive will raise the conductivity of the fluid and accelerate the rate of charge dissipation, but it is usually added to fuels and not lubricants. Antistatic additives have not been approved for use in hydraulic and lubrication systems.

- **Reducing the charge exiting the filter.** This was accomplished by using a static charge reducer (SCR)—a passive device that injects a charge of the opposite polarity into the charged fluid during flow. This was a less than ideal solution because of the lag time before the effects kicked in and the fact that the SCR became contaminated by conductive layers—making it ineffective.

- **Reducing the filter’s flow volume.** This was accomplished by increasing the filter size or using parallel filters. While this is a simple and effective solution, engineering considerations make it impractical in many cases.

- **Creating more time for the charge to dissipate.** This also was an effective but impractical (and costly) solution since it required re-engineering the system to increase the distance of the fluid route and/or adding a reservoir.

- **Adding a grounded conducting surface.** While this creates better conditions for discharge and seems to reduce or eliminate surface damage to materials, it doesn’t solve the basic problem of fluid charging.  

The only practical way to keep the filter and fluid from charging is to reduce the charge generation at its source (during filtration), which would mean altering the filter components.

“Sparks generated as this charge discharges generate very high localized temperatures, which literally burn the fluid, cracking the molecules and forming free radicals that further promote fluid degradation through additive depletion and oxidation,” Farooq explains. “The end result is accelerated fluid degradation and elevated levels of oil insoluble materials. Antistatic lube oil filters are available to prevent this from happening.”

**REMEDICATION**

The following are four types of varnish mitigation systems currently available:

- **Liquids—electrostatic liquid cleaners (ELC)/chemical cleaning fluids.** Using electrostatic forces to attract polar contaminants, ELCs work by passing the oil over a series of anodes and cathodes. Negatively charged particles are attracted to a positive collection zone and positively charged particles to a negatively charged zone. Electrostatic oil cleaners require a non-conductive environment to function and are sensitive to small amounts of water contamination. They are effective devices for removing submicron insolubles, including insoluble oil degradation products. Zhou says, “Our opinion is that the best technology for removing existing varnish is by using chemical cleaning fluid. It would be best that this fluid is compatible with in-service fluid and can efficiently remove varnish.” Farooq suggests adding chemical cleaning as a separate category (see Does Removing Varnish From the Fluid Also Clean the Surfaces Within the System?).

- **Charge agglomeration.** The particles are charged with electrostatic forces.
and forced to agglomerate in size. Agglomeration occurs not in the filtration equipment but when the oil returns to the lubrication system. When the sub-micron particles agglomerate to multi-micron sized particles, they are removed through conventional mechanical filtration. Like ELCs, agglomeration units are sensitive to water.

- **Depth media filters.** These units are effective at removing smaller amounts of polar submicron contaminants that are in suspension. However, if the oil is heated to above the melting point of the contaminants, all of the filtered oil degradation products will melt back into solution, re-contaminating the fluid.

- **Electrophysical separation process.** This technology was designed to remove organic soft contaminants from the lubricants. The unique aspect of this technology is its ability to remove oil degradation products that are both insoluble and soluble. It does not impact other additive components in the lubricant, nor is the filter media affected by water or other contaminants.6

“Opinions are widely divided on this topic (of remediation) and, somewhat unfortunately, tend to be highly dependent on product availability and the marketing approach,” says Duchowski. “They include everything from the use of highly absorbent/adsorbent cellulose-based filter media through systems employing high efficiency filter media assisted by oil cooling and, finally, to the use of ion-exchange resins, which function here also solely as adsorbent materials. The main point being that varnish precursors tend to be soluble at typical operating temperatures up to the point when enough of them accumulate within the system to agglomerate and form sludge. At that point, even relatively coarse filter elements would be subject to blockage, but that point is usually considered too late for effective varnish treatment.”

He continues, "Unfortunately, no quantitative data that could be used for an objective comparison of all these methods exist, making it very difficult to say which method provides the best results. In addition, the effectiveness of each depends on the available surface area, fluid turnover rate, the intrinsic propensity of the employed media to absorb/adsorb varnish materials and the operating conditions—most notably temperature. In practice, therefore, the treatment methods based on lubricant cooling and subsequent filtration seem to offer the best results on the grounds of superior surface area and ease of use.”

Farooq says, “The technology that we know works very effectively is the adsorbent media technology that is engineered to have high affinity for the polar varnish precursors in the lube oil. The media has large surface area and high void volume, relatively low fluid flux and has electro-chemical affinity for the varnish precursors. Its working principle is Physisorption—a process in which the adsorbent material and the adsorbate (varnish precursors) are bonded by weak electrostatic forces arising from induced dipole moments such as van der Waals forces. Because of its chemical structure, varnish molecules are attracted to the adsorbent through electrostatic forces and hydrogen bonding.”

**DEALING WITH SERIOUS VARNISH FORMATION**

Duchowki says, “The treatment of a serious varnish problem depends on the remaining additive content in the lubricant (about 75%). Should that additive content be measured sufficient by the established methodologies, the treatment method I referred to earlier (lubricant cooling and subsequent filtration) can be successfully applied. Should the additive content have dropped below 75%, the chemical flush remains the most appropriate option. Probably the best method for dealing with a serious varnish problem remains a thorough system flush, perhaps even a solvent or detergent assisted flush. At the very minimum the flush should be performed with twice the velocity or volume flow of that employed at normal operating conditions, but, better yet, conditions should be set up such that at least the minimum Reynolds number of 4,000 is reached, though values higher than 10,000 have often been employed and recommended.”

For systems experiencing serious varnishing issues, Farooq advises the identification of the underlying causes of varnish formation and their elimination as the long-term remedy. For the immediate control of the problem to keep the turbine running until the next outage (see Figure 4), as is the case in
most plants, he advises the following.

- Deploy a varnish mitigation system such as engineered adsorbent media type to start the cleanup of the oil.
- Measure the oil condition by Membrane Patch Colorimetry (MPC) Test on a weekly basis to monitor oil cleanup until the MPC ΔE values are under 15.
- Replace the servo valves, if needed, as a preventive measure to avoid turbine trip since that is the most costly and disruptive consequence of the varnish problem.

Zhou says the best way to handle a serious case of varnish formation depends on a root cause analysis of the system, but generally:
1. Identify the root cause of oil degeneration and varnish formation.
2. Clean the system using the appropriate varnish removal technology.
3. Put in place necessary engineering and maintenance controls for the system.

PREVENTION

Preventing varnish from developing in the first place with a well-balanced formulation of high-performance base stock and advanced additives is a sound strategy. To that end, the following should be considered.

- **Deposit control.** As mentioned earlier, varnish can be generated by thermal degradation, oxidation and contamination. Some oils generate more deposits than others, but advanced turbine oils are formulated to limit the generation of sludge and varnish, while keeping deposits in suspension.
- **Air release and foam control.** Entrained air in oil with inferior air release performance may be compressed in turbine bearings or high-pressure hydraulics, causing adiabatic compression (micro dieseleng). Adiabatic compression can cause localized elevated oil temperatures that may promote the formation of varnish. Similarly, excessive surface-level foaming can accelerate oxidation. Oils formulated for rapid air release and minimal foam formation will provide superior protection against varnish.
- **Filterability.** This refers to a fluid’s ability to pass through a filter with minimal pressure drop. Oils with poor filterability will pollute filters faster, which might require more frequent filter changes.
- **Antitrust and corrosion protection.** Rust and corrosion contribute to oxidation and the formation of contaminant-based varnish.
- **Wear protection.** Since wear metals act as an oxidation catalyst, wear material from machinery components can lead directly to varnish formation.9

Farooq says, “All turbine lube oils degrade during service, which produces oil insoluble products and the resulting deposits or varnish. As a preventive measure, it is recommended to install varnish mitigation systems to prevent buildup of the varnish precursors to a point that they form damaging deposits on critical operating surfaces such as servo valves and the rest of the lube system.”

Zhou says, “Using a properly formulated premium quality lubricant with proven low varnish potential is the most effective way to prevent varnish formation in turbine oil systems. Approaches to formulation of these types of oils include balancing the base stocks with carefully selected additives and/or having a lubricant with varnish dissolving properties. One example of a varnish prevention oil (see The 100% Varnish Prevention Solution) would be an oil, which passes the MHPS Dry TOST Test.”

### OIL ANALYSIS

Appropriate tests for analyzing sludge and varnish depend on the failure mechanism (see Figure 5). According

<table>
<thead>
<tr>
<th>Traditional Turbine Oil Tests</th>
<th>New Turbine Oil Tests for Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity @ 40 C</td>
<td>Viscosity @ 100 C and 40 C + VI (ASTM D445 &amp; D2270)</td>
</tr>
<tr>
<td>Water by Crackles</td>
<td>Water by Karl Fischer (ASTM D6304)</td>
</tr>
<tr>
<td>Oxidation by FTIR</td>
<td>Oxidation by FTIR</td>
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<tr>
<td>Acid Number</td>
<td>Acid Number (ASTM D664)</td>
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<tr>
<td></td>
<td>RULER—Remaining Useful Life (ASTM D6971)</td>
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<tr>
<td></td>
<td>Membrane Patch Colorimetry (MPC)—Varnish Potential</td>
</tr>
<tr>
<td></td>
<td>Foam (ASTM D892)</td>
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<td></td>
<td>Air Release (ASTM D3427)</td>
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<td></td>
<td>Water Separation (ASTM D1401)</td>
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<tr>
<td></td>
<td>Rust Test (ASTM D665A = DI Water / ASTM D665B = Sea Water)</td>
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<tr>
<td></td>
<td>RPVOT—Rotating Pressure Vessel Oxidation Test (ASTM D2272)</td>
</tr>
<tr>
<td></td>
<td>Particle Count (ISO 4406-1999)</td>
</tr>
</tbody>
</table>

Figure 5 | A list of traditional tests routinely employed for industrial oils at commercial labs versus a list of tests that should be considered with specific choices dependent upon the current operation of the turbine. (Figure courtesy of Lubrication Engineers, Inc.)
to some experts, common oil analysis testing methods do not accurately predict varnish. These tests include:

- Rotating Pressure Vessel Oxidation Test (RPVOT) ASTM D2272
- Acid Number ASTM D664 or D974 increase
- Particle Count with ISO 4406 Cleanliness Code.

A better approach is a combination of the following three tests:

- Ultracentrifuge, which predicts varnish.
- MPC identifies the contamination level in used oil as it relates to oil degradation and potential varnish development.
- Remaining useful life evaluation routine (RULER) identifies levels of antioxidants.

Sampling and testing should be performed at least quarterly—more frequently as the oil condition degrades. Trending yields valuable insights into the condition and remaining service life of the oil and equipment.

Varnish is a serious problem with the potential to shut down critical equipment and cost millions of dollars in downtime and lost productivity. So:

- Is varnish becoming an increasing problem? Yes.
- Do researchers know what causes varnish? Yes.
- Is varnish preventable? Yes.
- Is it entirely preventable? Probably not.
- Can it be removed once it starts forming? Yes and no.
- Is more research needed on varnish prevention? Definitely.

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REFERENCES


2. Group IV or PAO (polyalphaolefin) base stock is a chemically engineered synthetic. It has a highly stable chemical composition and is increasingly present in synthetic and synthetic-blend products for industrial and vehicle applications. Group V base stock is usually blended with other base stock. It is used in small amounts as secondary base stock to impart discrete lubricant properties. This base stock is capable of accommodating a wide variety of properties and custom formulas. Because of this it provides the base ingredient for many additives.


4. This is a generalization of the Arrhenius Equation: a formula for the temperature dependence of reaction rates. The equation was proposed by Svante Arrhenius in 1889.


7. The Reynolds number is an experimental number used in fluid flow to predict the flow velocity at which turbulence will occur.

