Developments in Measuring and Managing Hydraulic Oil Degradation

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Abstract

Oxidative stress on hydraulic oils creates deposits, causing a host of operational issues for fluid power applications. Much attention has been given to understanding other applications susceptible to deposits, such as turbines, including the development of testing and mitigation technologies. These technologies are not necessarily applicable to hydraulic fluids. This presentation will introduce a new method to test deposit tendencies in hydraulic oils, as well as innovations to address sludge and varnish challenges in hydraulic circuits.

1. Hydraulic oils have a tough life

There is a lot demanded of hydraulic oils. They are used to transmit energy, lubricate components, transfer heat, and carry away contaminants from critical surfaces. They often must perform their job in extremely dirty environments while withstanding significant thermal stress. Contaminated hydraulic oil accounts for most hydraulic system failures. However, another significant failure mode in hydraulic oils occurs when it degrades, producing varnish deposits.

Varnish is an oil-derived deposit. It produces a sticky, tenacious residue that plays havoc on the reliable performance of the hydraulic system. Varnish can cause valves to stick, risking the control of the system. It acts as an insulator, preventing the oil from performing its cooling function, resulting in hotter, less efficient systems. Varnish can foul filters, requiring frequent changes. These deposits may also accumulate, plugging up oil lines or heat exchangers. Oil has a hard time functioning if it can't reach its intended destination.

1.1. The Impact of Hydraulic Oil Varnish

Varnish deposits have significant implications depending upon the application. Mining shovels may experience erratic bucket movement or overheating, causing them to reduce production or be taken out of service. Varnish in plastic injection moulding machines decreases product yield and quality, requiring rework or increased scrap rates. Varnish in an amusement park may cause the ride to stop operating, stranding vacationing tourists up in the air. Varnish in a hydraulically-driven elevator may cause the car to stop early and the passengers to trip on their way out. The bottom line is varnish deposits impair the performance of the hydraulic system creating significant cost and safety issues. Understanding how varnish is generated, and how to detect or predict it, is essential information for any operator of hydraulic systems. This knowledge also leads to strategies to mitigate varnish.

Figure 1: Sticky Servo valve coated in varnish (Courtesy of A. Sasaki)

1.2. How hydraulic oils fail

There are multiple ways a hydraulic oil can fail, forming deposits. Oxidation is the most common and well-known degradation pathway. This reaction is initiated by the removal of an electron from an atom in a hydrocarbon molecule, producing a free radical. This reactive component will quickly find another healthy molecule to damage, creating more and more degradation products. Antioxidants are formulated into hydraulic oils to react readily with the free radical, thereby sacrificing themselves to protect the base oil. This is why it is so important to have antioxidants in your hydraulic oil, as base oil does not last long without this protection. The oxidative process is greatly accelerated by heat, air and certain contaminants like water, iron or copper. Other mechanisms may also aid in degrading hydraulic oil, such as micro-dieseling, electrostatic spark discharge (ESD), or reactions with incompatible fluids or contaminants that migrate into the system. Regardless of the mode of degradation, the first impact to the performance of the hydraulic oil is the generation of deposits.

2. The Critical Role of Oil Analysis

Oil analysis is essential to identify the potential of the oil to form varnish. And this is where this avoidable problem typically begins. In many applications, hydraulic oils are considered commodity products where the cheapest available oil is often selected. The same care goes into monitoring the oil. Often, if a condition monitoring program is deployed, the most basic oil analysis package is selected, which tells the operator nothing about the potential of the fluid to form varnish. Considering varnish is one of the primary modes of failure, doesn't it make sense to test for this condition, allowing you to take proactive action?

To adequately predict hydraulic oil varnish, the following tests are recommended:

- **Voltammetry, RULER (ASTM D6971)** – This test identifies the antioxidant health of both primary and secondary antioxidants (often ZDDP) used in hydraulic oils.
- **Molecular Spectroscopy using Fourier Transform Infrared (FTIR)** – The following two ASTM methods that can be of value in monitoring hydraulic oils.
    - ASTM D7414 measures oxidation
    - ASTM D7412 measures antiwear additives
- **Membrane Patch Colorimetry, MPC (ASTM D7843)** – This test method is effective to determine an oil's propensity to form varnish.
- **Ultracentrifuge (UC)** – Extracting and qualitatively measuring the amount of degradation products extracted through high centrifugal forces has been successful in predicting the onset of varnish in hydraulic oils.

The MPC test, originally developed for turbine oils, is the most common methodology for testing for varnish. As hydraulic oils are often much more contaminated than turbine oils, tweaking existing tests or performing other metrics may be considered.

2.1. The modified MPC test: Reduced Volume

One of the challenges of adding the MPC test to large equipment fleets is sample volume. Established programs have sample kits typically only collecting 100mls of oil per sample. Most of this volume is consumed with the customer's current test program, leaving nowhere near enough fluid to add an MPC test on to the test slate.

Hastings Deering, a leading industrial oil analysis and equipment supplier in Australia, took on this challenge. Customers were reluctant to move to larger sample bottles for hydraulic oil samples, so Hastings Deering developed an innovative approach. Instead of using the 47mm membrane, as specified in ASTM D7843, they used a 25mm membrane.

In order to put together a suitable volume for filtering through a 25mm membrane, they did a surface area calculation and determined the volume of sample should be between 7 ml and 10 ml. They then performed MPC tests on several samples to compare the results. The 7 ml sample size for the 25mm patch was closest in results to the 47mm result.

Next, an Analysis of Variance (ANOVA) was performed to compare the 7ml sample volume on the 25mm patch to the 50ml volume obtained on the 47mm patch. These results of the ANOVA can be seen in Table 1.

Table 1: ANOVA, Single Factor - Comparison between 7mL and 50mL

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
50mL	7	291.7	41.67143	10.96571
7mL	7	315	45	6.06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	38.77786	1	38.77786	4.555211	0.054139	4.74722
Within Groups	102.1543	12	8.512857			
Total	140.9321	13				

Analysis of Variance is a method of comparing means to each other via the F-test. In ANOVA the default hypothesis is that the means are the same and when the F-statistic is lower than the F-critical value (a value that accounts for differences in sample size), it assumes that the null hypothesis is correct.

The p-value provides an estimate of the probability that two random means from different data sets overlap. The default probability (alpha) assumes a 5% probability of overlap, and values over the alpha suggests that the two methods are similar.

The ANOVA calculation produced an F value of 4.6 whereas the F critical was 4.7. The p value is also larger than the alpha (0.05). These results translate to the MPC values produced with the augmented test method, using 7ml through a 25mm membrane are statisically the same as the ASTM D7843 test.

This test modification allows Hastings Deering to easily add MPC testing onto their customers existing oil analysis program. Because of this test modification, MPC testing is now a common test on varnish-prone applications, such as mining excavators.

3. When Contaminants get in the way of Varnish Testing

The MPC test is effective because oil degradation products form dark chromophores, allowing us to trend the changes in patch colour. What happens when there is so much contamination in the fluid that it interferes with the measurement of these chromophores? This often happens with hydraulic oil. In order to provide meaning to MPC tests, identifying whether the colour on the patch is related to oxidation products, dirt, or wear metals is critical.

3.1. Case Study 1: Mining excavator MPC challenges

The MPC was being trended in a large hydraulic mining excavator. Its values were steady around 20 and then suddenly jumped to 34. Most alarming however, the patch took on a silver hue, as can be seen in Fig. 2.

Figure 2: Silver MPC membrane from a mining excavator

This clearly didn’t look like varnish, having lost the characteristic brownish color from previous patches. SEM-EDX analysis was performed on the patch, showing a large concentration of chromium. Interestingly, elemental spectroscopy only showed the chromium increasing from 3 to 6ppm in the sample.

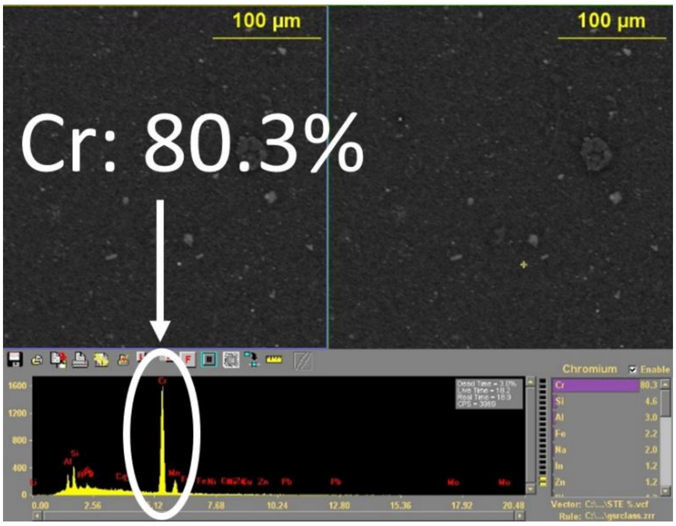

Figure 3: SEM analysis of the patch revealed that >80% of the membrane was made up of chromium.

The laboratory immediately informed the mine that the shovel was a experiencing severe wear in the hydraulic cylinders and to inspect the equipment.

3.2. Case Study 2: Pump failure getting in the way of varnish testing

The hydraulic control system of a gas turbine had its monthly varnish potential monitored. This gas turbine provided power to a univeristy campus. The MPC was less than 5 for almost a year, when the next month's result suddenly jumped to a value of 37. The other oil analysis parameters were acceptable, except for the iron, which escalated from 1 to 12ppm.

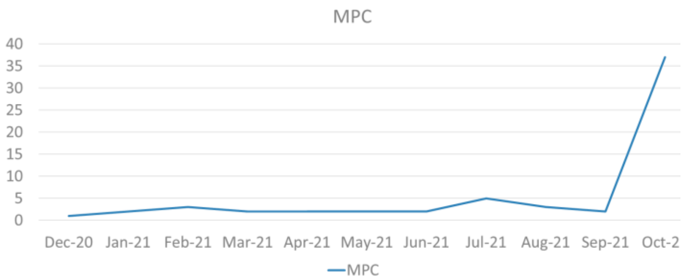

Figure 4: MPC results suddenly skyrocketed.

The PQ Index was determined. The PQ Index is a relative measurement of the total Ferrous (Iron) content in a sample by means of magnetic field detection. The higher the PQ index reading in a sample the higher the total concentration of ferrous material generally associated with wear.

Typically a result of >10 suggests a problem. The result of the sample came in at 263! The sample bottle was also visually inspected as can be seen in Figure 6.

Figure 5: The sample didn't appear like it had undergone any type of extreme degradation.

However, when the sample was turned upside down, a fine film of magnetically influenced debris was observed.

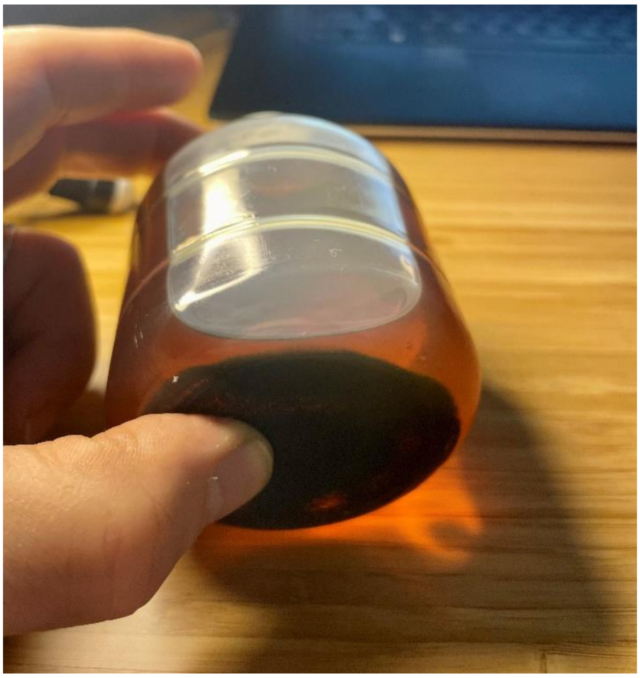

Figure 6: Black deposit film covering the sample bottom.

The test results suggested that a gear pump was failing, contributing to the iron content. The customer was able to schedule downtime before the pump failed. During the outage, the servo valves also had to be replaced as the iron particles were carried throughout the hydraulic system.

In this case, the iron particles obscured the accurate measurement of the varnish potential, but the MPC test still provided value in identifying another maintenance issue. The PQ index and visual observation of the sample bottle were able to determine that it was ferrrous particles, ultimately preventing an unplanned outage and more damage to the gas turbine.

3.3. Determining organic versus inorganic contaminants by solvent washing

SEM testing is not always practical to perform on MPC samples and would certainly increase sample costs. Also, inorganic contaminants other than iron may be present, making the PQ index of little value Another option to determining if the membrane color is made up of oxidation products or inorganic material is by rinsing the patch with a solvent, such as methyl ethyl ketone (MEK).

Oil degradation products are most often organic and soluble, having the ability to transition in and out of solution. Oxidized base oil fits into this category. There may be several inorganic contaminants which are not soluble in the sample, that may influence the MPC test. These include:

- Hydraulic oil antiwear agents such as zinc dialkyldithiophosphate (ZDDP), which form insoluble degradation products.
- Dirt and debris
- Wear metals

Sometimes, if an oil has undergone excessive degradation, the particles polymerize, become quite large and then behave like inorganic contaminants as they resist going back into solution.

It is often necessary to determine the type of degradation products that are making up the stain on the MPC membrane. To do this, one may rinse the MPC membrane with strong solvent. If the stain disappears, the degradation products are soluble. If the stain does not change colors, the degradation products are insoluble or polymerized and will not go back into solution. Eamples can be on the following patches.

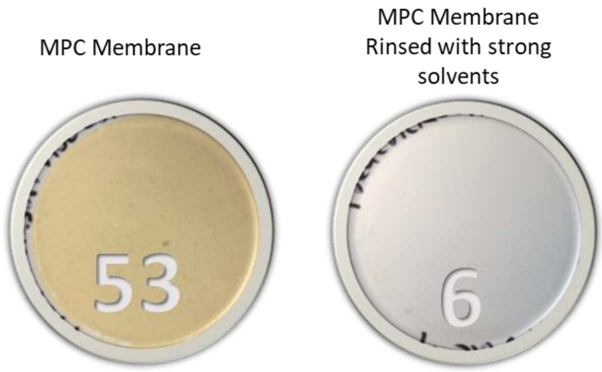

Figure 7: This MPC patch was rinsed with solvent, dissolving the oxidation products and removing the color bodies from the patch

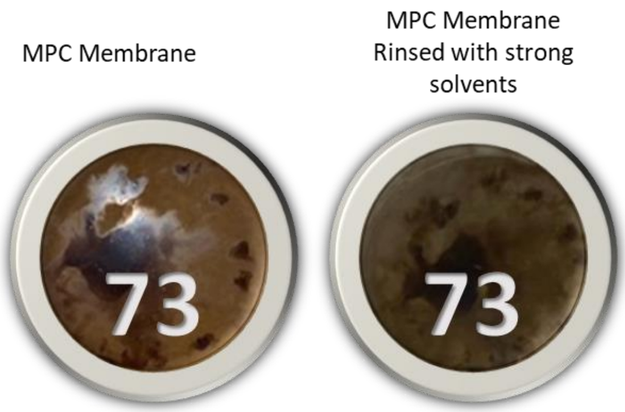

Figure 8: This MPC patch was rinsed with solvent but had no impact on lowering the MPC value suggesting that inorganics make up the majority of contaminants on the membrane.

4. A solution to hydraulic oil varnish

There are multiple technologies suitable for mitigating hydraulic oil varnish. Filtration technologies like electrostatic oil cleaning and depth media filters have been shown to be effective. These are impractical in mobile applications, such as mining excavators and are expensive in small reservoir applications.

Another option is to add a solubility enhancing agent to the in-service oil. This works by dissolving the degradation products into the oil and preventing further deposits from being generated.

The impact of a solubility enhancing agent on a lube oil heating bundle can be seen below. A 3% concentration of the solubility enhancing agent dissolved the deposits over the course of a month without impacting the other performance properties of the fluid.

Figure 9: The impact of adding DECON, a solubility enhancing agent to an oil. One can observe the deposits have been dissolved. This was done while the equipment was operating, with no adverse performance benefits to the system

5. Conclusion

Hydraulic oils are subjected to increased thermal and mechanical stresses in modern hydraulic systems causing varnish deposits. Hydraulic oil formulations are constantly being iterated to accommodate these more stressful environments, however varnish problems still persist. The leading reason why hydraulic oil users experience varnish problems with their fluid is due to inadequate oil analysis testing. Simply, oil degradation and deposit formation are not being measured in most condition monitoring programs.

This paper identified a modified test procedure to the MPC test using only 7 ml of sample volume. Statisical analysis of the procedure (ANOVA) illustrated that the results of this modified test produced similar results as ASTM D7843. This lower volume test procedure makes it much more practical to add on to existing sampling programs, as most sample sizes will have sufficient residual volume to accommodate this test. This modified procedure therefore helps address the biggest issue with hydraulic oil varnish, by making the test much more accessible.

Differentiating between oxidation products and inorganics is an important aspect of MPC testing for hydraulic oils. The paper identified three methods to do this:

1. SEM-EDX can identify the chemistry and size distribution of the material on the MPC patch, helping determine if the patch is comprised of oxidation products or inorganics.
2. PQ Index is useful tool if the patch turns a grey color to determine if iron debris may be present. This augments Inductively Coupled Plasma metal spectroscopy by identifying iron particles that are too large in size for ICP to measure (usually 3-5μm).
3. Using a strong solvent to rinse the MPC patch may also help differentiate inorganic contaminants from oxidation products. Oxidation products are dissolved into the solvent rinse, resulting in the MPC value being lowered, whereas inorganic contaminants are not.

Finally, the paper demonstrated that adding a solubility enhancing agent to an in-service hydraulic oil may help dissolve degradation products from the internals of the system. An example of a varnished heat exchanger bundle was shown, which was significantly decontaminated after adding 3% of a solubility enhancing agent into the in-service oil for 30-days. In addition, this technology has been shown to provide long-term varnish protection to hydraulic oil systems.