What Routine EHC Fluid Analysis Fails to Detect: Improved Phosphate Ester Maintenance Through Non-Routine Testing

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1. Abstract

Despite the critical nature of electrohydraulic control (EHC) systems, many steam turbine operators' oil analysis programs fail to detect fine insoluble contaminants that are responsible for costly downtime and failures. With minor modifications, however, gas turbine oil tests can be made suitable for use in steam turbine EHC applications. A modified version of the industry-standard membrane patch colorimetry (MPC) test, in particular, allows for the identification of "hidden" contaminants that are often responsible for costly EHC failures. By exploiting MPC analysis to its full potential, this method can be used to qualify application-specific problems like varnishing and dieseling in addition to quantifying their severity. Once these previously "hidden" problems have been identified, effective EHC fluid maintenance practices can be developed so that steam turbine performance and reliability may be ensured.

2. Introduction

Steam turbines are responsible for as much as 80% of global electricity production [1]. EHC systems are critical steam turbine components that employ a series of hydraulically controlled, high-precision servo valves [2]. These valves allow power output to be managed by controlling the flow of steam to the turbine. Because steam temperatures typically range from 370 - 600°C in this application, fire-resistant triarylphosphate ester-based lubricants have become the control fluid of choice in EHC systems [3].

Despite their excellent lubricating abilities and fire-resistant/self-extinguishing properties, phosphate esters (like other lubricants) are subject to breakdown during service. These fluids typically break down via 3 distinct pathways:

1.   Hydrolysis: reaction with water cleaves the phosphate ester into its phosphoric acid and phenol constituents [4].
2.   Oxidation: the phosphate ester's aryl substituents may react with oxygen to form polar breakdown products including weak acids [5].
3.   Thermolysis: phosphate esters are converted to black carbon/soot or coke when subjected to extreme temperatures (like those that occur during dieseling and sparking events) [6].

Regardless of their origin, all of the above breakdown products have a detrimental impact on EHC system performance and reliability. EHC fluid condition is, therefore, typically monitored by oil analysis [7]. Many users rely on low-cost or complimentary "routine" analysis packages provided by non-specialized oil labs or EHC fluid providers. Given the criticality of EHC systems, however, operators should carefully consider whether budget/complimentary analysis is good enough for their generating asset.

Typically, EHC fluid providers and commercial oil labs offer the following tests in their "routine" analysis packages:

•   Acid Number (ASTM D664 or D974).
•   Water Content (ASTM D6304 or D7546).
•   Resistivity (ASTM D1169).
•   Viscosity (ASTM D445).
•   Particle Count (ISO 15000:4406 or others).

Table 1: Condition of the EHC Fluid In-Service at Site "A" (Acceptable Parameters in Green; Off-Spec Properties in Red).

Package	Routine Analyses					Non-Routine Analyses	
Test	**Acid Number (mg KOH/g)**	**Resistivity (GΩ·cm)**	**Water (ppm)**	**Viscosity (SUS)**	**ISO Particle Count**	**Patch Weight (mg/50 mL)**	**Patch Photo**
Recommended Limits	0.20 (max)	5.0 (min)	1000 (max)	200 - 240	16/14/10 (max)	4.0 (max)	-
In-Service EHC Fluid	0.09	10.2	837	200	14/12/6	8.8	

Table 2: Condition of the EHC Fluid In-Service at Site "B" (Acceptable Parameters in Green; Off-Spec Properties in Red).

Package	Routine Analyses					Non-Routine Analyses	
Test	**Acid Number (mg KOH/g)**	**Resistivity (GΩ·cm)**	**Water (ppm)**	**Viscosity (SUS)**	**ISO Particle Count**	**Patch Weight (mg/50 mL)**	**Patch Photo**
Recommended Limits	0.20 (max)	5.0 (min)	1000 (max)	200 - 240	16/14/10 (max)	4.0 (max)	-
In-Service EHC Fluid	0.08	40.3	40	207	12/11/10	80.1	

3. Case Studies: Why "Routine" Phosphate Ester Analysis is Insufficient

While these "routine" test methods are useful for EHC fluid condition monitoring, they fail to detect some contaminants associated with failures in this application. Consider for instance, the Site "A" EHC fluid analysis outlined in Table 1.

Site "A" featured a Boiling Water Reactor with a generating capacity of 680 MW. Operators at Site "A" relied heavily upon the complimentary analyses provided by their fluid manufacturer. As Table 1 illustrates, these reports suggested to them that their EHC fluid was in good condition. They were, therefore, startled when a servo failure precipitated an unplanned 30 day outage. The cost of lost production during this span reached into the tens of millions of US dollars.

A subsequent root cause investigation revealed that the servo failure had been precipitated by "particulate etching." This proved confounding since "routine" oil analysis had shown acceptably low particle counts. Indeed, the EHC fluid's poor condition did not become truly apparent until it was passed through a 0.45 μm filter patch as part of a modified MPC test. This test revealed that high levels of fine insoluble breakdown products were present. The particle counts routinely carried out on EHC fluids are blind to these fine contaminants since they're smaller than 4 μm. Given the high levels of fine material detected by the modified MPC analysis, the finding that servo valves were etched is much less surprising; it is most unfortunate that the fines responsible for the failure were only discovered after it had already occurred.

Site "B" (Table 2) provides a similar example highlighting the inadequacy of budget/complimentary oil analysis in EHC applications. This site employed a 650 MW steam

turbine whose EHC fluid appeared to be in excellent condition based on the "routine" analyses conducted. Once again, the fluid's extremely low ISO particle count suggested that remarkably few insolubles were present. Patch testing, however, revealed extreme levels of fine contamination. Indeed, when one considers the entire 11,000 L EHC fluid reservoir associated with this system, patch testing identified 18 kg of potentially harmful solids that particle counts could not!

These case studies highlight a significant inadequacy in the current condition monitoring programs of many EHC users: costly and avoidable failures are occurring as a result of contaminants that aren't being "routinely" tested for. In an effort to remedy this situation, we sought to determine what these fine contaminants are in an effort to develop a test method that can be routinely applied to detect them. Ultimately, we were motivated by the desire to develop fluid treatment/filtration strategies that could then be used to eliminate them and prevent avoidable failures.

4. Composition of the Fine Contaminants that "Routine" EHC Fluid Analysis Misses

Although the EHC fluids in-service at Sites "A" and "B" were both found to contain high levels of fine insoluble contamination, the appearance of the fines captured on their filter patches differed significantly. The black appearance of the Site "B" filter patch is consistent with the carbon produced by phosphate ester thermolysis. The mechanisms by which such carbon forms are already well-established [6] and will not be elaborated upon herein.

The amber-brown appearance of the fines isolated from the Site "A" fluid, however, suggest that their composition differs from that of the black Site "B"contaminants. In an effort to elucidate the composition of these amber-brown phosphate ester deposits, we therefore evaluated the elemental composition of similar filter patches obtained from 7 different in-service phosphate esters by energy dispersive X-ray spectroscopy (EDS).

EDS elemental analysis of the in-service phosphate ester filter patches (Table 3) revealed that the amber-brown deposits thereupon were almost entirely organic, consisting of carbon, oxygen and phosphorus. While the same elements occur in phosphate ester fluids themselves, the deposits were found to be more oxygen-rich than EHC

fluids. This suggests that these amber-brown deposits are phosphate ester breakdown products and that oxidation plays a role in their formation. In analogy to the more ubiquitous Group I – IV lubricants employed in other turbine systems, these amber-brown insolubles can, therefore, best be regarded as *phosphate ester varnish*.

Table 3: Composition of the Amber-Brown Deposits Isolated from In-Service Phosphate Esters.

Patch	Patch Photo	C (%)	O (%)	P (%)
Virgin Fluid		74.82	16.97	8.21
1		70.65	22.74	2.11
2		70.94	22.3	2.78
3		58.62	29.44	7.81
4		67.29	18.67	0.35
5		69.87	17.64	0.51
6		67.99	19.55	0.49
7		69.01	21.3	0.87
Average In-Service	N/A	74.18	23.57	2.50

While varnish has been widely discussed in Group I – IV turbine oils [8], we are unaware of any detailed studies involving phosphate ester varnish. We, therefore, compared the average composition of the amber-brown patches to the expected composition of triarylphosphate esters (**A**) and a variety of their breakdown products (See Appendix for molecular structures). Since phosphate esters are synthetics, the structures of their degradation products are easier to predict than those of conventional turbine oils whose base fluid structures vary significantly.

4.1. Hydrolytic Phosphate Ester Breakdown Products

Given that hydrolysis is the most-cited phosphate ester breakdown mechanism, we began our investigation by comparing the composition of the observed deposits to that expected for every possible hydrolysis product (Table 4). Triarylphosphate ester hydrolysis is known to occur in up to 3 steps; each step yields a phenol (**B**) and a distinct acid (**C**, **D** or **E**). The phenols produced in this manner contain no phosphorus while each subsequent hydrolysis step yields an acid with increasing oxygen and phosphorus content. Since the patch deposits contained phosphorus, they were determined not to be phenolic in nature. While the trend of increasing acid oxygen content was consistent with the actual deposits' composition, the corresponding trend of increasing phosphorus content was not. Indeed, the observed deposits were found to be phosphorus-poor relative to the fluid from which they formed. This suggests that hydrolysis alone cannot account for the formation of phosphate ester varnish.

Table 4: Comparison Between Deposit Composition and that Expected for Hydrolytic Breakdown Products.

Species	C	O	P
A: New Triarylphosphate Ester	74.82	16.97	8.21
Experimental Deposit Average	**74.18**	**23.57**	**2.50**
B: Phenol	85.27	14.73	0.00
C: Acid 1	66.45	22.61	10.94
D: Acid 2	49.76	33.86	16.39
E: Acid 3 (H_3PO_4)	0.00	67.39	32.61

4.2. Oxidative Phosphate Ester Breakdown Products

Since hydrolysis alone could not account for the observed patch deposit composition, we expanded our investigation to include simple triarylphosphate ester oxidation products (Table 5). Such breakdown typically yields organic acid moieties at the oil's benzylic sites. Since each triarylphosphate ester may contain up to 6 such sites, we examined the expected composition of series of oxidized phosphate esters ranging from 1/6th oxidized (**F**) to completely oxidized (**H**). As anticipated, increasing degrees of oxidation were found to increase the degraded species'

oxygen content while decreasing its phosphorus content. Even the completely oxidized phosphate ester **H**, however, featured a phosphorus content that was more than double that observed for the patch deposits. This suggests that the deposits could not have formed from oxidation alone. Further, more complex oxidative coupling reactions, which produce dimers (**I**) and polymers (**J**), did not produce breakdown products whose composition was consistent with that of the phosphate ester varnish isolated.

Table 5: Comparison Between Deposit Composition and that Expected for Oxidative Breakdown Products.

Species	C	O	P
A: New Triarylphosphate Ester	74.82	16.97	8.21
Experimental Deposit Average	**74.18**	**23.57**	**2.50**
F: Minimal Oxidation (1/6th)	69.42	23.12	7.46
G: Partial Oxidation (half)	60.15	33.38	6.46
H: Complete Oxidation	57.54	36.95	5.50
I: Oxidative Dimerization	83.74	8.27	8.00
J: Oxidative Polymerization (Hexamer)	81.50	10.72	7.78

4.3. Condensation to Yield Second Generation Phosphate Ester Breakdown Products

While neither hydrolysis nor oxidation produced species whose composition matched that of the amber-brown phosphate ester deposits, both breakdown mechanisms yield reactive products. These species tend to undergo further reactions to produce second generation breakdown products. Indeed, condensation reactions may occur whenever acids and phenols are present. When 1 site on a triarylphosphate ester is oxidized, the newly formed weak acid may react with a phenol to generate a higher molecular weight product (**K**). If the triarylphosphate ester is further oxidized (at 2 sites for instance), the resulting acid may react with 2 phenols and so forth. An evaluation of the composition of such stepwise breakdown products (**K**, **L** and **M**) revealed that each successive oxidation/condensation reaction generated a species whose oxygen content was greater than and whose phosphorus content was less than that of the original phosphate ester (Table 6).

Table 6: Comparison Between Deposit Composition and that Expected for 2nd Generation Breakdown Products.

Species	C	O	P
A: New Triarylphosphate Ester	74.82	16.97	8.21
Experimental Deposit Average	**74.18**	**23.57**	**2.50**
K: Condensation (Oxidation + 1 Phenol)	84.56	9.38	6.05
L: Condensation (Oxidation + 2 Phenols)	82.64	12.51	4.84
M: Condensation (Oxidation + 6 Phenols)	**75.08**	**22.23**	**2.69**

These trends mirror those actually observed for phosphate ester varnish. Indeed, the composition of the high molecular weight breakdown product **M** that arises when a completely oxidized phosphate ester undergoes condensation reactions with phenols at all sites was a near-perfect match to the experimental composition of phosphate ester varnish. Moreover, this fully oxidized/condensed breakdown product features an extremely high molecular weight. As molecular weight increases, so too does the propensity to become insoluble like the phosphate ester varnish that was isolated.

Given the multiple avenues available for breakdown, phosphate ester varnish is, no doubt, a complex mixture of degradation products. The near-perfect match between the experimental composition of the patch deposits and that of the fully oxidized condensation product **M**, however, suggests that this degradation product is an excellent model for the many species that actually comprise phosphate ester varnish. We, therefore, conclude that *both* hydrolytic and oxidative pathways play a role in the formation of phosphate ester varnish.

5. Measuring the Fine Contaminants that "Routine" EHC Fluid Analysis Misses

Having identified the fine insolubles that often accumulate in phosphate ester EHC systems as being comprised of either carbon/coke or varnish, we next turned our attention to the development of a laboratory test that could be used to both quantify and qualify these contaminants. The filter patch testing described in the case studies above proved to be a reliable method for the reproducible quantification of fine insolubles. The development of objective methods for their qualification, however, required further work.

MPC is a well-established test method for the determination of varnish potential in Group I – IV turbine oils [9]. This test employs spectrophotometry to objectively quantify filter patch color using the CIE LAB color scale. With conventional turbine oils, the colorimetric intensity of their amber-brown patch deposits is known to correlate with their propensity for varnishing. Given that phosphate ester varnish was also shown to manifest in the form of amber-brown residues on filter patches, we therefore, sought to determine if MPC analysis could be used to evaluate phosphate ester varnish potential.

By plotting the MPC ΔE of the 7 amber-brown phosphate ester patches examined In Table 3 as a function of their oxygen content, we established that the intensity of the amber-brown patch residues correlated with their degree of breakdown (Figure 1). This finding suggests that MPC can be used as a predictor of phosphate ester varnish potential for amber-brown phosphate ester patches.

Unfortunately, the straightforward extension of MPC methodology to phosphate esters was hampered by
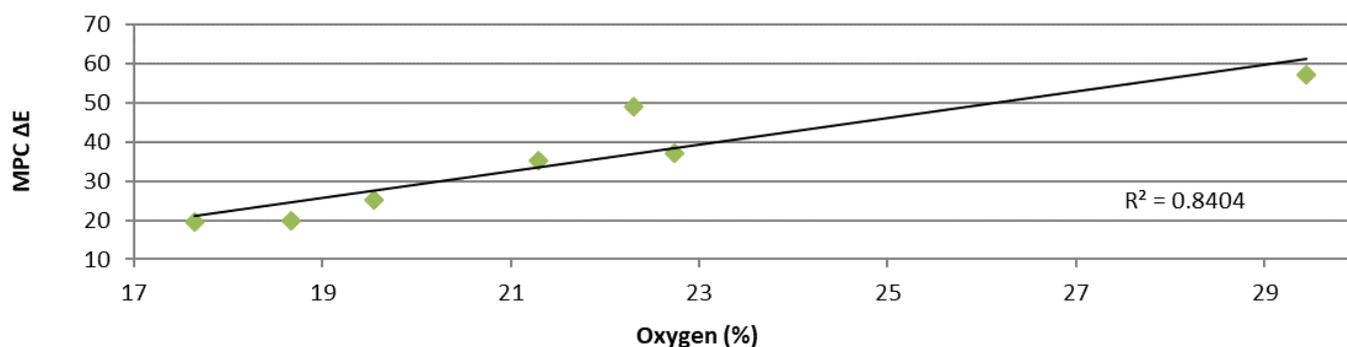
Figure 1: Colorimetric Intensity of Amber-Brown Phosphate Ester Deposits as a Function of the Degree of Oxidation.
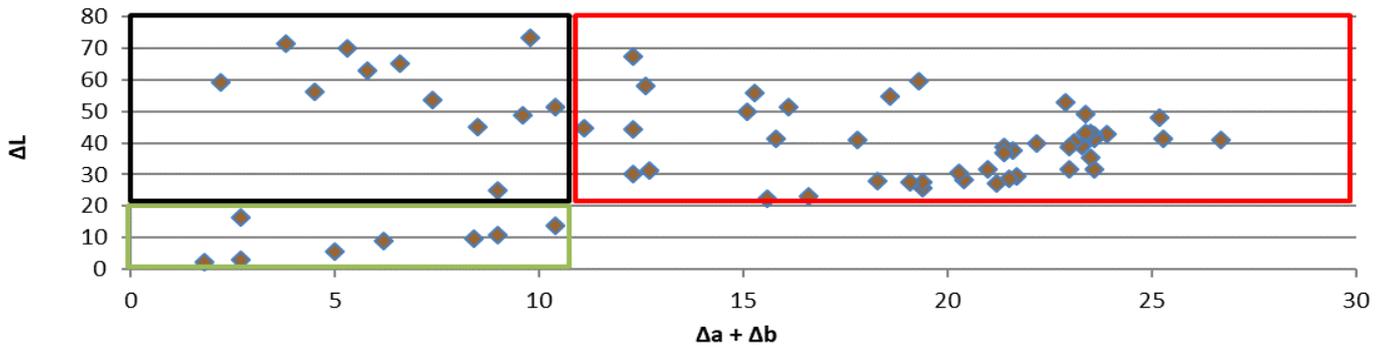
Figure 2: Spectrophotometric Contributions to Phosphate Ester Membrane Patch Colorimetry.

systems which left black, carbonaceous deposits on 0.45 µm filter patches (See Site "B" case study above). While these patches featured extremely high MPC ΔE values, their intense colors are the result of carbon/coke and not phosphate ester varnish. Carbon/coke are relatively common contaminants in EHC fluids, however, they're unlikely to produce varnish deposits.

Unfortunately, the few commercial oil labs that do perform MPC analysis on phosphate esters lack the expertise to make this distinction. As a consequence, EHC systems that have dieseling problems etc. are frequently and erroneously flagged as having high varnish potentials.
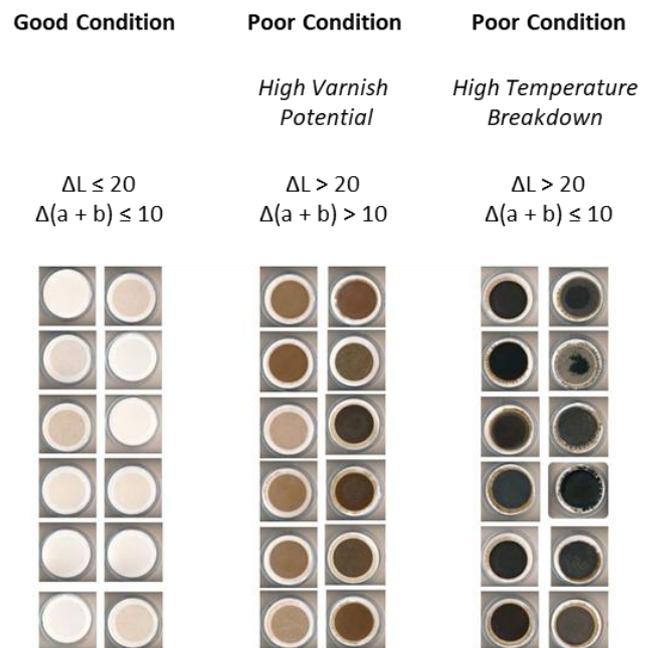
While the ubiquitously reported MPC ΔE offers no means of distinguishing between black carbon and amber-brown phosphate ester varnish, the spectrophotometers used to measure ΔE can also determine ΔL, Δa and Δb. Indeed, these parameters are the colorimetric contributors used to calculate ΔE (Equation 1), where L, a and b are the white/black, red/green and yellow/violet contributors to a patch's color, respectively. Amber-brown phosphate ester varnish, therefore, features a significant contribution from the a and b parameters. Patches that are black due to carbon, on the other hand, have a significant ΔL with little a or b contribution. This suggests that L, a and b could be used to objectively distinguish between carbon and varnish in phosphate esters.

$$(Equation\ 1) \qquad \Delta E = \sqrt{L^2 + a^2 + b^2}$$

An analysis of the spectrophotometric properties of 65 different in-service phosphate ester filter patches revealed no correlation between ΔL or Δ(a + b), however, the obtained data distribution was non-random (Figure 2). Examination of the plot revealed that 3 of its 4 quadrants bore data points while the 4th quadrant bore none; this

suggests that phosphate ester MPC measurements can produce 3 possible outcomes:

1.   When ΔL and Δ(a + b) are both low (green quadrant), there is little amber-brown or black contribution to patch color. These patches is light because there are few or no fine insoluble contaminants and the EHC fluid is in good condition.

2.   When ΔL is high but Δ(a + b) is low (black quadrant), the patch is dark with little or no amber-brown contribution. The EHC fluid is in poor condition owing to the presence of black carbonaceous insolubles; it is unlikely to produce varnish.

3.   When ΔL and Δ(a + b) are high (red quadrant), the patch is dark as a result of intense amber-brown deposits. The EHC fluid in this scenario is in poor condition, featuring a high level of phosphate ester varnish.

Good Condition	Poor Condition	Poor Condition
	High Varnish Potential	*High Temperature Breakdown*
ΔL ≤ 20 Δ(a + b) ≤ 10	ΔL > 20 Δ(a + b) > 10	ΔL > 20 Δ(a + b) ≤ 10

Figure 3: Application of Limits to Phosphate Ester MPC.

Based on the obtained results, it is apparent that MPC spectrophotometric contributions (ΔL and $\Delta(a + b)$) can be used to objectively qualify phosphate ester varnish potential. Indeed, phosphate ester EHC fluids which produce elevated MPC $\Delta(a + b)$ readings possessed elevated varnish potentials. This overcomes a significant limitation with the currently-established MPC test protocol since ΔE measurements fail to distinguish between the products of phosphate ester thermolysis and phosphate ester varnish. When limits are applied to phosphate ester MPC analysis, its potential utility as a condition monitoring tool for steam turbine operators becomes immediately apparent (Figure 3).

6. Removing the Fine Contaminants that "Routine" EHC Fluid Analysis Misses

The identification of failure-causing contaminants and the development of a test method for their objective measurement are only first steps to better steam turbine management. Once users can detect the fine insolubles (either carbon or varnish) that are commonly overlooked by "routine" testing, they must then be given the tools to remove them if they hope to avoid costly failures.

6.1.   Electrostatic Filtration

Fortunately, the electrical properties of phosphate esters make them particularly well-suited to electrostatic filtration. Electrostatic filter systems employ powerful electric fields which deflect particles from a fluid flow path as a function of mass [10]. Since all particles have mass, all particles can (in theory) be removed by electrostatic filtration. This is an important distinction from conventional filtration which removes particles as a function of their size and, hence, cannot remove extremely fine species like carbon and insoluble phosphate ester varnish. While electrostatic filtration is remarkably efficient with regard to carbon-removal, it is only moderately-so with regards to varnish-removal. The reason for this is that phosphate ester varnish exists in both soluble and insoluble forms. Since electrostatic devices can only remove insoluble species, they have little to no impact on soluble phosphate ester varnish levels.

6.2.   Ion Exchange Treatment

Ion exchange treatment allows for the removal of soluble contaminants from lubricants. Indeed, ion exchange resins are ubiquitously employed as acid-scavengers in EHC fluid

applications [11] and varnish-scavengers in Group I – IV turbine oil applications [12]. Typical resins are, however, of extremely limited utility when it comes to removing phosphate ester varnish. This is a consequence of the fact that phosphate ester varnish is chemically distinct from the varnish that hydrocarbon-based oils produce.

When one understands the composition and means by which phosphate ester varnish forms, however, novel next-generation ion exchange resins can be engineered to effectively remove the phosphate ester varnish that standard resins and electrostatic devices leave behind. Indeed, the recent development of resins that remove acidic *and* varnishing phosphate ester breakdown products represents the most significant improvement to EHC fluid maintenance practices in the past decade (Figure 4).
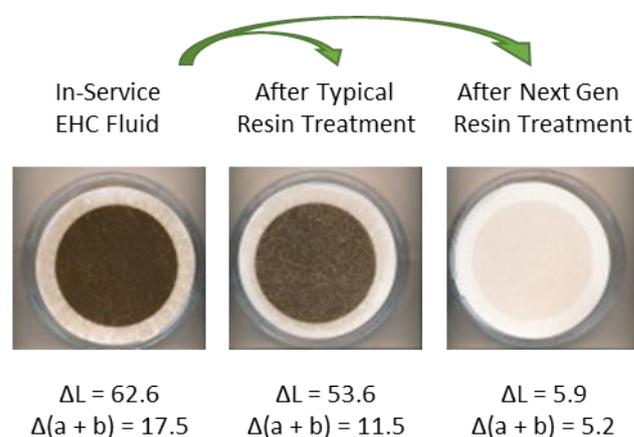
Figure 4: Improved Phosphate Ester Varnish-Removal Abilities of Next Generation Ion Exchange Resins.

While well-engineered ion exchange resins can remove phosphate ester varnish from in-service EHC fluids, they remain limited with regard to their ability to remove carbon/coke since these ultra-fines are wholly insoluble. Electrostatic filtration, therefore, remains the treatment of choice for systems with high MPC ΔL and low MPC $\Delta(a + b)$ values. Electrostatic filters may also be a more effective tool for the bulk removal of insoluble phosphate ester varnish from extremely contaminated systems since critical levels of insolubles can foul or overwhelm the finite removal-capacity of ion exchange resins. In general, badly degraded systems benefit from both electrostatic and ion exchange treatment to remove bulk insoluble contaminants and acids/remaining varnish, respectively.

6.3.   Case Study: Removal of Carbon and Varnish that "Routine" EHC Fluid Analysis Misses

The use of the earlier-described phosphate ester MPC test allowed operators of a 235 MW steam turbine at Site "C" to identify that their EHC fluid contained supercritical levels of fine insolubles. This analysis highlighted the presence of contaminants that were not apparent based on the fluid's 16/14/10 ISO particle count. The high ΔL and relatively low Δ(a + b) values produced by their fluid suggested that carbon and other potentially harmful thermolysis products were accumulating. Indeed, quantification revealed that their phosphate ester contained more than 15 times the maximum recommended level of fines. This is thought to have been the result of ongoing microdieseling.

In an effort to address the extreme level of contaminants detected by MPC, management at Site "C" installed an electrostatic contaminant removal system. Following this installation, regular phosphate ester MPC analyses were conducted to monitor the unit's effectiveness. Even before the first lab results were available, operators at Site "C" noted that the fluid's color and appearance improved rapidly (Figure 5). These obvious improvements were mirrored by similarly dramatic improvements in the fluid's patch weight and MPC values (Figure 6). Indeed, gravimetric patch weight determinations revealed that electrostatic filtration removed 98% of the fine insolubles present at Site "C" while its patch color also improved. It is interesting to note that, based on mass, the majority of the contaminants in this system were carbonaceous. These

Figure 5: Improvement of EHC Fluid Appearance Following Electrostatic Filtration.

were rapidly removed. Without these carbonaceous fines, the once-black MPC patches took on an amber-brown coloration. This suggested that the EHC system at Site "C" suffered from dieseling and varnish problems; the dominance of the former, however, masked the presence of the latter. While continued electrostatic filtration kept the fluid's patch weight low, its improved MPC values fluctuated between ΔL ≈ 20 – 45. These fluctuations were the result of the complex equilibrium between the soluble and insoluble forms of phosphate ester varnish.

While the electrostatic system removed insoluble varnish, it could not remove its soluble analog and MPC measurements continued to show that the fluid suffered from an improved but, nevertheless, elevated varnish potential. It should be noted that Site "C" operators had
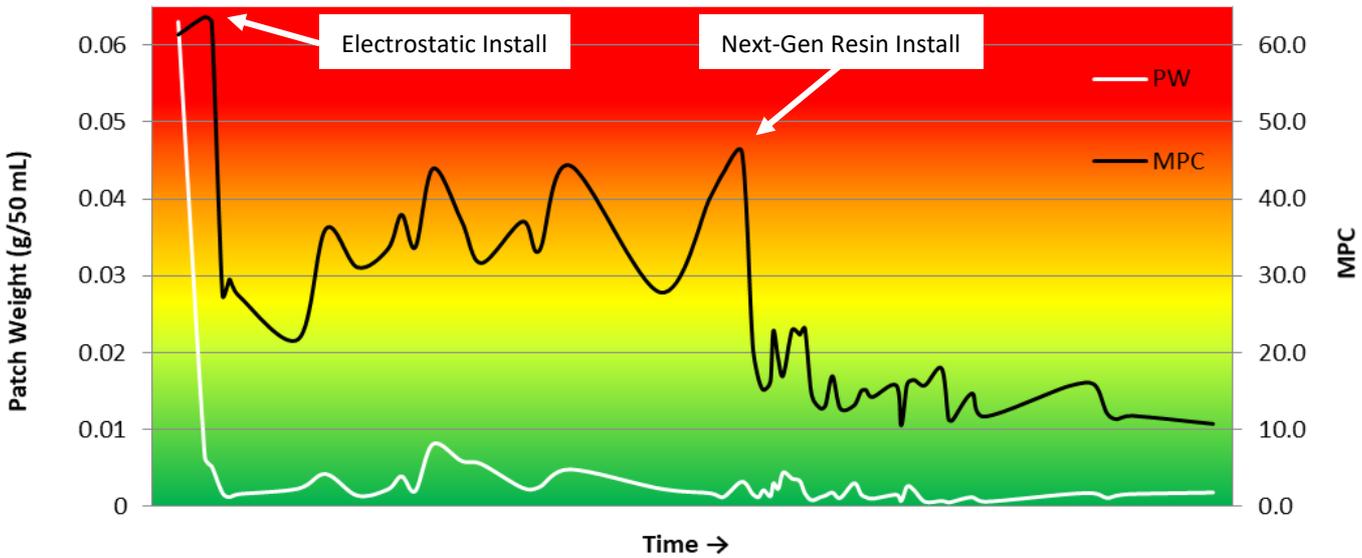

Figure 6: On-Site Removal of Carbon and Phosphate Ester Varnish via Electrostatic Filtration and Next Generation Ion Exchange Treatment as Measured by Patch Weight (PW) and Patch Color (MPC).

also been treating their fluid with a widely used ion exchange resin which allowed them to keep their system's acid number within an acceptable range. Neither this resin nor the electrostatic filter could completely address the phosphate ester varnish which persisted in the system.

In an effort to address their continuing varnish problem, operators at Site "C" elected to replace their conventional ion exchange resin with a next-generation product specifically engineered to remove phosphate ester varnish. Following this resin change, the fluid's MPC values improved by a further 77%. Complex equilibrium effects continued to lead to some MPC fluctuation, however, the next generation resin capably maintained MPC values within the acceptable range ($\Delta L \leq 20$) (Figure 6).

The results from Site "C" clearly demonstrate the utility of phosphate ester MPC testing as a tool for condition monitoring in addition to showcasing the effectiveness of both electrostatic filters and next-generation ion exchange resins as tools for the removal of the fine insolubles that "routine" EHC analysis misses. Indeed, the powerful combination of electrostatic contaminant removal and next-generation resin treatment led to cummulative 98% and 83% improvements in the fluid's patch weight and MPC values, respectively. Since their installation, operators at Site "C" have not experienced issues with their steam turbine's hydraulic control system.

7. Conclusion

The merits of lubricant condition monitoring are well-established and oil analysis is a key part of most turbine operator's maintenance practices. A variety of commercial labs offer turbine oil analysis packages tailored to meet gas turbine oil testing requirements. Despite the fact that steam turbines account for as much as 80% of global power production, commercial labs rarely offer the niche testing necessary to ensure good EHC fluid maintenance. Many EHC users, therefore, rely upon more widely available low-cost (or complimentary) "routine" oil analysis packages.

Unfortunately, the tests most "routinely" employed to this end are blind to common EHC fluid contaminants like fine insoluble carbon and phosphate ester varnish. As a result, "routine" EHC fluid analysis often misses fine breakdown products that can lead to avoidable failures.

However, this needn't be the case.

MPC is a well-established tool for gas turbine oil analysis and, as seen herein, can be adapted to both quantify and qualify the fine contaminants that "routine" EHC fluid analysis misses. Indeed, phosphate ester MPC analysis allowed operators at Site "C" to identify a fluid condition problem that they would have, otherwise, been blind to. Similar problems were also noted retrospectively at Sites "A" and "B". At Site "A", MPC testing could have prevented an unplanned outage whose costs ran into the tens of millions of US dollars; clearly operators of critical systems should not rely on complimentary/budget "routine" oil analysis like those at Site "A" did.

In EHC applications where fine breakdown products have been detected by MPC analysis, electrostatic filtration and next-generation ion exchange treatment can be used (either on their own or in combination) to remove them. Electrostatic devices provide an effective means of removing the carbonaceous fines that result from high temperature phosphate ester breakdown. They also allow for the relatively fast bulk clean-up of heavily contaminated systems (wherein patch weights exceed 4 mg/50 mL). Next generation ion exchange resins maintain the favorable acid-removal abilities of their predesessors while allowing phosphate ester varnish to be effectively removed for the first time.

The costly EHC failures that oft-"hidden" fine insoluble carbon and phosphate ester varnish are known to promote are, therefore, entirely avoidable.

8. References

[1] Reddy, A. S., Ahmed, M. D. I., Kumar, T. S., Reddy, A. V. K., Bharathi, V. V. P., Analysis of Steam Turbines. International Refereed Journal of Engineering and Science, Volume 3, Issue 2, Pages 32 – 48 (2014).

[2] Rohner, P., Industrial Hydraulic Control 4th Edition. John Wiley & Sons, West Perth Australia (2005).

[3] Leugner, L., The Practical Handbook of Machinery Lubrication 2nd Edition. Maintenance Technology International Inc./Oil City Press, Edmonton, Canada (2012).

[4] Boyde, S., Hydrolytic Stability of Synthetic Ester Lubricants. Lubrication Science, Volume 16, Issue 4, Pages 297 – 312 (2000).

[5] Cho, L., Klaus, E. E., Oxidative Degradation of Phosphate Esters, ASLE Transactions, Volume 24, Issue 1, Pages 119 – 124 (1981).

[6] Phillips, W. D., The High Temperature Degradation of Hydraulic Oils and Fluids. Journal of Synthetic Lubrication, Volume 23, Pages 39 – 70 (2006).

[7] Brown, K., Managing the Health of Fire Resistant Steam Turbine Electrohydraulic (EHC) Control Oils. Machinery Lubrication, Volume 5, Noria Corp. (2001).

[8] Sasaki, A., Hydraulic Valve Problems Caused by Oil Oxidation Products. Hydraulic Failure Analysis: Fluids, Components, and System Effects. ASTM STP 1339, Totten, G. E., Wills, D. K., Feldmann, D. Eds., American Society for Testing and Materials, West Conshohocken, USA (2001).

[9] ASTM D7843-16: Standard Test Method for Measurement of Lubricant Generated Insoluble Color Bodies in In-Service Turbine Oils using Membrane Patch Colorimetry. Book of ASTM Standards (West Conshohocken, USA) Pub. ASTM International (2016).

[10] Sasaki, A. Uchiyama, S., A New Technology for Oil Management: Electrostatic Oil Cleaner. SAE Technical Paper 2002-01-1352 (2002).

[11] Phillips, W. D., Improved Maintenance and Life Extension of Phosphate Esters Using Ion-Exchange Treatment. Journal of Synthetic Lubrication, Volume 13, Issue 3, Pages 225 – 261 (1996).

[12] Dufresne Jr., P., Hobbs, M. G., MacInnis, G., Lubricant Varnishing and Mitigation Strategies. Combined Cycle Journal, Fourth Quarter 2013, 34 – 40 (2014).
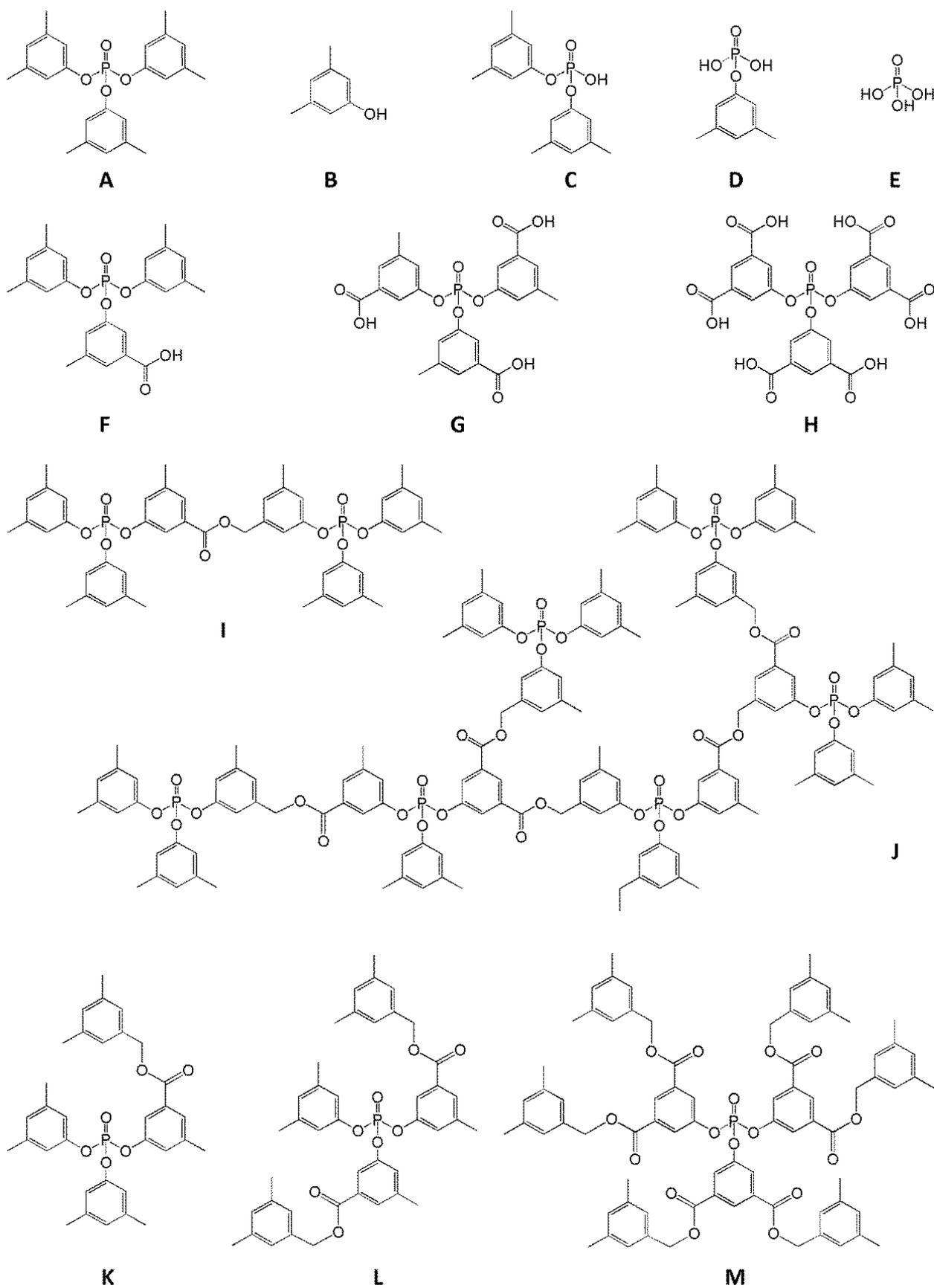
9. Appendix:

Figure 7: Proposed Phosphate Ester Breakdown Product Structures.