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Oil Condition Monitoring (OCM) with new tools – Comparison, challenges and solutions

This case study focuses on 67 representative oil samples from an Austrian steel producer. As part of the InTribology2 project, a multidimensional project was carried out together with the Austrian Competence Center for Tribology (AC2T research GmbH) and the measuring device manufacturer eralytics. The aim was to compare different measurement methods for the relevant variables in the field of oil condition monitoring. To put the lubricants in use into context, they were compared with fresh products and artificially aged samples.

Our goal was very ambitious: we wanted to carefully compare different measurement methods for critical variables in oil condition monitoring, for engine oils, hydraulic fluids and gear oils, which include both classic mineral-oil-based lubricants and fully synthetic ester-based lubricants. The measurement methods used range from infrared spectroscopy, determination of the element content, determination of the kinematic viscosity and the viscosity index to the determination of the water content and the TAN/TBN. Different measurement methods were used for the individual parameters, some of which follow established standards and some of which pursue completely new approaches. Although trending plays a major role in oil condition monitoring, the case study will compare the absolute measurement results with each other.

Introduction to Oil Condition Monitoring

Oil condition monitoring plays a crucial role in predictive and proactive maintenance strategies by providing valuable insights into equipment health and lubricant condition. By analyzing various oil properties, maintenance professionals can detect early signs of equipment and lubricant degradation, identify potential issues before they escalate into costly failures, and optimize maintenance schedules/strategies to prevent unplanned downtime.

Over time, the practice of oil condition monitoring has evolved to encompass various techniques and methodologies. These processes typically involve sampling oil from a machine, analyzing its properties, and interpreting the results to make informed maintenance decisions. While some organizations opt for in-house oil condition monitoring capabilities, others rely on third-party service providers for specialized expertise and equipment.

When considering oil condition monitoring, organizations must weigh the pros and cons of using third-party services versus in-house solutions. Third-party providers are known to offer specialized expertise, state-of-the-art equipment, and streamlined processes, but depending on the number of samples tested, using these providers can come with high costs and delayed reports. In-house solutions provide significantly faster results and therefore greater control and flexibility but require investment in equipment, training, and ongoing maintenance. With that said, innovations in condition monitoring technology have meant that in-house oil condition monitoring capabilities now stand out as the superior choice for organizations seeking control, precision, and integration within their maintenance operations.[1]

[1] Getting Started with In-house Oil Condition Monitoring: An Easy Way to Avoid Equipment Failure

Sample Matrix

As a starting point, 9 representative fresh industrial lubricants were selected. By artificially ageing these samples, 3 to 4 additional samples were prepared for each fresh oil. Finally, samples of in-service lubricants of the same type were added to the sample matrix. In total 67 samples were available for planned tests:

Oil Type	Engine Oil	Gear Oil	Hydraulic
Fresh oil	2	3	4
In-service oils	6	12	8
Artificially aged oils	8	12	12
	Total: 67 samples		

List of fresh lubricants and examples of in-service lubricants together with information about appearance:

Sample code	Lubricant	Use	Appearance	Color	Smell
F3671-000	SAE 10W40 / A	fresh	clear	brown	typical
G1349-000	SAE 10W40 / A	in-service	strong soot	black	typical
G1349-001	SAE 10W40 / A	in-service	strong soot	black	typical
F3672-000	SAE 10W40 / B	fresh	clear	light brown	typical
G1350-000	SAE 10W40 / B	in-service	strong sediment	brown	typical
G1350-001	SAE 10W40 / B	in-service	light sediment	brown	typical
F3673-000	ISO VG 150 / C	fresh	clear	red-brown	typical
G1345-000	ISO VG 150 / C	in-service	light sediment	brown	typical
F3674-000	ISO VG 220 / C	fresh	clear	red-brown	typical
G1345-001	ISO VG 220 / C	in-service	sediment	brown	typical
F3675-000	ISO VG 460 / C	fresh	clear	dark brown	typical
G1346-000	ISO VG 460 / C	in-service	strong sediment	dark brown	typical
F3676-000	HLP 46 / C	fresh	clear	light brown	typical
G1344-000	HLP 46 / C	in-service	clear	brown	typical
F3685-000	HLP 46 / D	fresh	clear	green	typical
G1343-001	HLP 46 / D	in-service	clear	green	typical
F3686-000	HFDU 46 / E	fresh	clear	light yellow	typical
G1342-000	HFDU 46 / E	in-service	clear	yellow	typical
F3677-000	HFDU 46 / C	fresh	clear	yellow	typical
G1343-000	HFDU 46 / C	in-service	clear	yellow	typical

Artificial Ageing

All samples were artificially aged to exploit the lifetime span of the lubricant. This applied ageing was thermo-oxidative ageing. Several preliminary tests were carried out to determine the correct duration and parameters. A modified method according to CEC-L-48-A-00 Method B[2] was used for the gear oils and engine oils. For the hydraulic oils, a test setup according to ASTM D2272[3], the so-called RPVOT test, was used. In order to simulate the actual conditions in real operation, a certain amount of water was added depending on the sample and the temperature was adjusted accordingly.

Parameters for “CEC” for gear oils and engine oils:

Parameter	Engine oil	Gear oil
Oil quantity	100 mL	
Air flow rate	10 L/h	
Test temperature	121°C	160°C
Duration	4, 8, 12, 16 days	7, 13, 16, 20 days

Parameters for “RPVOT” for hydraulic oils:

Parameter	Mineral oil	Ester
Oil quantity	100 g + water	
Added water	0.1 %	0.5 %
Initial pressure	6.2 bar	
Test temperature	95°C	
Duration	4, 8 days	

Oil Analysis – Methods Matrix

If an industrial company wants to carry out oil condition monitoring under its own responsibility, there are various analytical devices and different methods available. New and innovative solutions are entering the market, some of which use new measurement methods. This leads to differences in operation and handling. Practical workflows must also provide the basis for a functioning solution.

Oil condition monitoring reports typically include a range of key metrics that provide insights into equipment health and lubricant condition. These metrics may include parameters such as chemical condition (TAN and TBN), kinematic viscosity, additives analysis, contaminant and particle analysis, and ferrous debris content.[1]

These parameters can be measured using various analytical techniques. The in-house solutions typically employ methods which have easy operation and handling whereas third party labs typically employ more complex equipment, including sample preparation, and favor techniques with a higher degree of automation. Thus, the question arises whether the in-house solution and third-party techniques provide the same information in a realistic OCM scenario. To answer these questions, a set of typical third-party lab oil condition

[2] CEC L-48-00 Oxidation stability of lubricating oils used in automotive transmissions by artificial ageing
[3] ASTM D2272 Standard Test Method for Oxidation Stability of Steam Turbine Oils by Rotating Pressure Vessel

monitoring techniques (Method A) was compared to the methods applied in ERALAB OCM (Method B), eralytics' solution for in-house oil condition monitoring.

The following table shows the methods that were compared, and exemplary results are presented within this paper:

Parameter	Meaning	Method A	Method B
Kinematic Viscosity (& Density)	Lubrication	Stabinger viscometer ASTM D7042[4]	Differential pressure capillary viscometer
Elemental Analysis (Ca, Zn, P, etc.)	Contamination, wear, additives	ICP-OES spectrometer including microwave digestion ASTM D5185[5]	RDE-OES spectrometer ASTM D6595[6]
Infrared spectroscopy: Oxidation, Nitration, Sulfation, (Soot, Water)	Ageing	Laboratory FTIR ASTM E2412[7]	Oil Condition Monitoring FTIR ASTM E2412[7]
TAN / TBN	Chemical condition	Titration TAN: ASTM D664[8] TBN: ASTM D2896[9]	Oil Condition Monitoring FTIR Chemometric prediction

Kinematic Viscosity (& Density)

Viscosity is the most common test run on lubricants because it is considered a lubricant's most important physical property. This test measures a lubricant's resistance to flow at a specific temperature. If the viscosity is not correct, the oil film will not be sufficient for the load. Heat and contamination are also not carried away at the appropriate rates, and the oil cannot adequately protect the components. A lubricant with improper viscosity can lead to overheating, accelerated wear and ultimately the early failure of equipment.[1]

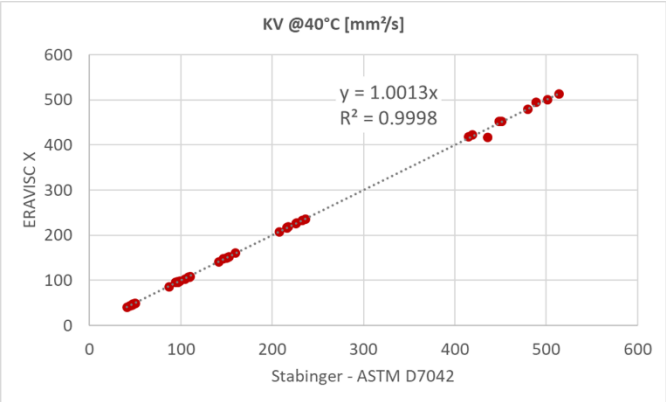
Because viscosity is such a fundamental and widely used property, there are numerous different viscosity measurement devices and techniques available on the market. Recently. the company eralytics, a manufacturer of laboratory analysis devices based in Vienna, Austria, launched the kinematic viscometer ERAVISC X, the first device on the market based on a novel differential pressure capillary method.[10]

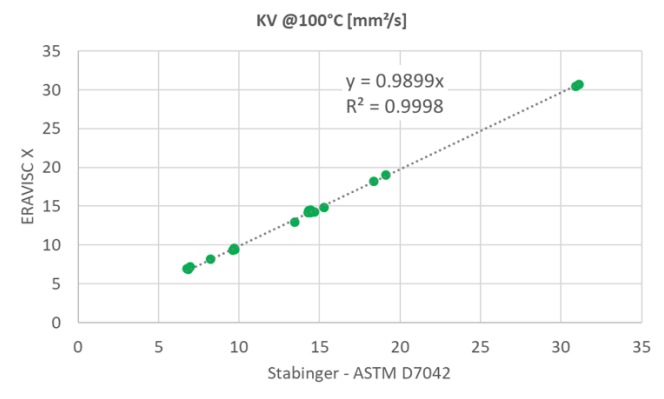
This innovative new method uses a small differential pressure in addition to gravity to force the sample through a capillary. The flow of the sample is measured by the decay of the applied differential pressure. This physical principle results in the simultaneous determination of both the kinematic and the dynamic viscosity. In extension to the viscosity an independent density cell is connected in parallel. Besides delivering a 5-digit density value at an individual temperature between 15°C to 100°C, it is used to improve the measured

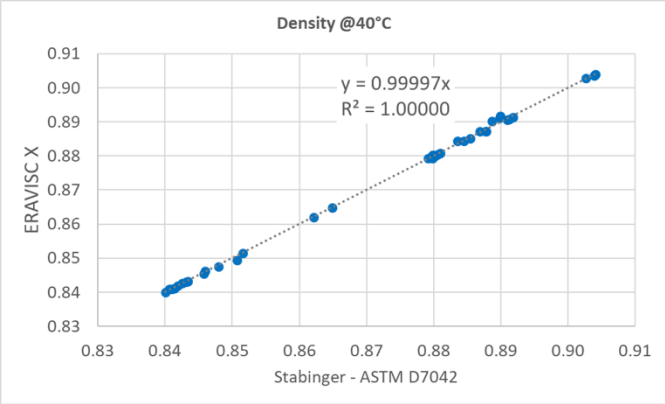
[4] ASTM D7042 Standard Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer
[5] ASTM D5185 Standard Test Method for Multielement Determination of Used and Unused Lubricating and Base Oils by ICP-AES
[6] ASTM D6595 Standard Test Method for Determination of Wear Metals and Contaminants in Lubricating RDE-AES
[7] ASTM E2412 Standard Practice for Condition Monitoring of In-Service Lubricants by FT-IR Spectrometry
[8] ASTM D664 Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration
[9] ASTM D2896 Standard Test Method for Base Number of Petroleum Products by Potentiometric Perchloric Acid Titration
[10] Let's talk about kinematic viscosity – The key to lubricant analysis, Lube Magazine, 04/2023

precision of the kinematic viscosity. This possibility arises from the fact that current measurements lead to an overdetermined parameter set that can be used for this optimization.

Within this study 42 results of kinematic viscosity (KV) and density at 40°C and 14 of kinematic viscosity at 100°C were compared. The number of measurements at 100°C was reduced because the volume of aged samples was limited, and other measurement parameters were found to be more important to be measured. In this study, the ERAVISC X, which uses the differential pressure capillary method, was compared with an SVM 3000 according to ASTM D7042[4].







The mean absolute difference for KV@40°C was 0.4% with a root mean square error (RMSE) of 0.74 % and for KV@100°C it was 1.1% with a RMSE of 1.7 %. The mean absolute difference for D@40°C was 0.0004 g/cm³ with a RMSE of 0.0003 g/cm³.

If these deviations are compared with the precision data of the method standards available on the market, it can be concluded that the deviations are well within expectations for in-service oils. The slightly higher variation in the measured values of the 100°C measurement is typical and can be explained, among other things, by the presence of water in the in-service oil samples.

Elemental Analysis

Elemental analysis is probably the most fundamental test in the oil analysis toolbox. Its history goes back to the 1940s and 1950s when it was used in the railroad industry to determine the presence of wear metals in diesel engine oils. However, elemental analysis, sometimes referred to as elemental spectroscopy, atomic emission spectroscopy (AES) or simply wear metal analysis is about more than just measuring the concentrations of wear metals such as iron, lead and copper.

In its present form, elemental analysis is used to determine the concentrations of 15 to 25 different elements ranging from wear metals and contaminants to oil additives.

Nearly all oil analysis labs use one of two types of atomic emission spectrometer, either an inductively coupled plasma (ICP) instrument, or a rotating disc electrode (RDE) instrument. The basic difference between the two lies mainly in the way in which the sample is vaporized and the atoms excited by the high-energy source.

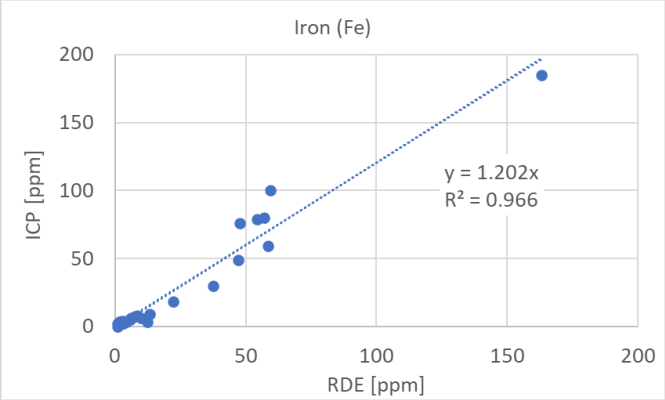
In an ICP instrument, the oil is injected into a high-temperature argon plasma, where the atoms are vaporized, excited and subsequently emit light. In an RDE spectrometer, sometimes referred to as an “Arc-Spark” instrument, the oil is vaporized and excited using a high-voltage discharge between an electrode and a rotating carbon disc.

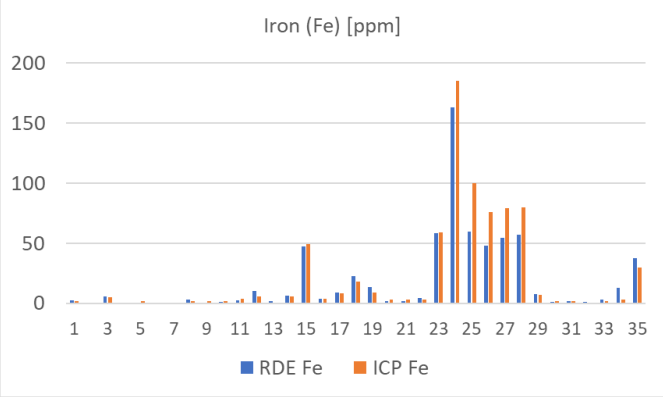
The rest of the instrument, whether it be an ICP or RDE spectrometer, is basically the same. The light emitted by the excited atoms is collected and focused onto the slits of the spectrometer. The spectrometer contains a diffraction grating, which is similar to a prism in that it splits light of different wavelengths or colors into discrete wavelengths, based on their angle of diffraction.

The light intensity at each angle, typically referred to as a channel, is measured using a light-sensitive photodiode and the resultant voltage signal converted to a concentration in ppm based on a simple calibration procedure.[11]

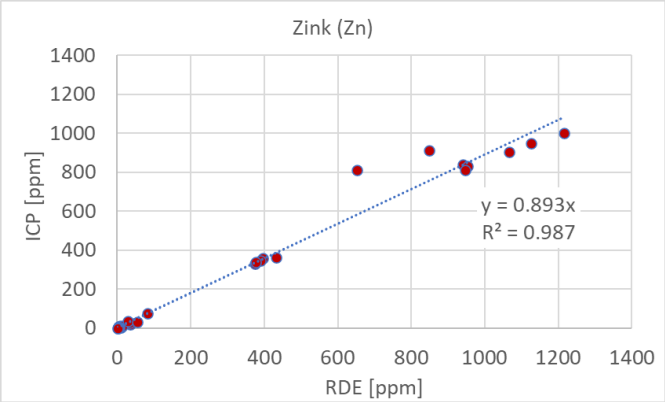
In the scope of this project, a 2500 ICP-OES spectrometer from Agilent according to ASTM D5185[5] and eralytics’ ERAOIL RDE-OES spectrometer according to ASTM D6595[6] were compared. All samples were first brought into solution for the measurements with the ICP using microwave digestion. Nitric acid and hydrogen peroxide were used at 190°C. In contrast, no sample preparation was used for the measurements with the RDE.

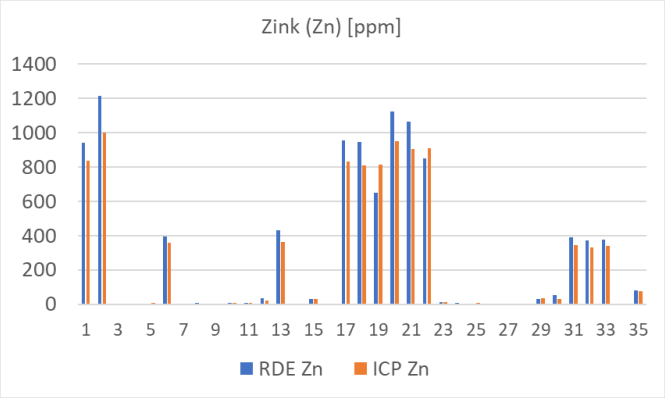
In total 16 elements were compared, and a sub-set of representative examples will be presented. The charts below show correlation for iron (Fe) measured for 29 samples, mainly the fresh and in-service lubricants:





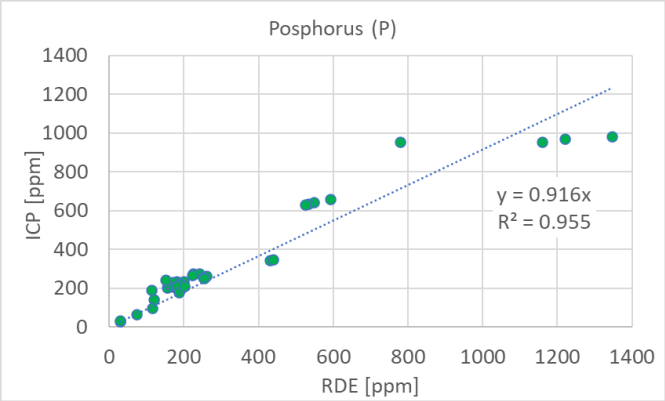
The data for zinc (Zn) measured on 33 samples gives a similar picture:

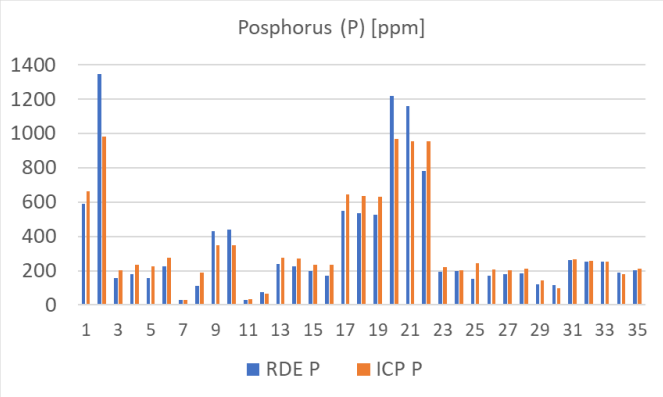




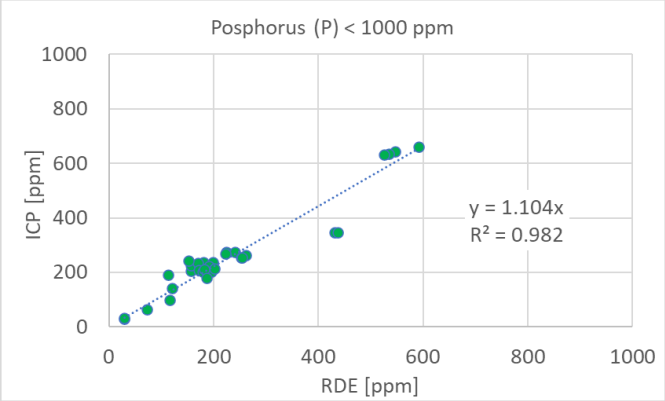
[11] Elemental Analysis Explained and Illustrated, Noria Corporation

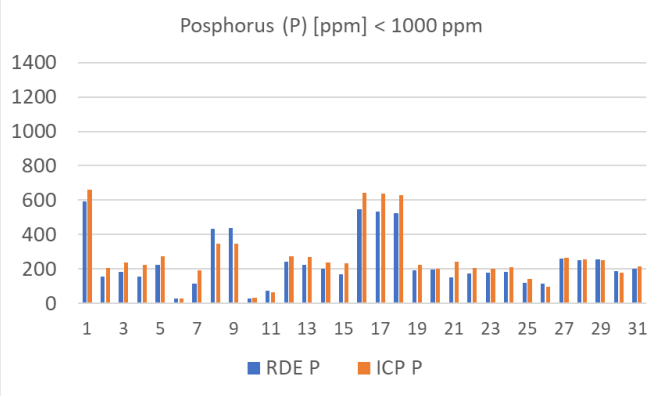
The result gained for phosphorus (P) also measured on 33 fresh samples gives a different picture. The apparent deviation seems to be explained by the fact that the ICP for this element reached saturation above 1000 ppm. However, further investigations are planned on this point:



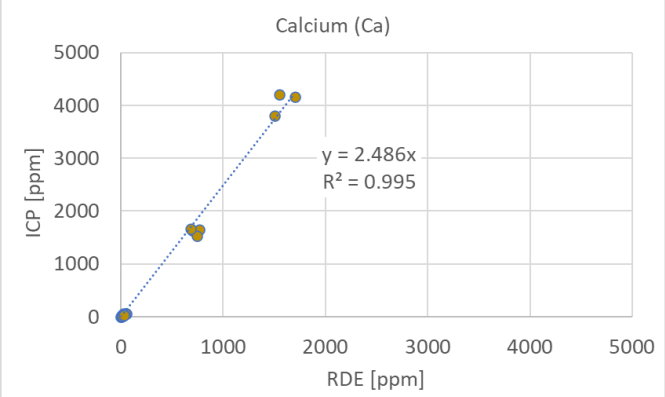


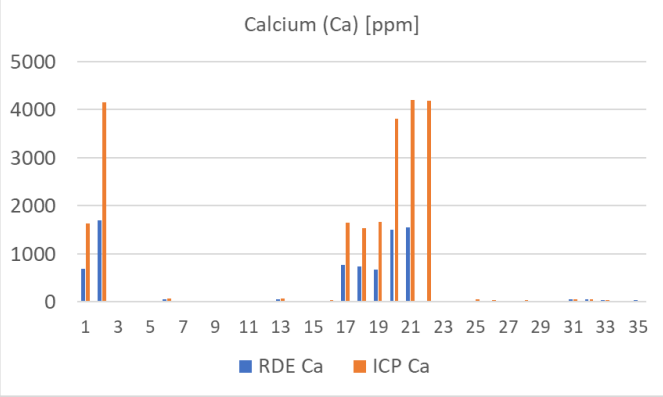
After excluding these samples, another example of a clear trend could be achieved:





Only the results for the content of calcium (Ca) on 35 samples gave a completely different picture:

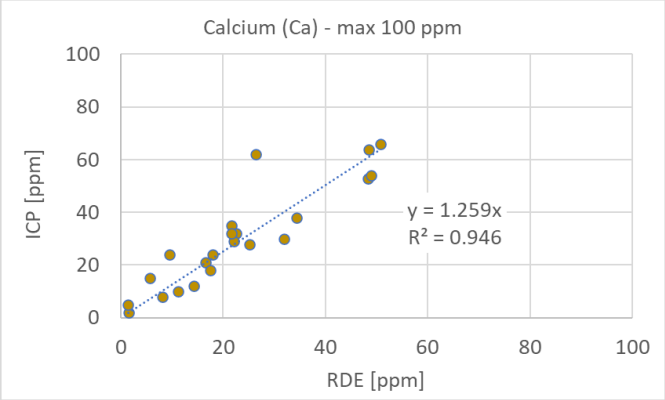


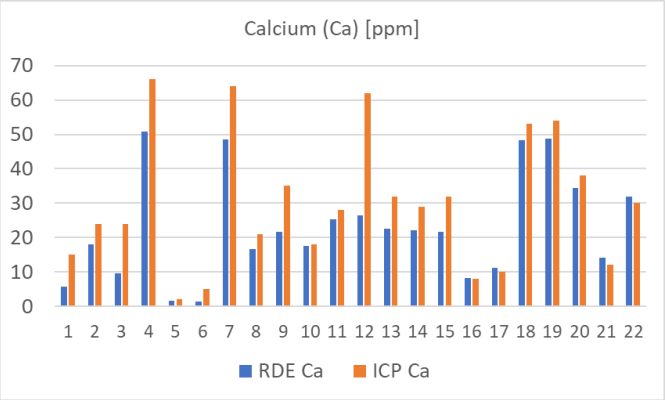


For high concentrations there was a clear underestimation by the RDE method. The samples with a high calcium concentration are lubricants to which various additives containing calcium have been added. Further investigations showed that the values measured by ICP with prior sample preparation provide the correct

results. It is assumed that the calcium particles are bound by the detergents in so-called micelles and that these are not excited to the full extent by the electric spark of the RDE method. It could also be shown that there is no significant difference in the chemical composition of the additives and the basicity of the lubricant.[12]

At low concentrations, which do not come from the base buffer additives, sufficient agreement can be shown:





Infrared spectroscopy

Mid-infrared spectroscopy is a cost-effective technique that can increase insight into oil condition. With a single measurement and within seconds multiple degradation processes like oxidation or additive depletion can be determined simultaneously. A very useful guideline is given according to ASTM E2412[7]. Additionally, properties like TAN or TBN can be predicted from the recorded infrared spectrum.

During its combustion, fuel is oxidized, forming water and carbon dioxide at high temperatures. Incomplete combustion, especially during the warm-up of the engine, however, can lead to a series of by-products. Partial oxidation of fuel may lead to esters, ketones, carboxylic acids and other substances dissolving in the lube oil. Especially the carboxylic acids decrease the pH of the oil and are typically neutralized by the base reserve of the oil to counteract acidification. Reactions with nitrogen stemming from the combustion air can lead to nitration forming mainly nitrogen oxides. Sulfur contained in some heavy fuels may lead to the formation of SO_2 and SO_3 resulting in sulfation of the lubricating oil.[13]

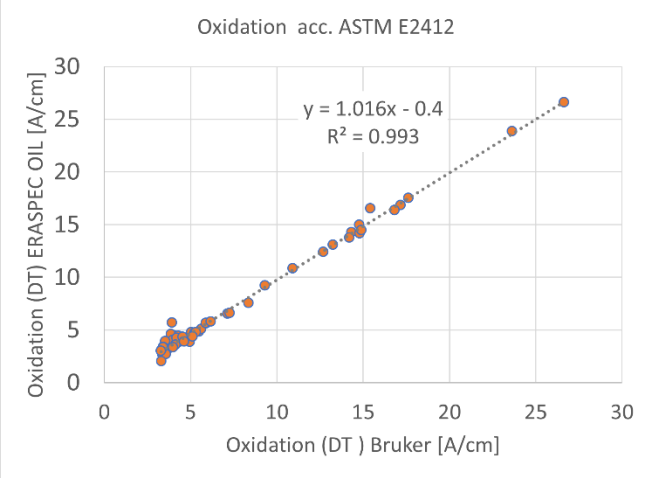
In modern laboratories FTIR spectrometers are often in use because they bring clear advantages due to high signal-to-noise ratios. There are several brands and types of so-called “laboratory spectrometers” available. These analyzers are typically a general approach and not specified for any application. The operator often needs to calibrate and define required parameters. The ERASPEC OIL device, on the other hand, is a specifically defined portable FTIR spectrometer for the purpose of measuring fresh and in-service lubricants with all relevant standards pre-programmed.

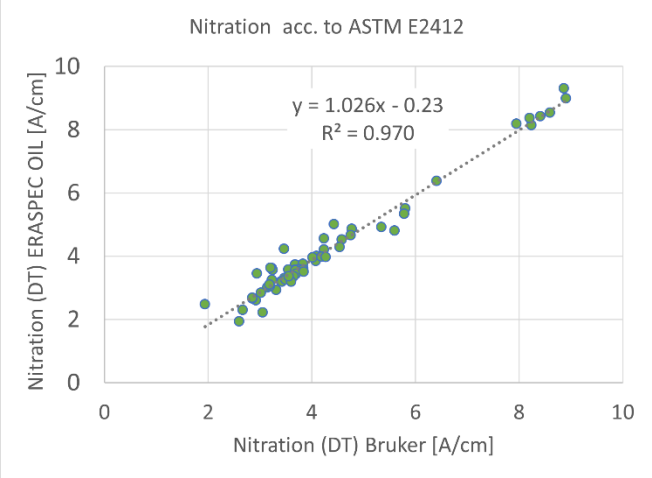
In the following, results are compared between a conventional laboratory FTIR from Bruker and the portable “Oil Condition Monitoring-FTIR” ERASPEC OIL. Both instruments use ASTM E2412 evaluation of the spectra. Since the Bruker used background measurements with air, an additional correction to the spectra were applied to account for the cell window absorption as described in ASTM E2412 and ASTM D7414. Since the results were comparable for all parameters, the example shows the comparison of oxidation using ASTM D7414 and nitration according to ASTM E2412[7]

12 Assessing elemental content in lubricants: purposes, techniques, and insights; Dr. Niklas Christensson; Lube Magazine

13 Oil Condition Monitoring Using a Portable FT-IR Spectrometer

A clear correlation could be shown between both instruments for both parameters. The agreement is in both cases significantly better than the published reproducibility (R) of 4 A/cm at 15 A/cm calculated according to ASTM D7414[14].





To summarize, it can be stated that the measurement results of both measuring devices are comparable and the quality of the results of the portable ERASPEC OIL match the precision of lab-grade equipment found in third-party labs.

Total Acid Number (TAN) and Total Base Number (TBN)

TAN measures the acidity level of oil resulting from the oxidation process. As oil ages and undergoes thermal stress, its molecular structure begins to break down, leading to the formation of acidic byproducts. These acids can accelerate corrosion, degrade lubricant performance, and compromise equipment integrity. Consequently, monitoring TAN levels provides valuable insights into the extent of oil degradation, enabling proactive measures to mitigate potential damage and prevent costly equipment failures.

In contrast, Total Base Number (TBN) measures the alkalinity and reserve alkalinity of a lubricant to neutralize acids and maintain chemical stability. As oil ages and reacts with contaminants and combustion byproducts, its alkalinity gradually diminishes, reducing its ability to counteract acidic compounds. Monitoring TBN levels allows maintenance professionals to assess the remaining alkaline reserve of the oil and predict its remaining useful life. Declining TBN values signal the depletion of additives and the onset of lubricant degradation, highlighting the need for proactive maintenance interventions, such as replenishing additives or replacing the oil, to prevent accelerated wear, corrosion, and equipment damage.

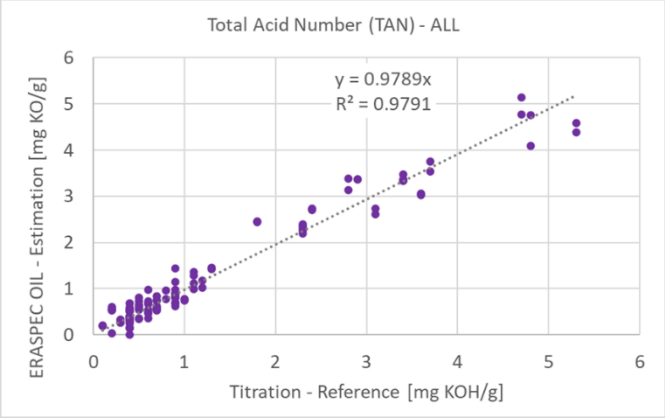
TAN and TBN are both measured classically by titration. However, Fourier Transform Infrared Spectroscopy (FTIR) – a powerful analytical technique used to assess the chemical composition and condition of lubricating oils - offers a very interesting alternative. Chemometric analysis with FTIR involves statistical methods for analyzing spectra and predicting parameters such as the concentration or composition of substances. By correlating spectral patterns with known data, chemometric models can accurately predict various properties. This technique can be easily and quickly applied to estimate TAN and TBN and can be determined simultaneously with the additives and the chemical condition.[1]

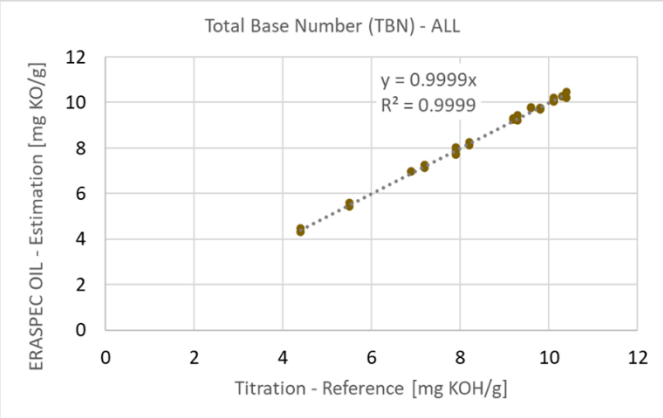
In the course of this case study, models for both parameters were calculated using ERASPEC OIL and analyzed in terms of accuracy. This Oil Condition Monitoring-FTIR includes a chemometric model according

14 ASTM D7414 Standard Test Method for Condition Monitoring of Oxidation in In-Service Lubricants by FT-IR Spectrometry

to the multi-linear regression method (MLR) for TAN and TBN as standard. The advantage of the MLR method is the robustness of the model and the relatively small number of calibration samples required.

For total acid number (TAN), the reference of choice was a potentiometric titration according to ASTM D664[8], which was used to build the model by adding reference values to measured FTIR spectra directly on the instrument. A useful parameter to describe the accuracy of a chemometric model is “SEC”, the standard error of calibration. For a total of 112 samples, including some duplicate determinations, a SEC of 0.27 mg KOH/g could be achieved. This is clearly a proof of concept if it is compared to a reproducibility (R) of 0.56 mg KOH/g at 3 mg KOH/g according to ASTM D664[8]. The same conclusion could be drawn for the total base number (TBN), where a SEC of 0.10 mg KOH/g could be compared with a reproducibility (R) of 0.6 mg KOH/g at 8 mg KOH/g according to ASTM D2896[9] for 32 samples:





The chemometric estimation by FTIR of the parameters TAN and TBN cannot completely replace the determination by titration, as it is the reference method. In addition, the validity of the model must be checked for the different product groups. In any case, this alternative approach offers good potential for reducing the effort involved and the chemicals used, which are often topics of concern.

Conclusion

In summary, this comprehensive case study has successfully demonstrated the comparability of the methods used in typical third-party oil condition monitoring labs with the results from ERALAB OCM and in-house oil condition monitoring. Any deviations found, particularly the difference in calcium content between ICP and RDE, are recognized but can be corrected if required. The study shows that the dedicated analyzers match the typical lab equipment both in terms of repeatability and also in terms of accuracy. Even the results obtained from the chemometric FTIR model for TAN and TBN agree very well with the values obtained with the lab-based titrators. Overall, these results underline the robustness and applicability of the applied methods and instrumentation and provide valuable insights into the characterization and assessment of ageing processes. This study makes an important contribution to the use of analytical techniques in this field and provides practical solutions for monitoring and maintaining oil and, subsequently, machine condition.

Acknowledgments

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