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INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

**ON-LINE OIL CONDITION SENSOR
FOR INDUSTRIAL GAS TURBINE CONDITION ASSESSMENT**

by

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ABSTRACT

Traditionally, the condition of lubricating oils and the presence of contaminants within these oils are determined by periodic oil sampling and remote sample analysis using laboratory instruments. These results are then utilized to assess the condition or health of the equipment. Where the results indicate slow and progressive changes, this methodology will work adequately well. However, where the change is sudden or where the equipment is particularly important, the periodic sampling method may not be effective. GasTOPS is developing an on-line fluid condition sensor based on the use of a miniaturized infrared (IR) spectrometer, which can continuously monitor the condition of lubricating oils and eliminate the requirement for oil sampling. The sensor has been designed for application to industrial engines and is capable of measuring several parameters simultaneously including water, additive depletion, and thermal and oxidative degradation. This paper describes the use of IR spectrometry for oil condition monitoring, the development of the on-line sensor, and its potential application to industrial gas turbine condition monitoring.

Table of Contents:

	<u>Page #</u>
Title Page	1
Authors	2
Abstract	2
Table of Contents	3
Introduction and History	4
Why On-Line Applications?	7
What is Infrared Analysis?	8
Contaminants	9
Oil Condition Sensor	13
Conclusions	14
References	14

INTRODUCTION and HISTORY

Lubrication fluids used in high-performance engines chemically degrade over time and eventually lose their effectiveness, while becoming a receptor for metallic debris shed by moving parts. Traditionally, periodic sampling and laboratory analysis of fluids from turbines, diesel engine crankcases, gearboxes, and hydraulic systems has been a primary means for assessing the condition of these critical components. Elemental analysis and lubricant condition and liquid contamination monitoring encompass the major analyses.

Elemental analysis, by definition, provides information on what atomic elements comprise the sample. Spectral data are obtained by energizing the material to a level where individual atoms emit energy. Since individual elements emit energy of a characteristic wavelength, a complete elemental analysis is obtained. It is important to realize that elemental analysis destroys molecules in the process of energy addition, this method is silent on complex molecular constituents of the oil or any liquid contaminant. It is however very effective in identifying the presence of wear metals as well as elemental constituents of some additives and/or liquid contaminants. Elemental spectroscopy whether atomic emission (AE) or atomic absorption (AA), has been employed since the start of used oil analysis in the late 1940's by the railroads.¹ Automation of the spectral interpretation in the late 1950's allowed the testing to be performed by technicians rather than trained chemists. In recent years^{2,3,4}, x-ray fluorescence (XRF) has become cost effective and automated enough to join the list of instruments used for routine elemental analysis.

Lubricant condition monitoring traditionally employs physical property tests, which were developed for new oil qualification. These tests include kinematic viscosity, base number, acid number, flash point, insolubles, etc. and provide only indirect information regarding oil condition and contamination faults.

The application of molecular spectroscopy techniques, such as infrared, to lubricant and hydraulic fluids analysis provides direct information on the molecular species of interest, including additive packages, fluid breakdown products and external contaminants. Molecular spectroscopy has many similarities to elemental spectroscopy; the important distinction is the method of adding energy, which preserves the molecular structure of additive and contaminant compounds. This is achieved by the use of the InfraRed (IR) region of the electromagnetic spectrum. The use of infrared spectroscopy for lubricant analysis developed in the 70's soon after the introduction of commercial recording infrared spectrophotometers. The output however consisted of a hard copy graphical infrared spectrum, which would then be interpreted by a trained chemist or spectroscopist^{5,6,7}. This method was labor intensive, required extensive training and was thus unsuitable for routine lubricant analysis.

With the introduction of commercial Fourier transform Infrared (FTIR) spectrometers with computers performing the mathematically intensive Fourier transfers, the application of molecular analysis of lubricants by infrared became commonplace for routine (production) oil analysis laboratories. Initially, the analyses were for petroleum based diesel engine oil.^{8,9,10} In the early to mid-90's, the US military refined the existing methods and included methods for a wider variety of lubricant types, such as polyol esters used in gas turbines^{11,12,13,14}. The

government organization defining these methods, the Joint Oil Analysis Program (JOAP), has shown that infrared spectroscopic analysis of synthetic and petroleum lubricants could replace traditional physical property tests as used for condition monitoring. The JOAP development was the culmination of thousands of samples from diesel and gas turbine applications to verify the data extraction methods, spectral regions, baseline corrections and algorithms for each oil condition indicator. In 2004, this infrared technique became an ASTM Practice, E2412.

One of the major breakthroughs in the 1990's with infrared analysis of lubricants was the realization that specific oil analysis algorithms are required for each lubricant class, for example, diesel petroleum and polyalphaolefin oils, gas turbine polyol ester lubricants and hydraulic fluids. In addition, the military work concentrated on generating condition indicators for the required lubricant failure mechanisms.

In 1995, the US Army introduced infrared analysis as a replacement for manual physical property tests. The change was made in part to reduce laboratory costs, to improve condition measurement reliability and thus move to on-condition maintenance. In 1998, the US Army documented a 45 million-dollar cost avoidance in new oil purchases through their initiative of on-condition oil changes.¹⁵ The switch from scheduled oil change to on-condition was possible due to the reliability of infrared analysis in determining actual oil condition.

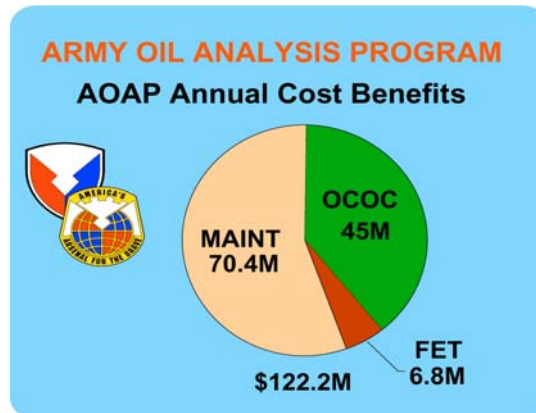


Figure 1: 1998 Benefits for Army Oil Analysis –On-Condition Oil Changes (OCOC) avoided 45 million dollars in new oil purchases. OCOC was possible due to the reliability of infrared analysis in determining actual oil condition.

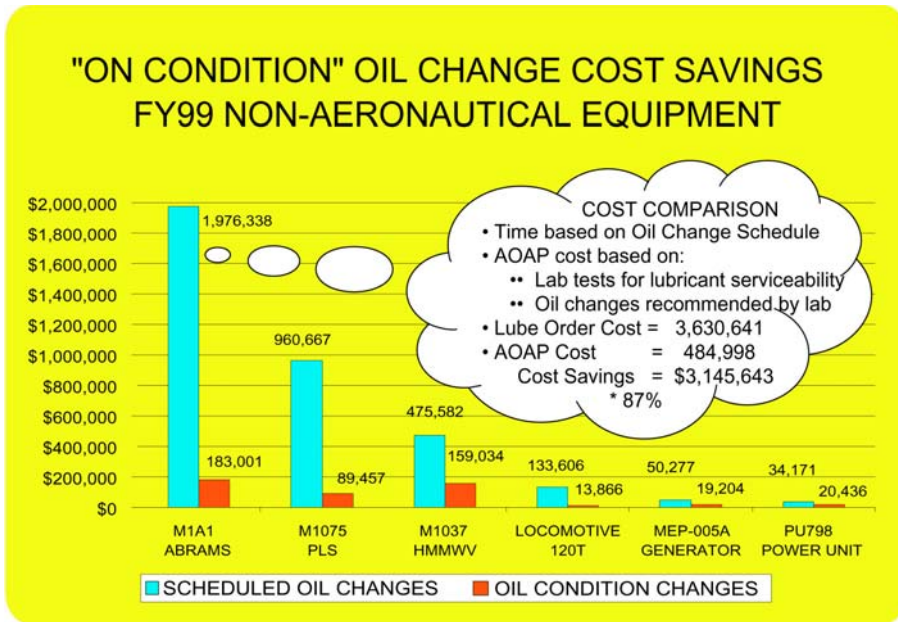


Figure 2: These 1999 examples demonstrate the difference between the cost of scheduled oil changes and on-condition oil changes (OCOC). The M1A1 Abrams tank gas turbine engine utilizes a polyol ester fluid. OCOC resulted in savings of 1.8 million dollars or a 91% reduction in the cost of oil for the Abrams. Even the small number of power units reflected significant savings.

Once this simple-to-use laboratory method with automated result interpretation was available, the US Air Force initiated research projects for this application to move to on-line oil condition monitoring. In 1998, an on-engine test (T-63 Allison turboshaft engine) was conducted at Wright Patterson Air Force Base, Ohio, which demonstrated the ability to monitor oil condition and contaminants by on-line infrared analysis.¹⁶ The US Navy is currently in a large scale demonstration of a Total Oil Monitoring System (TOMS) utilizing an on-line oil condition monitor and an on-line metal (ferrous and non-ferrous) detection sensor for their gas turbine generators.

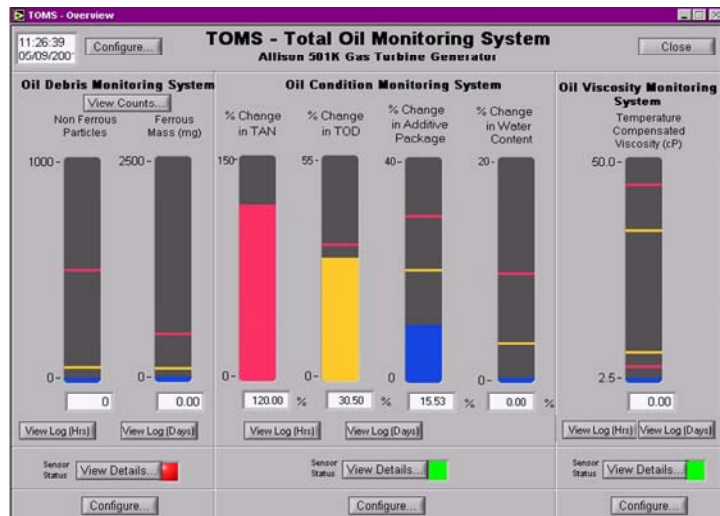


Figure 3: Screen for TOMS

WHY ON-LINE APPLICATIONS?

The goal of every condition-monitoring program is condition assessment at the first opportunity that the data can reliably indicate an adverse change in system condition or performance. Until recently, this ability has been problematic due to the following:

- Time between samples. Most maintenance operations tend to utilize long sample intervals to reduce laboratory costs. The result is poor or indeterminate trends, last minute alarms, or worse yet a failure before the data is available.
- Analysis costs. The costs associated with the analysis, which include on-site personnel for the sampling and mailing (and don't forget training the staff for these functions); mailing costs, sample analysis costs, and time for interpretation of results once received at your facility.
- Turn around time. The time it takes from first sampling the system, delivering the sample to the laboratory, analysis of the sample and finally receipt of the results adds to the time elapsed before an alarm is identified. This time often is measured in weeks
- Real world conditions. Samples get mislabeled, documentation misplaced, labels soiled, operators distracted, etc.
- Sample handling reliability. The overriding concern of a production laboratory is generating results for the greatest number of samples in a day.

If the above concerns are not addressed, the analytical methods developed and approved will often fail in a production environment. In addition, all fluid condition problems will progressively generate wear metal problems and finally equipment failure. To realize the maximum benefits, the emphasis on condition monitoring must move from wear metal (damage) assessment to all condition indicators that are precursors to machinery wear. These include fluid condition indicators.

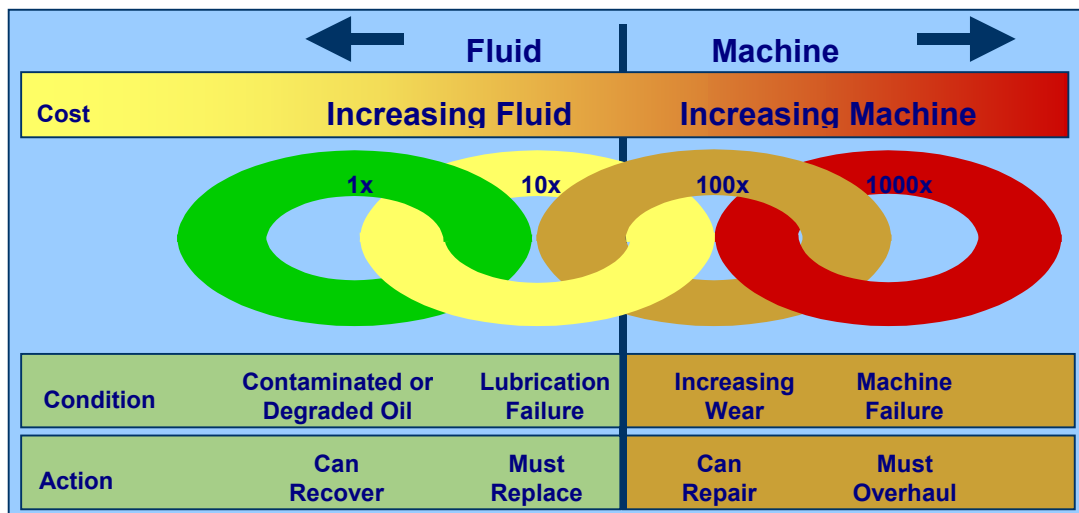
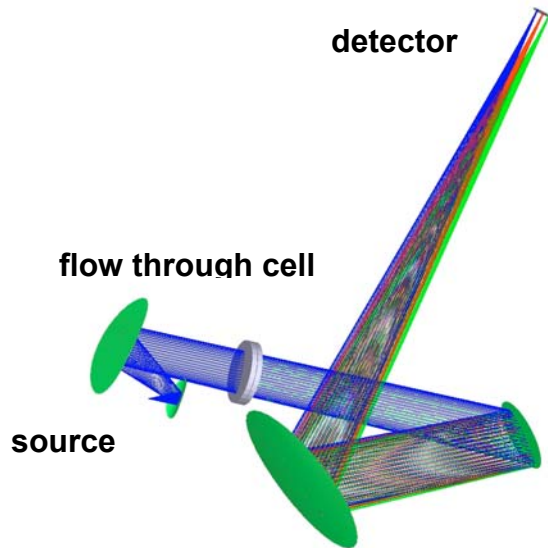


Figure 4: To maximize benefits, the earliest possible indication of an abnormal condition is required.

To maximize benefits, the earliest possible indication of an abnormal condition is required. Real-time, autonomous lubricant monitoring can accomplish the goal of condition monitoring and eliminate the need for oil sampling and remote laboratory analysis, thus avoiding the long turn-around times and associated costs. On-line systems coupled with automated data reduction and interpretation will include condition reports up to and including corporate maintenance work orders.

WHAT IS INFRARED ANALYSIS?

Infrared spectroscopy is an analytical measurement method used to characterize and identify the structure of organic molecules, in this case, lubricants and their contaminants. Infrared energy from the source passes through the oil sample to a diffraction grating, prism, filters or



interferometer and then on to one or more detectors. The lubricant's chemical constituents absorb some of the IR energy at specific and reproducible frequencies. Infrared energy absorbed by an organic molecule induces excitation of vibrational, rotational and bending modes of the bonded atoms, while the molecule itself remains unchanged, in its electronic ground state. A detector measures changes in the transmitted light from the incident light. These changes are due to the lubricant, its condition (by-products) and any contaminants in the fluid.

Figure 5: Schematic of one option for Infrared analysis

If we apply IR spectroscopy to several oils of interest to industrial gas turbine applications, results typical of Figure 6 will be obtained. As can be seen from the data, all hydrocarbon compounds respond at a wave number of 2900 cm^{-1} , however, at lower wave numbers, the different oils respond differently and can thus be readily identified. Introduction of additives and/or contaminants will respond in yet a different way making it possible to identify and quantify them.

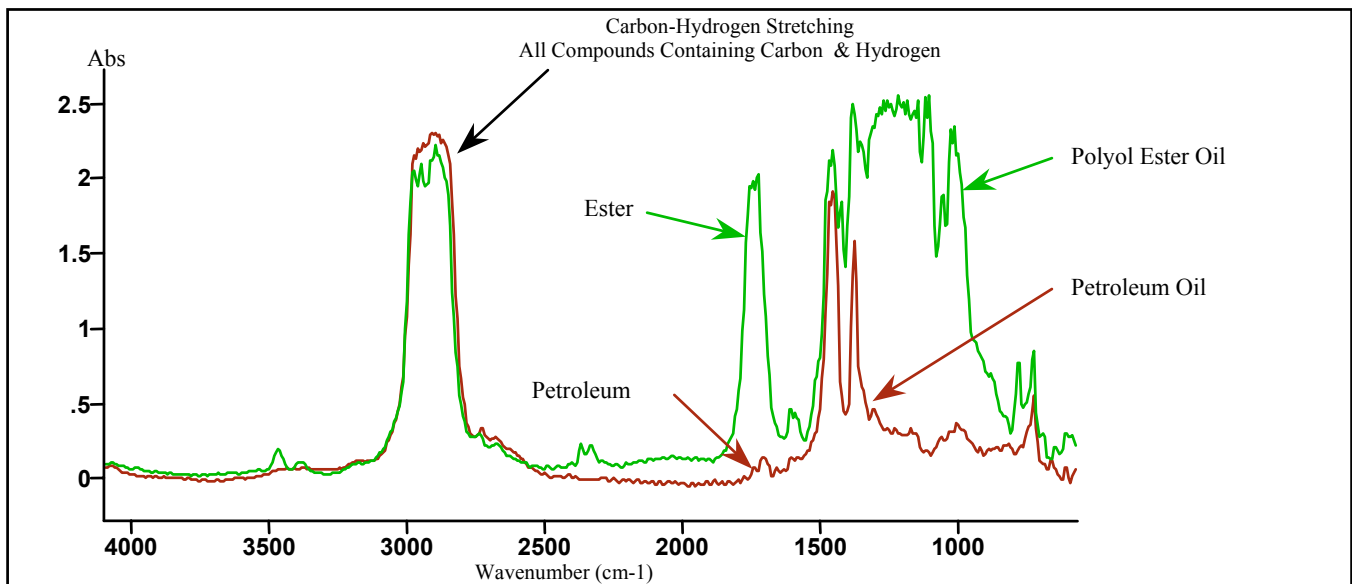


Figure 6: Infrared spectra of a petroleum oil and a polyol ester oil

Typical laboratory class IR spectrometers are capable of covering the full range of spectra and are thus large and expensive. For a given application, only specific wavelengths are required. This state of affairs suggests the possibility of tailoring the IR spectrometer to a specific purpose with no practical loss of functionality.

The concept of an on-line oil condition sensor is predicated on the ability to miniaturize the optics and electronics so that the package size and costs are brought down to acceptable levels. Once a design for size and cost are achieved, it is necessary to harden it to the point where it can survive in a realistic industrial environment. Such a design is described below.

CONTAMINANTS

The remainder of this paper will present the various oil condition and contamination parameters that are required for reliable lubricant monitoring. The vibrational modes for the molecular components of interest were taken from Sadtler's IR-Mentor program.¹⁷

Coking/Acidic By-Products: Coking is the by-product of lubricant and additive breakdown from oxidation. Oxidation of lubricants is caused by exposure to high temperatures and stresses in the presence of oxygen, resulting in the formation of partially oxidized compounds. Antioxidants are added to many lubricants to inhibit this process in the base fluid. Many different compounds can be employed as antioxidants and the monitoring of antioxidant levels are discussed later.

- **Oxidation Products, Petroleum Oils:** Infrared determines the level of oxidation by-products in petroleum lubricants by a general response in the carbonyl region. In this region, infrared energy is absorbed due to the C=O stretch from ketones, esters, carboxylic acids, carbonates, aldehydes, anhydrides, and amides, to name a few. Monitoring this region is thus

a direct measurement of the oxidation level, as compared to a secondary measurement technique such as acid number. The infrared area is measured over the range of 1800 to 1670 cm^{-1}

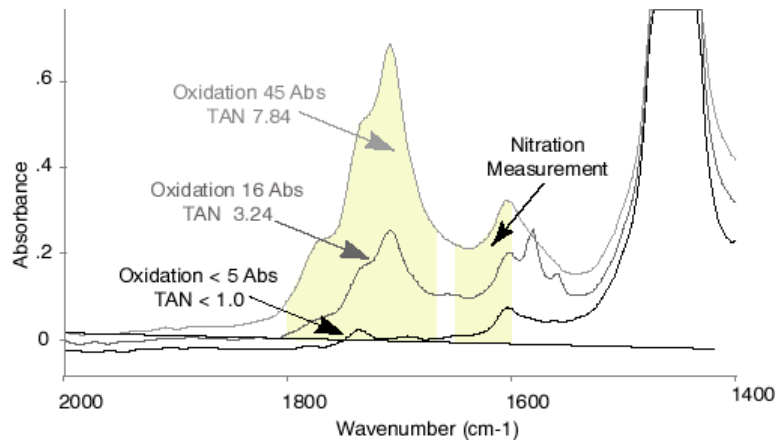


Figure 7: Oxidized petroleum oil with associated acid number readings.

- Oxidation Products, Polyol Ester Oils:** Base stock breakdown (oxidation) in polyol ester synthetic lubricants is seen in two regions. One are around 3535 cm^{-1} indicates that the breakdown products are mostly composed of weakly hydrogen bonded alcohol or acid groups (starting products to make an ester). The second area is in the hydrogen bonded O-H stretch region used for petroleum oils and are due to the numerous hydrogen bonded by-products formed from the polyol ester lubricant breakdown.

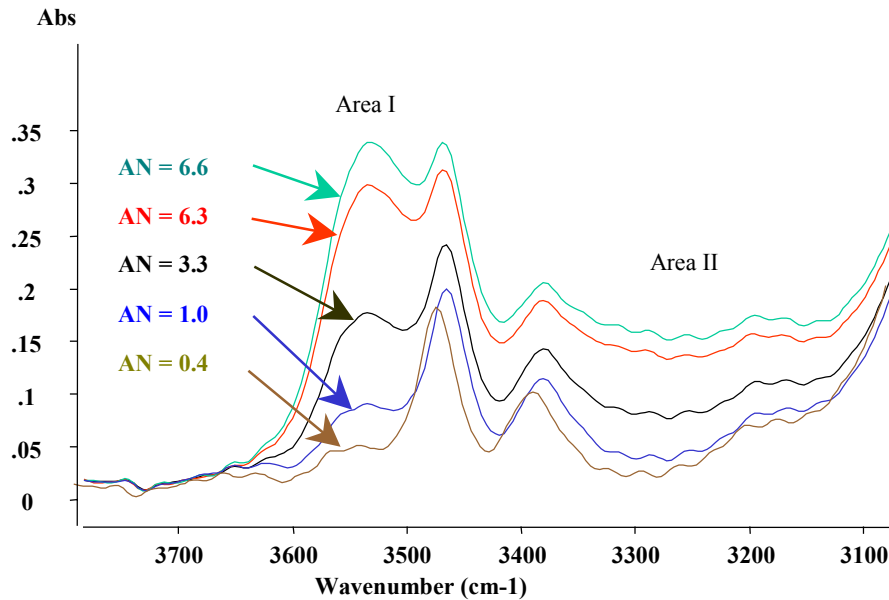


Figure 8: Oxidized (degraded) polyol ester lubricant with associated acid number readings

Water Contamination: As the most common compound on the surface of the earth, water is also the most common contaminant found in any lubricant system. Water ingress can come from external sources (rain, washing), internal sources (coolant system leakage, condensation), normal operation (combustion products), or even from reactions between additive packages. Water degrades the load bearing lubricant film and is one of the most destructive contaminants to mechanical machinery.

- **Water, Petroleum Oils:** (Figure 9) As a very strong infrared absorber, water is perhaps the easiest to detect. The hydrogen bonded O-H stretch vibrations (symmetric and asymmetric) of liquid water are found over the range of 3500 to 3150 cm^{-1} in petroleum based lubricants.

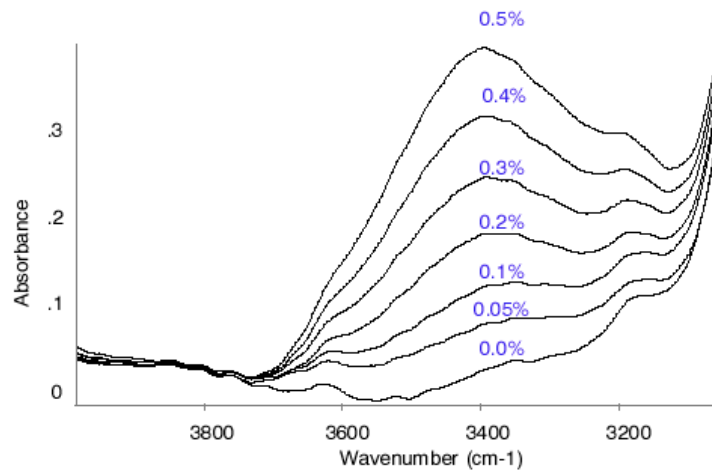


Figure 9: Incremental water contamination in a petroleum lubricant

- **Water, Polyol Ester Oils:** (Figure 10) The traditional hydrogen bonded hydroxyl area was not successful for measuring water content in polyol ester (synthetic) lubricants. There are two peaks (at 3640 and 3550 cm^{-1}) for water in polyol esters corresponding to a free hydroxyl group (no hydrogen bonding) and a single bridge hydroxyl group, respectively.

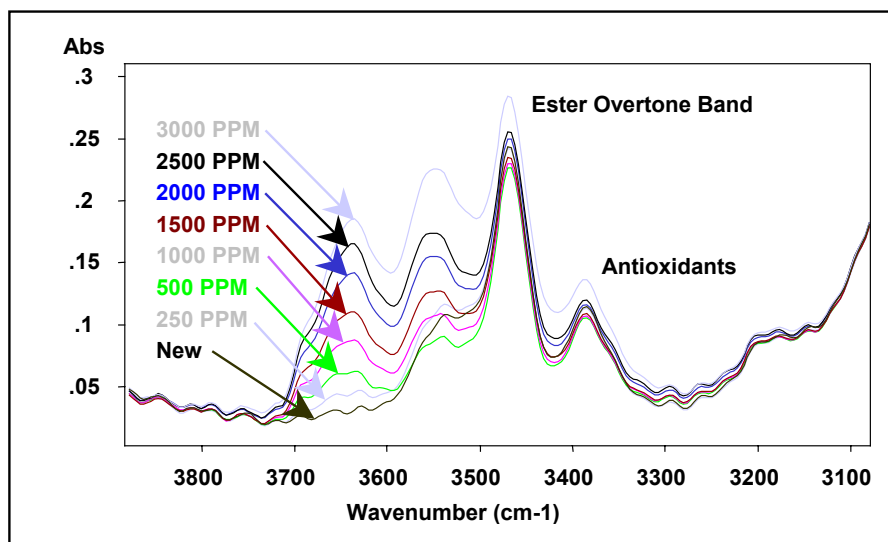


Figure 10: Incremental water contamination in a polyol ester

These peaks are distinct from the regular hydrogen bonded O-H region for water found in petroleum oils and are expected considering the hindered structures of polyol ester lubricants used in high performance gas turbine engines. Note that the same amount of water was added to both the petroleum and ester lubricant in Figure 11.

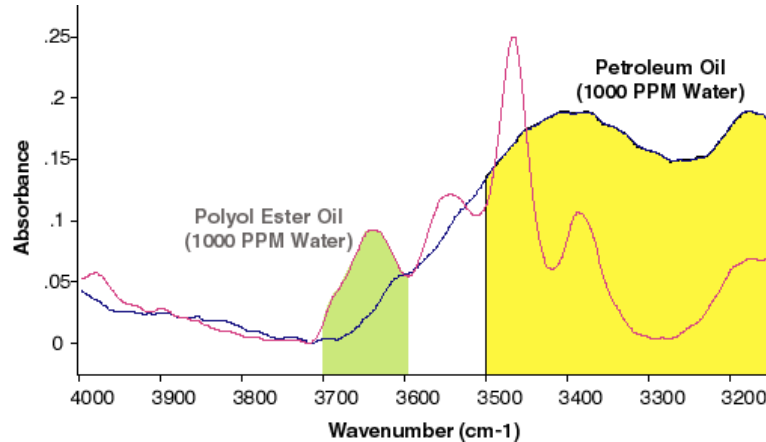


Figure 11: 1000 parts-per-million water in polyol ester oil and petroleum oil.

Oil Coolers/Heat Exchangers: Many industrial plant systems utilize oil coolers and heat exchangers. Leaks may develop in these systems and contaminant the lubricant. An example is given for glycol (antifreeze) contamination.

- Glycol Contamination:** It is important to determine the presence of glycol contamination accurately and quickly, as a coolant leak can cause rapid sludging and aging of the oil, not to mention the damage to metal parts. The strongest absorbance bands from glycols will occur in the O-H stretch region. As noted above, water will also absorb in this region. The strongest, distinctive absorbance in glycols is from the C-O stretch doublet, located around 1080 cm^{-1} and 1040 cm^{-1} , although this region will be masked in a polyol ester fluid. Consequently, these peaks are only useful in petroleum/PAO applications.

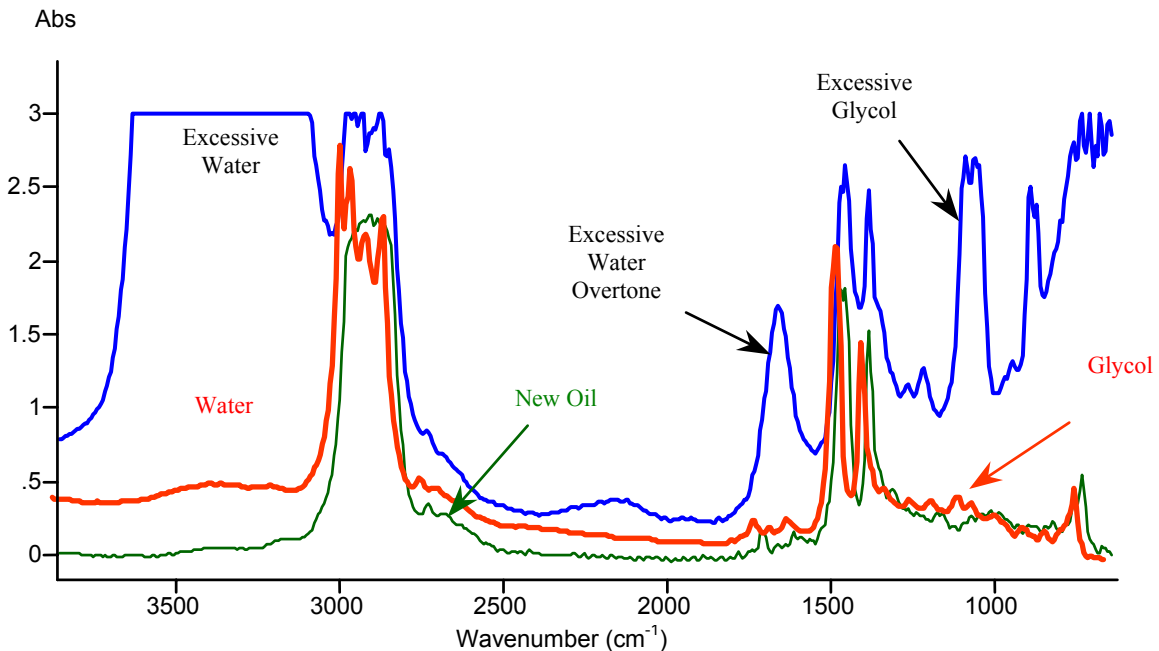


Figure 12: Glycol contamination in a petroleum oil.

The infrared is also useful for detecting additional fluid condition indicators such as additive depletion (anti-oxidant, anti-wear) fuel contamination, soot/insolubles, additional oxidation by-products (nitration and sulfation) and contamination by an incorrect fluid.

OIL CONDITION SENSOR

The oil condition sensor, shown in Figure 13, is an example of a miniaturized version of an infrared spectrometer which includes IR source, a transmission cell for the oil to flow through, a means to differentiate the spectral areas of interest, a detection system, signal conditioning and data interpretation electronics. This sensor is an example for on-line monitoring of lubrication oil developed within a project supported by the European Commission.¹⁸

On-line sensors are designed to be located on or near operating machinery. The sensors integrate with machinery lubrication systems by means of a partial flow circuit; tapped off the primary oil system or a kidney loop such as may be used for supplementary filtering. The sensor should be placed after filtration equipment to prevent large debris from clogging the flow through cell. The sensor requires a small amount of fluid and requires only a minor pressure differential to provide adequate flow.

The sensor system is designed to be interfaced with industrial control equipment. The output of the device is a serial data communication interface such as RS485. The control equipment or separate data interpretation computer converts the sensor data into useable information for equipment operators and maintainers. The data interpretation computer performs data reduction, trending and expert diagnostics. This information can be routed to machinery control monitors or database management systems.

The sensor is limited by temperature, pressure and type of lubricant. The operating temperatures affect the performance of electronic components. Consequently the maximum operating temperature is limited to 80°C, higher temperatures will require external cooling. The minimum operating temperature is -30°C. Since the sensor does not need to be mounted on the turbine, these temperatures should not be an issue. The flow through cell is limited to a maximum pressure of 6×10^5 Pa (6 bars).

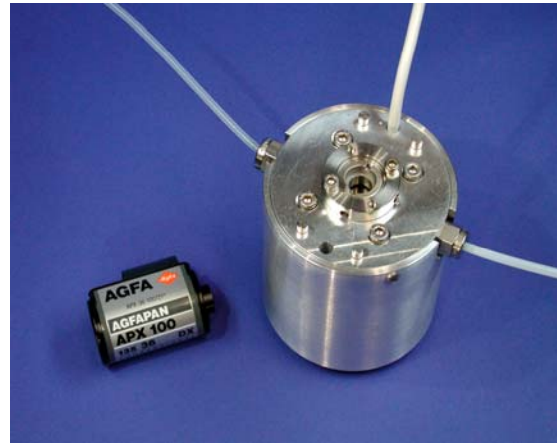


Figure 13: Example of an infrared sensor

The key to the design of an on-line IR sensor is its tailoring to the lubricant type. The sensor is designed to measure specific chemical species related to specific lubricant and contaminant chemistry. Heavy Frame-type industrial gas turbines tend to utilize petroleum or polyalphaolefins whereas aero-derivative gas turbines utilize polyol ester lubricants. Petroleum lubricants are long chain hydrocarbons while polyol esters are hindered phenols. Due to the structural differences in these lubricants (see Figure 6), contaminants may be identified in different regions of the infrared spectrum. These differences were highlighted in the previous section.

The on-line IR sensor is a multi-parameter sensor. The optics can be tailored to the contaminants and fluid conditions of interest. Trending and limits for equipment in the data interpretation are dependent on the fluid type as well as the reservoir volumes. Different volumes, 30 gallons for an aero-derivative gas turbine versus 3000 gallons for a Frame-type gas turbine, obviously necessitate different limits and guidelines.

CONCLUSIONS

The availability of an on-line sensor for continuous fluid condition and contamination monitoring allows maintenance managers to receive immediate reports of condition changes in their machinery fluid systems. On-line infrared analysis of used lubricants produces direct information on additive packages, fluid breakdown products, and external contamination. The sensor provides the essential lubricant condition parameters in a single measurement, reducing ad hoc sample intervals and off line analysis to near real time reports, generated when a change in condition warrants maintenance action. The combination of on-line oil quality and wear metals measurement^{19, 20} can eliminate the need for oil sampling. The absence of historical evidence of abnormal conditions may be used to reduce associated maintenance activities.

From a practical perspective, the IR technology has a fully qualified fault library to support it and the on-line sensor is presently being lauded for industrial applications.

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