Modular System for Multi-Parameter In-Line Machine Fluid Analysis

Bary W. Wilson, Norman H. Hansen, Timothy J. Peters,
Pacific Northwest National Laboratory
PO Box 999 Richland, WA 99352
509 375-2817

Gene Silvernail
Belhaven Applied Technologies
415 Quay Ave. Kennewick WA 99336
509 735-9446

Ben Cross
Cross Applied Technologies
Richland, WA
509 375-3373

Abstract: Modular oil analysis systems under development at Pacific Northwest National Laboratory (PNNL) can provide near-real-time analytical data related to lubricating and hydraulic oil condition, contamination and wear metals content. The system described here comprises an x-ray fluorescence spectrometer, non-dispersive multi-channel infrared analyzer, viscometer, and debris monitor, together with control and sample acquisition modules. Depending on configuration, these modular systems can determine oil cleanliness, oxidation status (TAN, TBN, synthetic oil breakdown products), viscosity, fuel and water contamination and wear metal concentrations. They can also provide ferromagnetic and non-ferromagnetic particle counts and particle size distribution. These devices are designed for installation directly on the host engine or machine and as such become an integral part of the lubrication or hydraulic system. They can also be used as portable stand-alone systems for machine fluid analysis in the field. In operation, the devices require no reagents or consumables. Software that has been developed for gas turbine engine health monitoring is being adapted for use on the systems. The software trends sensor and analytical module data. It will be capable of analyzing complex data sets to provide equipment operators with information about the present and predicted future condition of the machines on which the systems are used.

Key words: lubricant analysis, condition based maintenance, x-ray fluorescence, infrared analysis, wear metals, lubricant contamination.

Introduction: Recent reviews of scheduled off-site oil analyses programs used by the military have shown them to be far less cost effective for than previously believed. Knowledge of machine fluid condition, contamination, wear material concentrations and the relationships between these data and component failure modes is of undisputed value in machinery maintenance programs. However, for most military applications, scheduled off-site fluid analysis is no longer the most cost effective means by which to obtain this important information. Passage of time between sampling and receipt of results, cost of

manual sampling and testing, difficulty in interpretation of analytical data, and lack of clear action advisories based on infrequent sampled oil analysis methods are all disadvantages associated with present off-site analysis practices.

Advances in analytical sensors and instrumentation, microprocessor performance, and software have made on-board and in-line analysis of lubricating and hydraulic oils feasible. For most applications, the new automated in-line system described in this paper provides all of the important analytical data generated in the oil analysis laboratory. Moreover, it makes the data available early enough to permit remedial maintenance to be performed before expensive equipment damage occurs. This new product has been designated as the On-board Intelligent Lubrication Prognostics (**OILPro**) system (*Wilson et al., 1999*). Battelle Memorial Institute continues to develop this in-line system for use by the military and industries outside the railroad. Expansion and adaptation of the system for use in the mining industry is being supported by the USDOE.

This modular in-line fluid analysis system provides for automated near-real-time determination of important oil analysis parameters for most applications. Battelle OILPro comprises four analytical modules that are on-line versions of instruments used in the oil analysis laboratory. Analytical and sensor modules that comprise the full function Battelle OILPro system include:

- **X-ray fluorescence spectrometer with computer controller**,
- **Multi-band non-dispersive infrared spectrometer with microprocessor**,
- **Miniature piston viscometer with microprocessor**
- **Quantitative debris detector with computer controller**
- **Sample acquisition module (sample flow rate, temperature and filtration)**
- **System controller / interface**

The microprocessor-based controller / interface operates the system and provides data files that can be uploaded via a communications interface, wireless technology or acquired directly by other condition monitoring systems. Analysis and trending may be accomplished on-board the system or remotely, depending upon requirements. Software that provides sensor data fusion and trending of oil condition and contamination parameters provides a prognostics function that is of great value in maintenance scheduling under condition-based maintenance programs.

In designing the hardware and software functionality for the Battelle OILPro system the Battelle team assumed that an effective oil analysis system would be integrated into a condition-based maintenance program that has the following attributes:

- **Capability to measure the relevant physical and chemical parameters of in-service oil**
- **Knowledge of fluid and oil-wetted component failure modes for each machine type**
- **Standardized data interpretation and maintenance recommendations**
- **Intelligent data interpreter that can adapt to machinery operations and maintenance conditions**
- **Quick analysis turnaround**
- **Integration into an overall maintenance plan**

The in-line system is designed with these program attributes in mind**.** Battelle OILPro was designed to constitute a comprehensive continuous on-board health monitoring and prognostics system that will provide both diagnostic and prognostic information about the host equipment. This allows implementation of true condition-based maintenance procedures even during routine operations. Alternatively, Battelle OILPro could be incorporated into condition monitoring systems wherein it is operated periodically according to a maintenance schedule.

Battelle OILPro presently provides for determination of oil quality including oxidation, nitration, sulfonation, turbidity, total acid number/ total base number (TAN/TBN), synthetic breakdown I and II, and additive package condition using miniaturized fixed-band infrared spectrometric instrumentation. Dynamic and kinematic viscosities are determined directly and provide data on oil quality as well as possible oil dilution by fuel, water, or the unintended addition of improper lubricants. Elemental composition of dissolved metals or wear particles is determined by an advanced miniaturized x-ray fluorescence spectrometer. Wear particles are quantitatively determined by size, mass, and metal type (ferromagnetic or non-ferromagnetic), in real time, by an off the shelf, flow-through sensor system.

The entire OILPro system is the size of a suitcase (approximately 30 cm x 60 cm x 90 cm), depending on configuration, and is controlled by a microprocessor. It is anticipated that the size of the system will be substantially reduced in the near future. Technologies that would accomplish this reduction are currently being demonstrated at PNNL (Pacific Northwest National Laboratory, operated by Battelle Memorial Institute). A graphic user interface provides for alert and alarm annunciation by a variety of methods, including wireless paging. The system features wireless communications capability. The user interface also provides for tabular and graphic presentation of oil condition and machine wear condition information.

Benefits to machinery owners and operators include the potential for very early detection of water and other contaminants in engine and reduction gear lube oils; and determination of lubricant condition. The system also accomplishes the collection and interpretation of machine wear data in near real-time. The ultimate aim of the technology is to greatly reduce, or potentially eliminate, the need for off-site oil analysis with its attendant costs.

Battelle OILPro Sensor Module Description and Specifications

In the following section we describe the individual modules that comprise the Battelle OILPro system. Performance specifications for these modules are provided.

Elemental Analysis: Energy dispersive X-ray fluorescence spectrometer

In-line elemental analysis is accomplished with a specially designed energy-dispersive X-ray fluorescence (XRF) spectrometer. In XRF spectrometry, analyte elements are determined from the energy spectra of X-rays that are emitted by fluorescence processes from inner shell electrons. When an inner shell electron is dislodged by incident X-ray, the electron that subsequently fills the empty orbital emits a photon to conserve energy. The energy of the photon emitted in this fluorescence process is roughly proportional to the nuclear mass of the atom. By measuring the number of photons in given energy

intervals, spectra are generated that allow identification and quantitation of the metals in the oil matrix. Incident X-rays are generated either from a small amount of radionuclide in a shielded source block or by an X-ray tube.

The Battelle OILPro XRF system (CT-5000) uses minute amounts of ^{109}Cd or ^{241}Am in a sealed and shielded chamber as a source of excitation X-rays. Unlike inductively coupled plasma or other atomic emission methods used in many laboratories, wherein the plasma source is not capable of analyzing metal particles larger than approximately 3 microns, the in-line XRF system provides elemental analysis based on all forms of the analyte element in the oil. Because of the low fluorescence energy for inner shell electrons in lighter elements, XRF detection limits increase for elements with Z-numbers less than approximately 20.

When used to quantitatively determine wear metals and certain contaminant elements in oils, laboratory XRF systems are capable of replicating NIST oil standards values within 0.3%. For most elements of interest in oils, the CT-5000 can determine elements at the 1-3 ppm level with precision of better than 10%. In the 100 ppm concentration range, precision is better than 3%. Table 1 lists detection limits at 10% precision for various elements of interest in oil analysis.

Table 1 Detection Levels and Precision for Wear and Contamination Elements in Oil*

Element	Z	Detection Limit	Typical Caution**	Element	Z	Detection limit	Typical Caution**
Chromium	24	1-3 ppm	40 ppm	Zinc	30	1-3 ppm	25 ppm
Copper	29	5-10 ppm	35 ppm	Tin	50	10 ppm	40 ppm
Iron	26	1-3 ppm	50 ppm	Molybdenum	42	3-5 ppm	(additive)
Nickel	28	5-10 ppm	50 ppm	Titanium	22	3-5 ppm	10 ppm
Lead	82	1-3 ppm	50 ppm	Vanadium	23	5-10 ppm	(additive)
Silver***	47	1-3 ppm	05 ppm	Antimony	51	1-3 ppm	10 ppm

***15 mCi ^{109} Cd source for 3 years unless otherwise specified**
**** Typical limits for large industrial diesel engines, or gas turbines**
***** Requires ^{241} Americium source (see specifications below).**

It is of interest that bench-top XRF has recently shown significant prognostics value when used to analyze to small particle debris from F404 jet engine filters on the FA-18 (*Whitlock et al., 1999*). The Battelle OILPro system has similar capability to the system used in these studies but is much smaller and lighter. Size, weight, environmental, and power requirement specifications for the CT-5000 are shown in Table 2.

Table 2. Battelle OILPro CT-5000 XRF Specifications

Component	Description / Specification
Main Source Optional Source	15 mCi ^{109}Cd in failsafe sealed tungsten source block 10 mCi ^{241}Am in failsafe sealed tungsten source block
Source Replacement Intervals	^{109}Cd: source replaced interval: 5 years ^{241}Am source replacement interval: 30 years
Detector	Thermoelectrically cooled Silicon PIN (2-120 keV)
Multi Channel Analyzer	256 channels
Oil Flow rate	Nominal 60 cc/m
Power Requirements	10 watts @ 12 to 24 volts
Dimensions	Approximately: 20 cm x 26 cm x10 cm.

Infra Red Absorption: Multi Band Non-Dispersive IR Spectrometer (NDIR)

The Battelle OILPro multi-band non-dispersive infrared absorption module is designed for near-real-time in-line fluid analysis. The module, supplied by Belhaven Applied Technologies of Kennewick WA, is designed to be part of a larger system and may be easily adapted for specific applications by the end-user. The system is designed for continuous self-calibration, ruggedness and ease of maintenance under field conditions. Depending on customer requirements, the NDIR minimizes or totally eliminates the need for moving parts other than sample flow. The system features plug-in IR and optical modules, allowing the end-user to specify the bands of interest for specific applications. End-user requirements are matched up with off-the-shelf pre-qualified sub-components. As presently configured, the NDIR uses no moving parts and no dispersive optical elements that can be sensitive to misalignment or contamination.

The Battelle OILPro NDIR sensor module can be pre-set to measure oil condition indicators shown in Table 3, as required. The indicators can be determined for petroleum crankcase and turbine oils, gear oils, polyol ester turbine oils and phosphate ester oils are shown in Table 3 (*Toms et al*.)

Table 3. Condition indicators and corresponding IR bandwidth in reciprocal centimeters

Condition Indicator	IR Measurement Wavelength (cm^{-1})
Water in Crankcase Oils	Peak in the 3500 to 3150 band
Water in Esters	Peak in the 3700 to 3595 band
Water in EP Oils*	Peak in the 3400 to 3250 band
Soot Loading**	Peak at 2000
Oxidation by-products	Peak in the 1800 to 1670 band
Nitration by-products	Peak in the 1650 to 1600 band
Sulfate by-products	Peak in the 1180 to 1120 band
Ester Breakdown I	Peak in the 3595 to 3500 band
Ester Breakdown II	Peak in the 3330 to 3150 band
Phosphate Antiwear (TCP, ZDDP)	Peak in the 1025 to 960 band
Gasoline Dilution	Peak in the 755 to 745 band
Diesel/JP-5/JP-8 Dilution	Peak in the 815 to 805 band
Ethylene Glycol Contamination	Peak in the 1100 to 1030 band

* Water contamination of EP oils causes a baseline tilt that must be corrected in software.
** Soot causes a baseline shift, that must be corrected in software.

NDIR sub-modules (individual source or source detector sets) are controlled by a microprocessor. The controller performs additional tasks such as communications, parametric computation, automatic calibration, sub-component utilization record keeping and reporting, system performance verification and maintenance logging and reporting. Sub-module parameters such as detectivity, sensitivity, peak frequency response, power over frequency and calibration over life data are integral to each module. Incorporation of these smart modules permits interchangeability without realignment or calibration after replacement, thus easing maintenance turn-around times while maintaining compliance traceability. Specifications for the NDIR system are shown in Table 4. The system may be delivered with 4, 6, or 8 channels for bands corresponding to those shown in Table 3 above.

Table 4. Non-dispersive infra-red module description and specifications

Parameter	Description or Specification
Spectrum / Bandwidth	4 or 6 channels: bandwidths in the mid and near IR Battelle OILPro channels pre-set
Typical Performance (Precision by band: avg. % error)	0.8 microns +/-0.4% 2.9 microns: +/- 0.013% 5.7 microns +/- 0.23% 6-9 microns: +/- 0.62%
Operating Temp.	5 to 40 degrees C
Packaging	Extruded anodized aluminum with integral passive heat exchanger
Power Requirements	80-440VAC, 45 Watts / 12-80 VDC, 45 Watts
Weight (Standard)	6.5 kg
Dimensions	4 channel: 25.4 x 25.4 x 10.0 cm / 6 channel: 25.4 x 25.4 x 13 cm
Manufacturing Quality Program	Manufactured and tested under the quality assurance standards of ASME NQA-1 and ANSI Z-540. All calibrated components certified traceable to standards of the National Institute for Standards and Technology.

Viscosity: Miniature Piston or Capillary Differential Pressure Viscometer

Viscosity is determined either by a high precision differential pressure capillary viscometer or an off-the-shelf electromagnetically actuated viscometer from Cambridge Applied Systems. The latter viscometer is small and robust. It is temperature compensated and provides measurement precision of 1% within the range of viscosities normally encountered in commercial machinery.

The high precision viscometer, designed and built by Battelle, has a simple and robust instrument that is incorporated directly into the lubrication system. The viscometer is accurate over a wide range of flow rates and inlet pressures. It operates on the principle that the pressure differential between two longitudinal points along a capillary tube in which a fluid is flowing in the laminar regime is directly proportional to the dynamic viscosity. Capillary viscometers of this design are precise and accurate, and can be optimized for any nominal viscosity and temperature required. With the use of on-board software for statistical analysis, uncertainty in the resulting viscosity measurement is 0.5%. Viscometer specifications are shown in Table 5.

The Battelle OILPro viscometer controls the temperature of the incoming oil. Should oil entering the viscometer be at a temperature other than the specified set point temperature, the controller flags the resulting measurement as faulted and waits for the next determination.

Table 5 Battelle OILPro Capillary Viscometer Specifications

Parameter	Specification Value
Oil Flow Range:	Overall: 10 to 100 cc/min: nominal: 40 to 60 cc/min
Inlet Temperature Range:	180 to 220F
Inlet Pressure Range:	50 to 120PSIG
Measurement Range	Set at factory +/- 10% of center value
Measurement Precision:	0.1cSt (+/- 0.5% for repeated measures)

Quantitative Debris Detection: MetalScan Oil Debris Monitor

High quality oil debris detectors are currently available on the market. For possible inclusion in the Battelle OILPro delivery scope, we evaluated three such detectors (GasTOPS Metal Scan ODM, Eaton Vickers Smart Zapper Oil Debris Monitor and Eaton

Tedeco QDM). We have selected the Smart Zapper in gas turbine applications. However, the GasTOPS™ (MetalSCAN) unit is recommended for use with Battelle OILPro.

The GasTOPS Oil Debris Monitor comprises sets of coils that are wound in opposing directions around the oil flow path. Two coils carry opposing high-frequency AC currents and a third sense coil detects changes in AC magnetic field as metallic particles pass through the coils. This arrangement allows the system to distinguish between larger ferromagnetic and non-ferromagnetic wear particles by the waveform resulting as they pass through the coils. Rough mass calculations for particles larger than about 100 microns are possible by integrating the total area under the sense coil deflection curve for each particle. The controller system bins the responses into particle weight ranges as they are detected. Passing particles can be classified as ferromagnetic or non-ferromagnetic, the integrated mass of the particles detected can be determined and a size distribution for passing particles can be generated. This capability allows the system to measure and trend mass loss from bearings or gears and is useful in estimating the remaining useful life of critical components. Oil condition information provided by MetalSCAN includes:

- **Particle number**
- **Particle mass distribution**
- **Particle detection rate**
- **Total accumulated particle mass**
- **Comparison of health indices to pre-set limits**
- **Warning and alarm signals**

Computer, Controller and Software Modules

The Battelle OILPro system controller computer and software modules are configured to allow the system to control and obtain data from a variety of sensors and on-board instrument packages. The controller (one or more may be used depending on configuration) is an off-the-shelf system (Z-World Rabbit 1800) with an X86 processor capable of supervising a variety of modules (up to 128 control and data channels). Analyses and reporting cycles may be initiated internally according to a pre-set schedule or in response to an internally detected caution, alert, or alarm flag. Measurement cycles may be initiated externally in response to a request or command. Most system parameters (measurement intervals, calibration checks, flag limit values, etc.) are remotely programmable. Figure 1 shows an individual system module and one system configuration with modules as installed on the case backplane.

The system computer can be located on-board or at a remote location. Oil analysis software is programmable to provide specific alert and alarm signals tailored to specific engine applications and operator requirements. A flexible user interface can provide data in tabular or graphic format, as well as trending and advisories on specific recommended maintenance steps or developing problems.

System Expandability and Auxiliary Modules

Battelle OILPro has been designed with capability to expand into an overall health monitoring system, such as a prototype health monitoring system (designated as REDI-PRO) that PNNL developed for the M1 Abrams main battle tank (*Greitzer et al., 1999*). REDI-PRO monitors gas turbine engines using 48 sensor inputs and is designed to

Figure 1. **a) XRF module in stand-alone mode with lap-top computer, b) OILPro system showing placement of component modules on case backplane.**

diagnose and predict faults well ahead of any damage to the engine. The performance of this system has shown that data from existing engine sensors, when augmented by oil analysis data, can often be useful in making unambiguous fault calls. Available software is capable of computing frequency domain power spectra from accelerometer data, for example, when these are used as auxiliary sensor modules on Battelle OILPro.

References:

Greitzer, F. L., L. J. Kangas, K. M. Terrones, M. A. Maynard, B. W. Wilson, R. A. Pawlowski, D. R. Sisk, and N. B. Brown. GasTurbine Engine Health Monitoring and Prognostics. SOLE '99 Symposium, August 31- September 2, 1999, Las Vegas, Nevada.

Toms A. (Personal Communication, 1999): Draft Proposed ASTM Method (Standard Practice for Condition Monitoring of Used Lubricants by Trend Analysis using Fourier Transform Infrared (FT-IR).

Whitlock R, Humphrey GR, Churchill D: X-Ray Fluorescence Spectroscopy: The Next Generation of Wear Debris Analysis. Practicing Oil Analysis: vol. 1 pp 17-21, 1998.

Wilson, B. W., N. H. Hansen, C. L. Shepard, T. J. Peters, and F. L. Greitzer. Development of a Modular In-Situ Oil Analysis: Prognostic System. SOLE '99 Symposium, August 31- September 2, 1999, Las Vegas, Nevada.