LIMITATIONS OF OFFLINE OIL ANALYSIS FOR DETERMINING GEARBOX HEALTH

Ryan Brewer
Poseidon Systems, LLC
200 Canal View Blvd.
Rochester, NY 14623
ryan.brewer@poseidonsys.com

Alex Pelkey
Poseidon Systems, LLC
200 Canal View Blvd.
Rochester, NY 14623
alex.pelkey@poseidonsys.com

Art Miller
EDF Renewables
19533 McLane Street
North Palm Springs, CA 92258
art.miller@edf-re.com

ABSTRACT

The vast majority of wind turbine operators perform oil sampling and analysis twice per year, corresponding with semi-annual preventative maintenance cycles. Operators rely upon these analyses to provide assessments of the lubricant's health, contamination levels, and gearbox condition. While offline analysis is a useful tool for assessing the health of the lubricant, it provides limited utility as a diagnostic indicator of gearbox health.

The limitations of offline oil sampling and analysis for gearbox health monitoring stem from sampling practices and the nature of gearbox fault progression. Wear rates are highly variable in wind turbine gearboxes; with limited sampling frequency and only a small volume of oil analyzed, fault detection by offline oil analysis is unlikely.

This paper provides an overview of offline analysis methods and highlights the limitations of these approaches to gearbox health assessment. This is demonstrated in a study of the performance and offline oil analysis data of 137 wind turbines over several years. Numerous unsuccessful attempts were made to correlate offline oil analysis data with gearbox failures during the studied timeframe. The utility of offline oil analysis for identifying gearbox failures is compared to that of online wear debris monitoring. Ultimately, the evidence shows that offline oil analysis results provide little-to-no correlation with gearbox health while online wear debris monitoring provided direct correlation to gearbox health, supporting the necessity of online wear debris sensors for reliable monitoring of gearbox health.

OVERVIEW OF OFFLINE ANALYSIS METHODS & GEARBOX WEAR DEBRIS

Wind turbine operators typically check an oil analysis report for increases in metal concentration values and ISO codes as indicators of an impending failure. However, without a full understanding of the procedures used to calculate these numbers, operators may draw the wrong conclusions about the health of their systems.

To determine the concentrations of various elements in an oil sample, laboratories rely on one of two spectrometric techniques - Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) or Rotating Disk Electrode Atomic Emission Spectroscopy (RDE-AES). These techniques use a high-energy source to excite atoms within the sample. As the atoms return to their normal state, they emit wavelengths of radiation specific to their associated element, where the intensity of the energy emitted is proportional to the concentration of the element in the fluid. The elements characterized through spectrometric techniques include wear metals, oil additives, and contaminants. These methods detect oil-soluble elements and particles in the 0-5µm range (12µm at the most). They will not detect or quantitatively determine the number of particles that are insoluble or larger than 12µm [4], while the majority of particles associated with gearbox failure are much larger than 12µm. Therefore, while ICP-AES and RDE-AES are useful for detecting changing levels of additive elements and contamination, they are unsuited for wear metal analyses pertaining to gearbox health.

Optical particle counting is another common technique used to monitor the health of wind turbine gearbox oil. This test method determines the size distribution and concentration of particles in an oil sample by measuring scattered light as the particles pass under a high-energy light source. Results are generally reported as particle counts per milliliter of fluid with particles grouped according to size. Common bins sizes used are 4-6µm, 6-10µm, 10-14µm, 14-25µm, 25-50µm, 50-100 µm, and 100+µm. ISO cleanliness codes, per ISO 4406:99, are generated based on the cumulative number of particle counts >4µm, >6µm, and >14µm. This test method can sometimes neglect particles larger than 100µm, due to a combination of filtering and equipment limitations. Since optical particle counting only looks at scattered light, often they cannot determine the composition of the particles detected, sometimes even detecting air bubbles as particulate. Dirt, dust, and other soft particles cannot be distinguished from metallic particles, yet metallic particles are a much more important indicator of gearbox health than soft particles [1,3]. Additionally, a small difference in ISO codes can translate to a large difference in particle counts. The range limits of particle counts per bin double with each increase in ISO designation. Thus, a 300% difference in particle counts could be represented by a difference of only one ISO code. This system can downplay large differences in particle counts between samples allowing key changes in gearbox health to be missed easily.

Both spectrometric techniques and optical particle counting methods are also subject to the inherent limitations of oil sampling. An oil sample taken from a wind turbine gearbox is typically between 4 and 8 fluid ounces, which is very small compared to the 80 gallons of oil present in a GE 1.5 gearbox. Even when the sample is taken in accordance with ASTM D4057, it is nearly impossible for the sample to be homogenously mixed with a distribution of wear debris particles representative of the entire dynamic system. Small samples can be unrepresentative due to: (1) particle settling, the tendency for debris to stay at the bottom of the oil sump; (2) particle aging, sampled particles may not have been recently generated; and (3) particle dilution, a small number of wear particles within a high volume of oil are unlikely to be captured in a small sample [2].

THE DATASET AND RESEARCH DESIGN

A study was conducted to determine whether data from offline oil sampling reports could provide useful, reliable information about the health of wind turbine gearboxes. Oil analysis reports were compiled from 137 wind turbines located at an EDF Renewables wind farm. Between 6 and 14 offline oil samples were included for each of the turbines over a period of 2-4 years for a total of 1,229 oil sample reports. All samples were sent to the same oil analysis lab and underwent ICP-AES, optical particle counting, Karl Fischer water tests, viscosity tests at 40ºC, and total acid number tests. The tests pertaining to elemental spectroscopy and particle counting were compiled and analyzed for this report. Out of the 137 turbines, 18 experienced failures that required gearbox replacement. 184 offline oil samples were taken from these gearboxes pre-failure. In cases where a turbine's gearbox was changed, subsequent oil reports where removed from the dataset. Each turbine was placed into one of two categories:

- Healthy – No significant gearbox repairs were required in the three and a half years since the completion of the sampling phase of this report.
- Faulty – Required gearbox repair or replacement during the sampling phase of this report or within three and a half years since the end of the sampling period.

If offline oil sampling reports are truly a useful indicator of gearbox health, reports from the 18 faulty turbines would be expected to show an increase in metal concentration or particle counts over time, indicating the impending failure of the gearbox.

Results & Discussion

ICP-AES Results

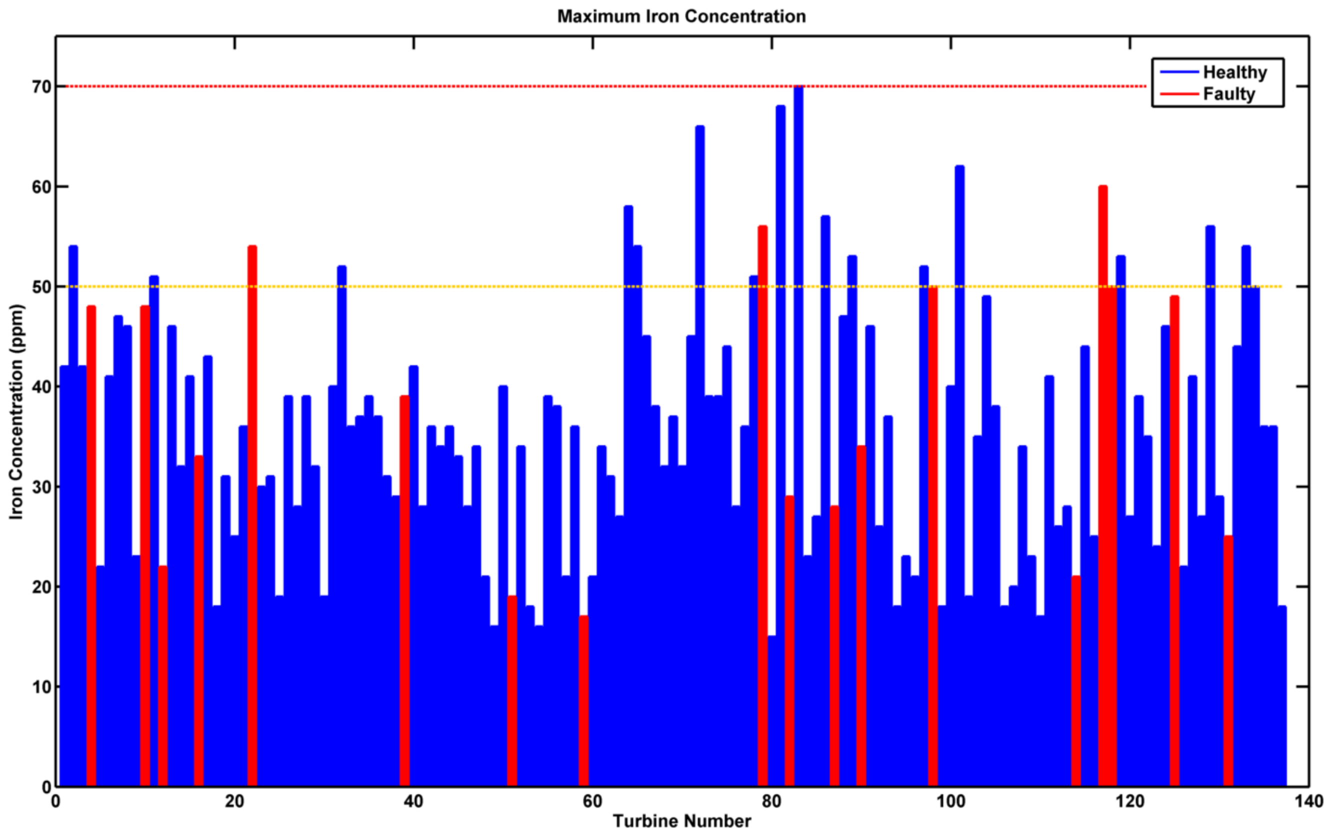

Figure 1: *The maximum iron concentration, determined by ICP-AES, for all sampled turbines. Warning limits (dashed yellow line) and alarm limits (dashed red line) are set to the oil lab recommended values.*

To determine whether ICP-AES test results provide a useful indicator of gearbox health, ICP-AES-determined iron concentration data for each turbine in the dataset were examined in conjunction with the turbine's status as faulty or healthy. As wind turbine gearboxes are composed of mostly ferrous material, iron is the reported element most likely associated with gearbox wear. The laboratory performing the oil analysis recommended iron concentration warning and alarm limits of 50 and 70 ppm, respectively. There was no significant difference in the number of turbines flagged by the iron concentration warning limit between healthy and faulty turbines. When examining the maximum iron concentration for each of the turbines in the dataset, at the warning limit, 72% (13/18) of the faulty turbines were not flagged while 76% (16/21) of the flagged turbines were actually healthy (Fig. 1). The single turbine that reached the alarm threshold experienced no failure and was deemed healthy; resulting in a 100% missed detection rate and a 100% nuisance rate. This data shows that there is poor correlation between the iron concentration results from offline ICP-AES testing and gearbox health.

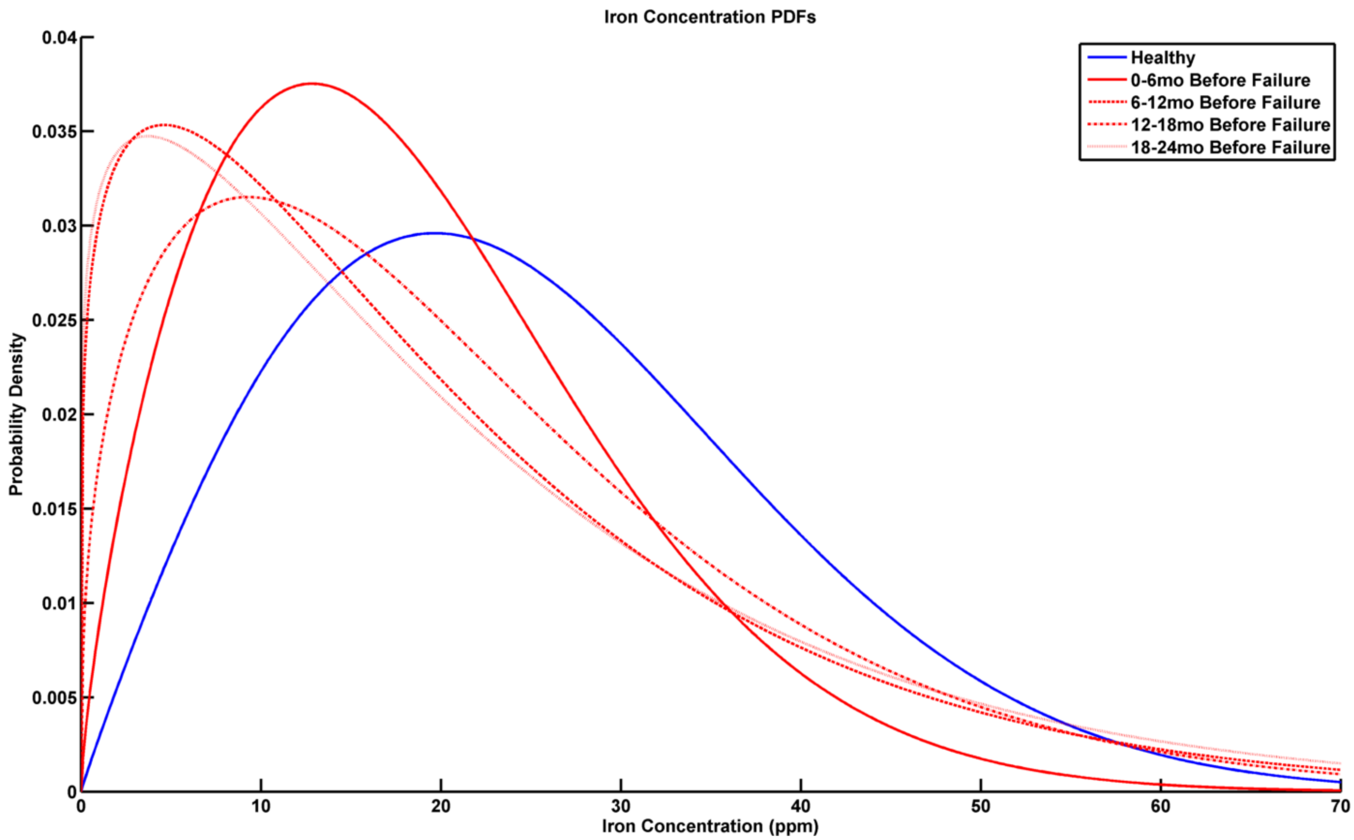

Figure 2: *Iron concentration data for each turbine fit to a Weibull probability distribution.*

The iron concentration data from each wind turbine was also fit to a Weibull probability distribution to determine the mean iron concentrations in samples from healthy and faulty turbines (Fig. 2). Data from faulty turbines was divided based on the time lapse between the oil sample date and the gearbox failure date. Theoretically, healthy turbines should have lower mean iron concentrations than gearboxes with impending failure. Additionally, it is expected that the oil samples taken closer to failure would display higher iron concentration values. However, within the studied turbines, the samples from healthy turbines actually have a higher mean iron concentration than those from the faulty turbines. Furthermore, on average, samples taken 12-18 months before failure have a higher mean iron concentration that those taken 6-

12 months before failure. These results also demonstrate the lack of utility ICP-AES iron concentration data has as an indicator of gearbox health.

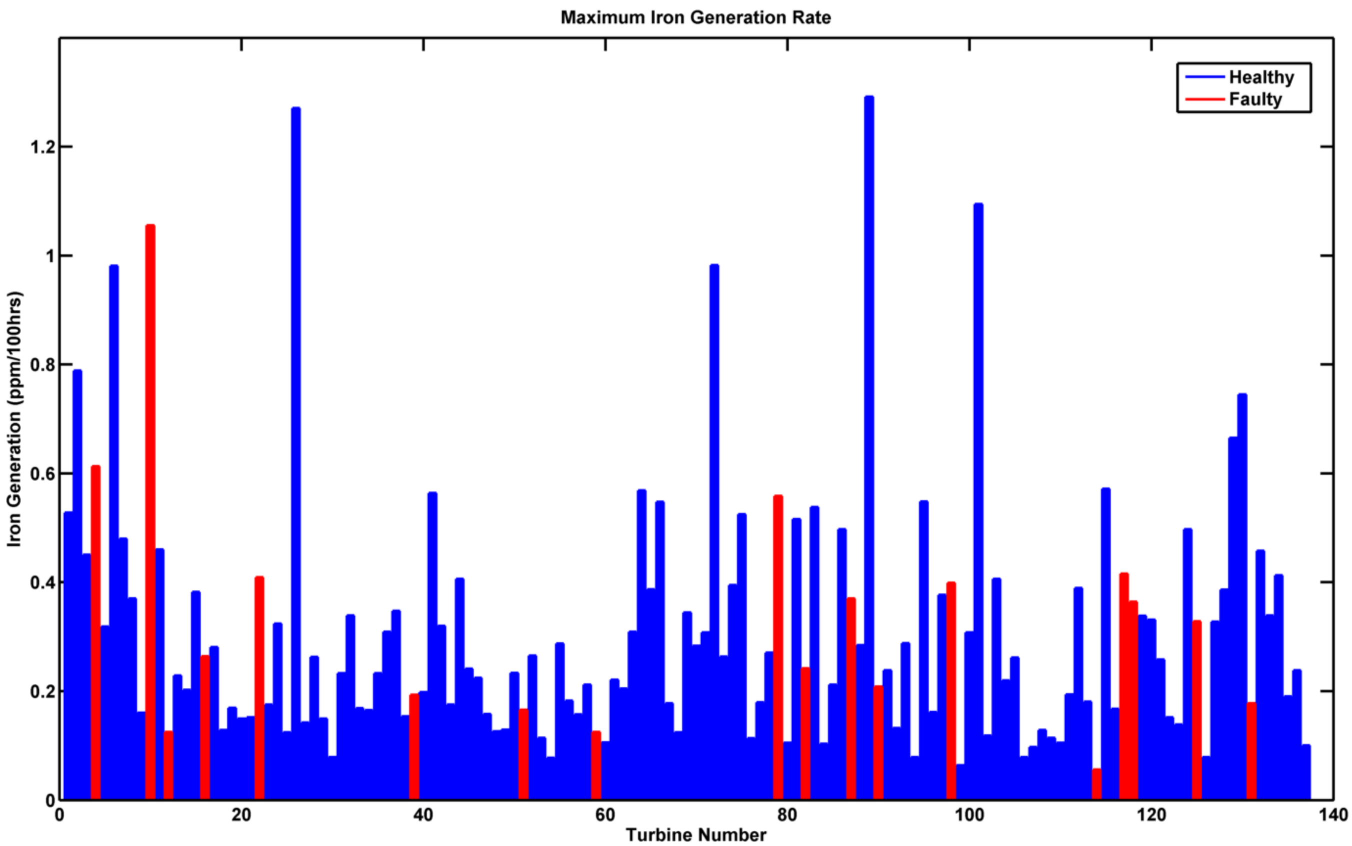

Figure 3: *The maximum wear generation rates over a 100-hour period calculated from ICP-AES data.*

Furthermore, increases in iron concentration in oil samples are unlikely to be a reliable indicator of increases in wear generation rates. It is estimated that 10 to 30 percent of the oil volume is left behind on internal components after an oil change. Since the oil that remains in the gearbox is located on moving components or settled at the bottom of the sump, it can contain more than 50 percent of the debris that was present before the oil was drained [6]. Iron particles detected by this method of analysis are also small enough to pass through the filtration system. Thus, over time, even though the oil is being changed and filtered, the concentration of iron within the oil will likely increase, regardless of whether wear generation rates have increased. Therefore, iron concentration is unlikely to be a reliable indicator of gearbox health. Calculating the iron generation rate over a moving time window, however, is a generally accepted way of making the estimation of the gearbox condition more accurate [6]. By normalizing wear data over a period of 100 hours of operation, the rate at which wear is generated can be monitored. The maximum wear generation rate calculated from ICP-AES over any 100-hour period was determined for each turbine in the dataset (Fig. 3). There was no significant association between healthy and faulty turbine oil samples with iron generation rates. Out of the 137 wind turbines, only one faulty turbine showed relatively high iron generation rates (> 0.8 ppm/100hrs), while five healthy turbines had similarly high rates. Even when examining the data in terms of iron generation rates, there is still no correlation between the offline spectroscopic analysis iron data and the health of the gearbox.

Optical Particle Counting Results

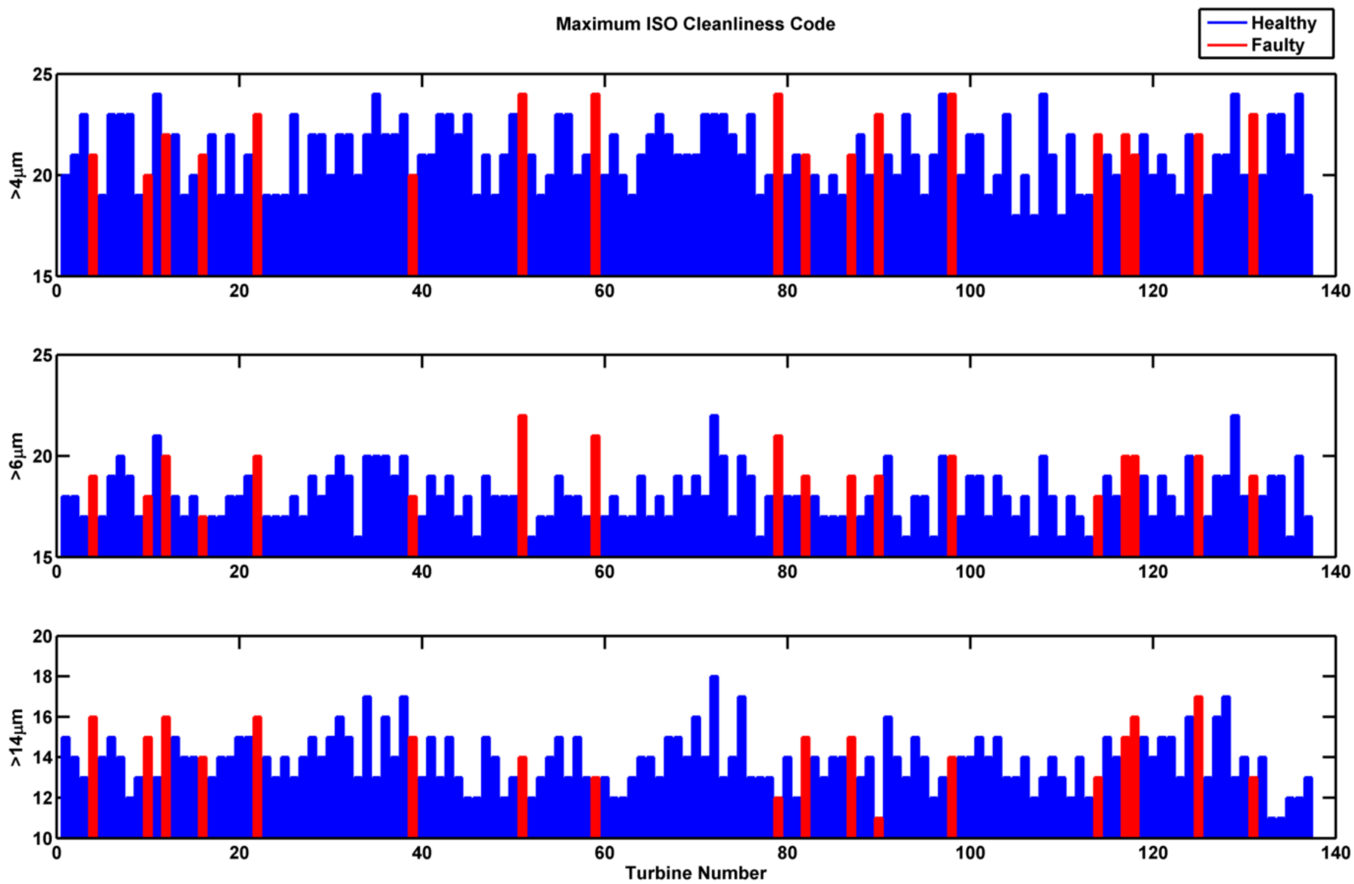

Figure 4: *Maximum ISO cleanliness codes broken down into the three reported bins for each turbine.*

Optical particle counting reports provide operators with ISO cleanliness codes to quantify the contamination levels within the oil sampled. According to ISO 4406:99 the recommended cleanliness limit for a wind turbine gearbox during service is 18/16/13, which corresponds to 2,500-5,000 particles >4µm, 640-1,300 particles >6µm, and 40-80 particles >14µm within a 1mL sample of oil [1]. The maximum ISO cleanliness codes reported for each wind turbine were plotted for analysis (Fig. 4). Every turbine exceeded the ISO cleanliness limits in at least one bin, and many exceeded the limits in all three bins. The frequency of reported ISO codes above the cleanliness limits in each bin is equal between healthy and faulty gearboxes, indicating poor correlation with gearbox health. Using this data to determine gearbox health would result in both high rates of false alarms as well as missed detections.

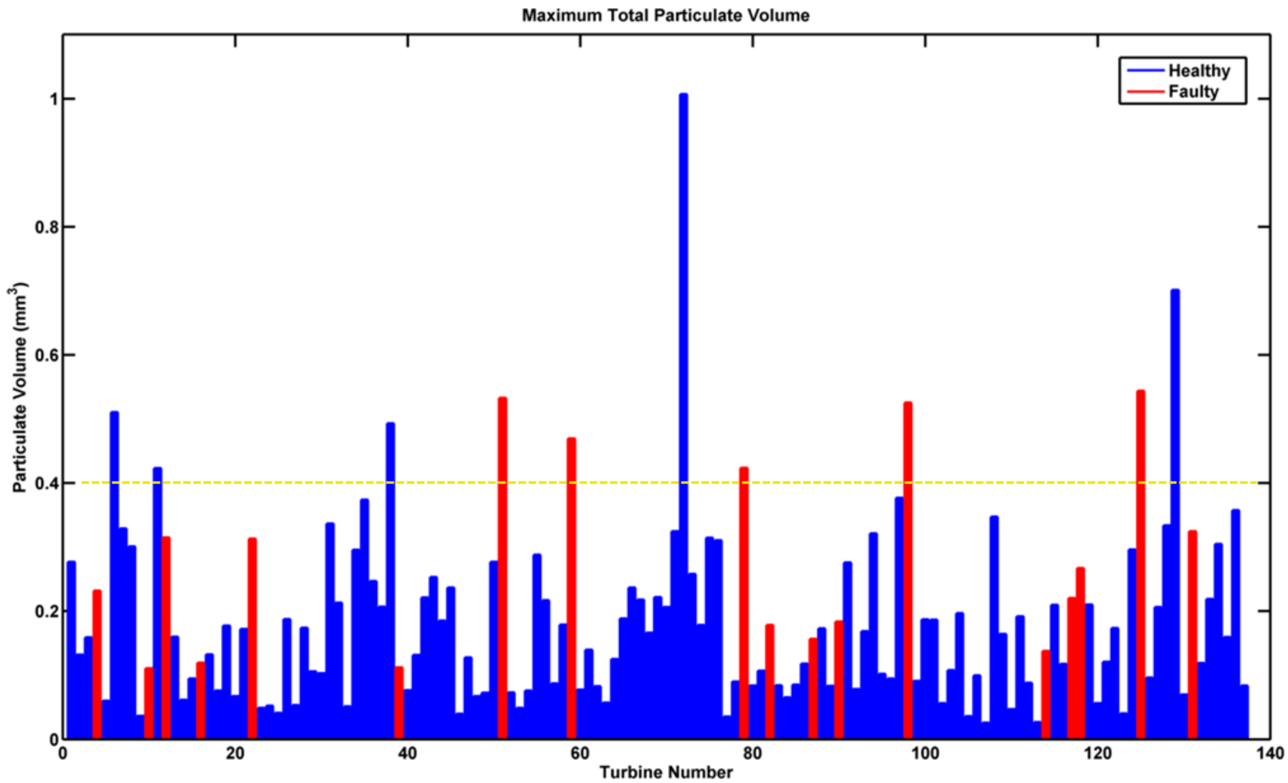

Figure 5: *The maximum particulate volume for each turbine as calculated using optical particle count report data.*

The total particulate volume for each oil report from each turbine was calculated from the optical particle data reported by number of particles in size ranges of 4-6µm, 6-10µm, 10-14µm, 14-25µm, 25-50µm, 50-100 µm, and 100+µm. With the assumption that that particles are roughly spherical, the total particle volume was estimated using the average particle size in each bin as the diameter of the particles. The particulate volume was calculated and summed across all bins, resulting in the total particulate volume for each turbine. The maximum particulate volume for each turbine was determined (Fig. 5).

Examining the data in this fashion should provide more reliable results than ISO cleanliness code results because it considers the total particulate volume and has greater particle size resolution. The alarm threshold for maximum total particulate volume was set at 0.4mm^3. However, using this method, there is still a 72% missed detection rate and a 50% nuisance rate, as 13/18 of the faulty turbines were not flagged and 5/10 flagged turbines were healthy.

Where is the Wear?

The above analyses demonstrate that elemental and optical particle counting tests performed on oil samples do not provide meaningful gearbox health information. But why? If a gearbox is faulty and generating wear debris, why isn't it observable in the oil samples? One possible answer is simple: it has been filtered out. Filtration systems generally remove particles larger than 5-50μm. Therefore, most of the wear debris that is useful for indicating gearbox health will be filtered out before the oil sample is taken for offline analysis.

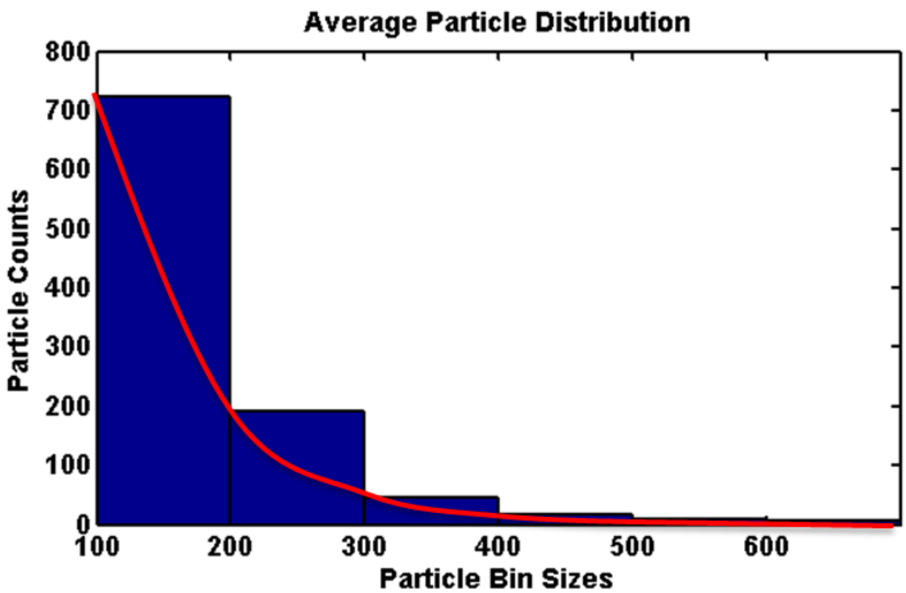

Figure 6: *Average particle size distribution measured by online wear debris monitors on 100 turbines of identical make and model, and from a similar environment as the studied turbines.*

Additionally, even if the sample is taken before filtering it is still extremely unlikely that a representative sample of debris will make it into the 4-ounce sample beaker. The average particle-size distribution of wear debris particles from a typical fleet of wind turbines was measured by online wear debris monitors (Fig. 6). By approximating the volumetric flow rate through online wear debris monitors, the concentration of even the most abundant particles, particles from the 100μm-200μm bin, was found to be approximately 1 particle in every 20 liters of oil. If a 4 fluid ounce sample is taken, there is roughly a 0.6% chance that one of these particles will be collected in the sample.

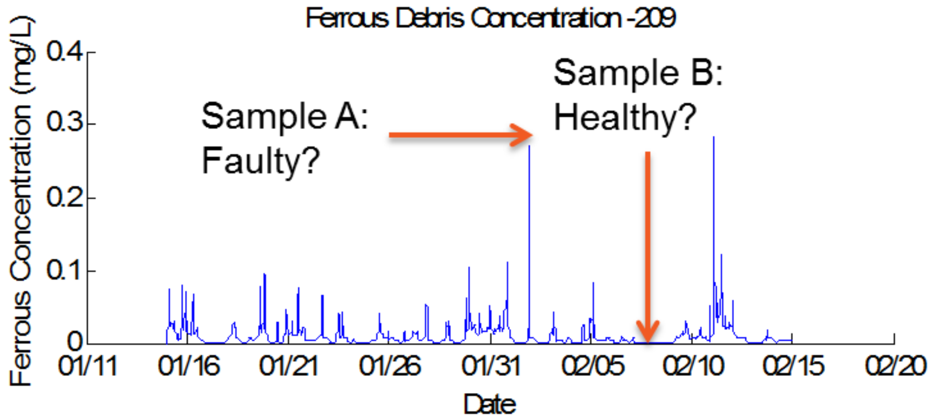

Figure 7: *Ferrous concentration within the oil of a typical wind turbine measured using an online wear debris monitor capable of detecting and sizing particles >40µm.*

Another main factor resulting in a lack of useable wear debris data from offline samples is that wear metal generation in wind turbine gearboxes is not a continuous or predictable process. Wear metal generation rates vary dramatically based on the fault progression stage and operating conditions, such as temperature or wind speed. Wear debris can get stuck, be released, or settle depending on the gearbox conditions at any point in time, making it nearly impossible to collect a small sample that will be representative of the current health of the system.

The stochastic nature of wear debris becomes evident when examining the ferrous debris concentration within a single gearbox over time as measured by an online wear debris monitor (Fig. 7). If an oil sample was taken at point A, the number of ferrous particles in that sample could be high enough to trigger an alarm condition. If a similar sample was taken at point B, the results of offline oil sampling analysis would be within a healthy range. This example illustrates how periodic sampling is a fundamentally flawed method for determining gearbox health; oil samples drawn just minutes apart can yield very different results.

Determining Gearbox Health using Online Wear Debris Monitoring

Online wear debris sensors provide the unique capability of constantly monitoring the levels of ferrous and nonferrous wear debris particles within a wind turbine gearbox. Accelerating wear generation rates and momentary surges in particle counts can be easily recognized and acted upon before a critical gearbox failure occurs. The utility of online wear debris monitoring as a means of detecting mechanical component failures and continually assessing their severity is best illustrated by a timeline of historical data from a gearbox with such a failure.

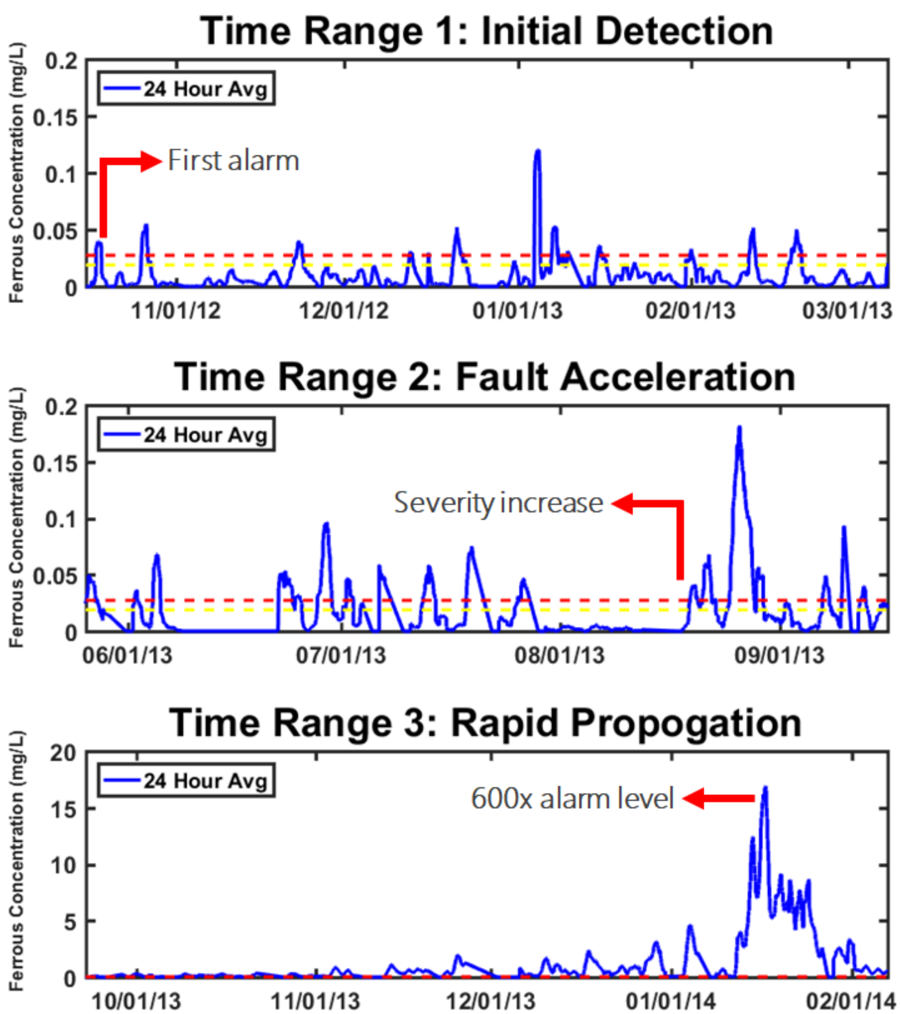

Figure 8: *Tracking wind turbine gearbox fault progression with online wear debris monitor data.*

Estimated ferrous concentration data from an online wear debris monitor installed on a wind turbine gearbox indicated abnormally high levels of ferrous material roughly 14 months before a gearbox repair was required (Fig. 8). In Time Range 1, a low fault severity assessment was assigned due to elevated, yet relatively stable, wear debris generation. Operational parameters also remained unchanged and no maintenance actions were taken. In Time Range 3, peak concentration levels observed by the online wear debris monitor increased slowly in the months after the initial detection, indicating progression of the fault and worsening gearbox health.

Over a year after the initial detection of abnormal wear debris generation, during Time Range 3, a rapid increase in both peak ferrous debris concentration and a corresponding decrease in the amount of time between these peaks indicated greater probability of catastrophic component failure. Based on this escalation reported by the debris monitor, and in order to avoid such a failure, the turbine was de-rated and subsequently repaired. Upon investigation it was found that indeed the gearbox damage had propagated as an axial crack in two planet bearing raceways with significant secondary damage in the adjacent area.

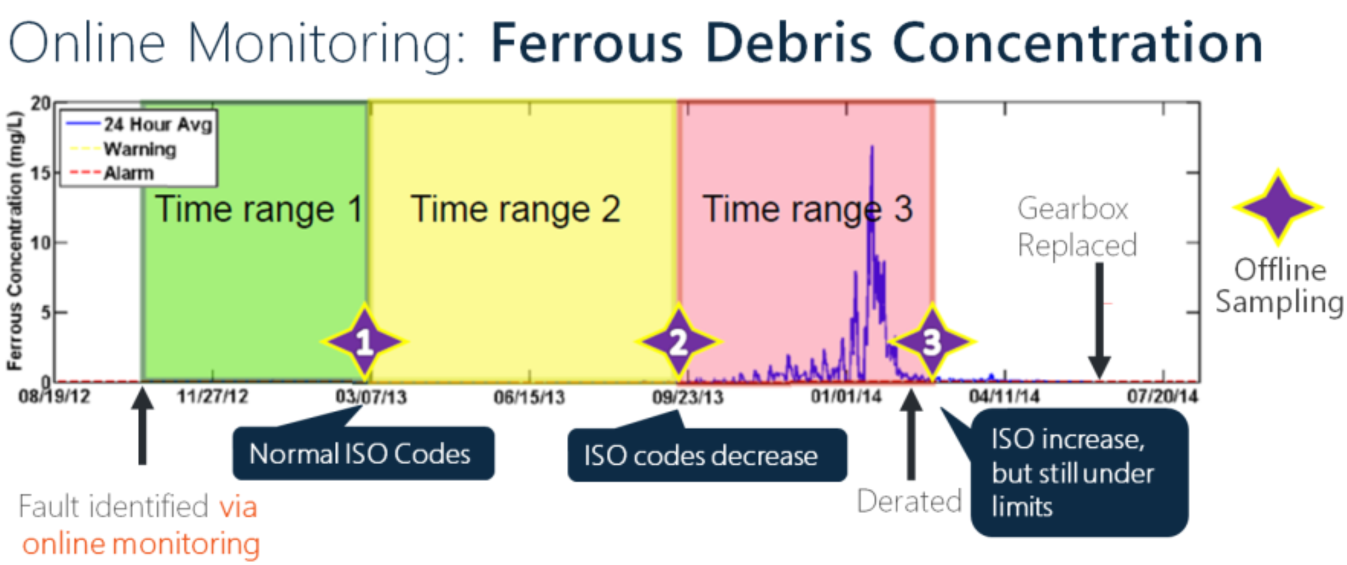

Figure 9: *Wear debris timeline of a bearing raceway axial crack fault within a wind turbine gearbox.*

During this 14-month timeline, periodic oil samples were taken for analysis with no significant findings. In fact, the reported oil cleanliness actually exhibited improvement based on reported ISO cleanliness codes as concentration levels reported by the online debris monitor increased (Fig. 9). It is important to note that although the peak debris concentrations were increasing, the momentary concentrations remained highly variable. Mechanical faults such as the one observed in this example can propagate quickly, developing from a state of low risk of major component failure to high risk in a matter of weeks, if not days. Online debris monitoring of metallic debris enables these changes in severity to be observed and tracked in real-time, allowing adjustments in operation to prevent catastrophic failure and extend operating life until a repair or replacement can occur.

Online wear debris monitors provide the additional benefit of allowing the analyst to correlate wear debris data with turbine output, temperature, and other sensor data to pinpoint the cause of fault progression, as identified by debris concentration spikes. For example, a large increase in wear debris corresponding to a startup condition could be caused by particles settling and clumping in the gearbox. This additional information would be important when determining the severity of an alarm being triggered.

Determining Oil Health using Offline Oil Analysis

Though the study finds that traditional offline oil sampling is unreliable for assessing gearbox health, nevertheless operators have found value in offline oil analysis. The value is generally associated with the discovery of poor oil cleanliness, water contamination, or degrading oil quality; all of which can prevent the lubricant from adequately protecting machine components. Proactive maintenance actions such as changing oil, replacing filter media, and changing desiccant breathers, based on oil laboratory analysis results, can lead to better-running machines with less chance of mechanical failure.

Laboratory analyses such as ICP-AES are able to provide a detailed evaluation of the lubricant's additive condition and contaminants that may be present. As additives are depleted over time the oil becomes less effective in providing surface protection, has more difficulty dealing with moisture, exhibits unwanted changes in viscosity, and is more prone to foam, sludge, and varnish. Tracking the depletion of additives, as well as monitoring other characteristics such as viscosity and acidity, can help ensure the lubricant is within the manufacturer's specification and performing as intended.

Optical particle counting performed on oil samples enables operators to maintain good oil cleanliness that will improve machine performance and longevity. While online wear debris monitoring focuses on metallic debris and is significantly more reliable for assessing the health of a gearbox, oil cleanliness also accounts for small non-metallic debris like dirt, dust, and sand. These small particles can disrupt the oil film causing micro-indentations and initiating surface wear [1]. In this way, oil cleanliness can affect future gearbox health, but does not necessarily indicate current gearbox health. The source of particulate must be determined when abnormal oil cleanliness is detected in order to take corrective action.

Less commonly performed oil laboratory analyses such as ferrography and filter media analysis can sometimes provide insight into the mechanical failure mode that is present. Filter analysis is useful for determining total debris mass per filter change and also isolates large metallic particles for further testing. Ferrography can determine particle composition and the dominant wear mode present in the gearbox. Tests such as these are useful tools and, in some instances, the level of detailed information can help operators isolate failures down to an individual component. Unfortunately, these methods of analysis are generally more expensive than a standard oil analysis and can still fall victim to the inherent limitations of sampling methods and variations in debris over time.

Field tests performed by the National Renewable Energy Laboratory have shown that vibration, acoustic emission and wear debris monitoring are able to indicate when there is damage within a wind turbine gearbox [7]. These field tests also showed that although periodic offline oil sampling is too sporadic to be used for identifying increases in gearbox wear generation, it can be useful for determining which components within the gearbox are damaged, based on the presence of different metals within the oil.

CONCLUSION

The best approach for monitoring and managing the lubricant and gearbox health is one that combines offline and online analysis methods. While both offline and online methods provide meaningful data about the system, it is important to establish exactly what information can be reliably inferred from analysis results to allow the operator to make informed maintenance decisions. Offline oil analysis is an important tool for maintaining the lubricant health and should be used to trend additive depletion, water contamination, and oxidation. Maintaining healthy lubricants ensures internal components are appropriately protected and can significantly increase the service life of equipment.

Online wear debris monitoring provides real-time information about the health of the gearbox that cannot be reliably determined from offline oil analysis. Wind turbine operators use online wear debris monitoring to accurately detect, assess, and manage gearbox component failures, sometimes years before a fault would otherwise be discovered. This advance knowledge allows operators to adjust operational parameters and optimize the scheduling of repairs, leading to less downtime and minimizing the risk of catastrophic component failure; often leading to a payback period of less than one year. A combination of both online and offline oil analysis allows the wind turbine operator to not only maintain the quality of the oil but also determine gearbox health, putting the operator in the best position to effectively maintain the equipment and minimize operations and maintenance costs.

REFERENCES:

1 Robert Errichello and Jane Muller, Geartech, "Oil Cleanliness in Wind Turbine Gearboxes", Machinery Lubrication Magazine, July 2002.

2 Drew Troyer, Noria Corporation, "Secondary Oil Sampling Pinpoints Wear Problems", Practicing Oil Analysis, September 1999.

3 Jan Ukonsaari and Hans Møller, Elforsk, "Oil Cleanliness in Wind Power Gearboxes", October 2012

4 Marine Beauvir, Thermo Fisher Scientific, "Lubricating Oil Analysis According to ASTM D5185 Using Thermo Scientific iCAP 7400 ICP-OES", 2013

5 ASTM D5185, astm.org, April 2014

6 Matt Spurlock and Jeff Keen, "Understanding the Rate of Change Danger with Alarms", Uptime Magazine, October 2012

7 S. Sheng, H. Link, W. LaCava, J. van Dam, B. McNiff, P. Veers, and J. Keller, National Renewable Energy Laboratory, S. Butterfield and F. Oyague, Boulder Wind Power, "Wind Turbine Drivetrain Condition Monitoring During GRC Phase 1 and Phase 2 Testing", 2011

8 Paul Dvorak, "Think Synthetic Lubricants for Improved Wind Turbine Availability", October 2013