Going Beyond: Aligning Oil Analysis with Failure Modes Effects and Criticality Analysis (FMECA)

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Oil analysis has proven time and time again to be a beneficial part of any reliability driven maintenance program. From providing a predictive early warning of impending failure, to seeking a proactive root cause solution, there can be little doubt that oil analysis is an effective condition-monitoring tool. However, for every success story, there's a litany of stories recounting problems missed and failures that have occurred despite routine oil sampling. When this occurs, the usual reaction is to blame either the technology or the oil analysis lab for having failed to warn of impending doom. In extreme cases, the temptation may be to seek out a different lab which, rightly or wrongly, is billed as "better" than the incumbent lab. But is it really the lab's fault when an oil analysis program goes off track? While it is true that the lab should bear some accountability for the success or failure of the program, oftentimes a good, long, hard look in the mirror is all it takes to find the true root cause of the problem. Put simply, the problem may simply be that the program has not been properly engineered or designed.

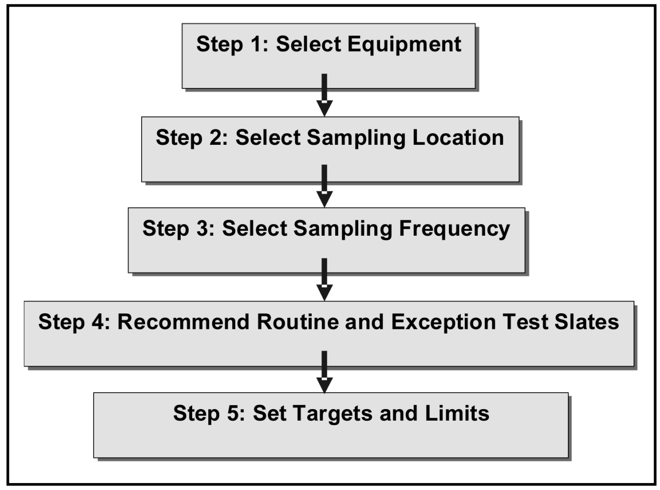

Figure 1: Steps involved in designing an effective Oil Analysis program

Steps to Designing a World-Class Oil Analysis Program

Developing an effective oil analysis program requires careful planning. All too often when plant personnel decide to invest in oil analysis, they choose a lab and start sending samples without thinking about what they are trying to achieve. This fire, aim, ready approach to oil analysis is a guaranteed recipe for disaster. Instead, the program should be developed with a careful game plan in mind, based on a stated series of reliability goals.

There are five basic steps to developing and designing an oil analysis program (Figure 1). Miss any one of these steps and the program is destined for, at best, mediocrity. So what should drive decisions around machine selection, sampling location, sampling frequency, test slate selection and limit setting? The answer is simple: what are you looking for? While this may seem like an obvious comment, it is one that is often overlooked when designing and deploying oil analysis programs.

Develop a game plan based on reliability objectives

Like every other maintenance tool, oil analysis program design should be influenced and driven by an RCM (Reliability Centered Maintenance) process. Developed in the 1960s by the commercial aviation industry, RCM can essentially be characterized as a process for evaluating the reliability of any asset or process, followed by a systematic and engineered approach to reviewing the best method(s) for insuring the required reliability for that asset is attained. This might include doing nothing (the asset is either reliable or non-critical), improving some maintenance practice (e.g. better lubrication, improved alignment specs, etc.) or deploying a re-design or redundant system. Where oil analysis fits in is in providing a condition-based maintenance tool for "improving maintenance practices" or in supplying root cause failure data in support of deploying a re-design or redundant system. But again, unless the program is specifically designed to provide the right data, success will be limited.

Fundamental to the RCM process is Failure Mode Effect Analysis (FMEA). FMEA is a systematic process aimed at identifying potential failure modes in advance of failures actually occurring, allowing appropriate maintenance strategies to be selected to mitigate their effects. This is in sharp contrast to the more commonly applied oil analysis approach in support of Root Cause Failure Analysis (RCFA) which seeks to identify causes after a failure has occurred.

FMEA is fundamental to the oil analysis design process because once the failure modes and effects have been noted the oil analyst can decide:

- Is oil analysis is the correct technology to address the potential failure modes?
- If so, what is the optimum sampling location to give the earliest warning?
- How often should samples be taken (this will depend upon the P-F interval for the failure mode as discussed later)?
- What tests should be performed to detect the problem?
- What limits should be set to define when the measured parameter(s) are out of condition indicating the onset of the potential for failure to occur?

For each of these five critical decision points, each failure mode as defined by the FMEA process can and should influence our decisions in the design steps outlined in Figure 1.

Step1: Select Equipment

Whether a specific machine should or should not be sampled is, of course, the first decision to make. This should be based on a combination of machine criticality, anticipated failure modes based on our FMEA and the degree to which other predictive technologies can support or provide better detection of the impending problem.

When it comes to machine criticality, this is really a decision which can only be made by plant production, maintenance and reliability management. Factors to consider include the effects on production, potential safety risk if a specific machine fails and environmental compliance. What is not a consideration in machine selection for oil analysis (though it should be in sample point and method selection, test slate selection and limit setting) is sump capacity. The reason is because oil analysis is about more than just measuring the condition of the fluid. While using oil analysis for condition-based oil changes on a small sump system is likely not justifiable, oil analysis can provide early warning of other mechanical or contamination related wear modes assuming this small system is critical to production, safety or environmental compliance, no matter what the sump capacity happens to be.

Deciding which predictive technology is best suited to each failure is the next step in the design process, again factoring in to whether a machine should or should not be considered for oil analysis. Generally speaking, problems associated with the lubricant (wrong oil, degraded fluid, contaminated oil) are best detected through oil analysis, while mechanical problems (misalignment, imbalance, etc.) which, although they may manifest themselves as wear debris in the oil, are better detected with vibration analysis. The key is to integrate all predictive technologies (vibration analysis, oil analysis, thermography, ultrasonics, motor current analysis, etc.) so that the correct technology – or group of technologies – is applied to each machine. Figure 2 provides general guidelines of the typical failure modes our FMEA process may identify and which PdM technologies are best suited to each situation.

	Detection P-F Interval (what's going to happen)			Root Cause Failure Analysis (why did it happen?)		
	Lube Analysis	Vibe Analysis	Therm Analysis	Lube Analysis	Vibe Analysis	Therm Analysis
Root Causes Control						
Lubricant contamination	excellent	poor	poor	excellent	poor	fair
Misalignment	fair	excellent	fair	fair	excellent	fair
Imbalance	fair	excellent	fair	poor	excellent	fair
Wrong lubricant	excellent	poor	poor	excellent	poor	poor
Degraded lubricant	excellent	poor	poor	excellent	poor	poor
High operating temp.	fair	fair	excellent	fair	fair	excellent
Failure Detection						
Wear	excellent	good	fair	excellent	fair	fair
Cavitation	good	poor	fair	fair	poor	fair
Gear tooth fracture	poor	excellent	poor	fair	fair	poor
Structural resonance	poor	excellent	poor	poor	excellent	poor
Fatigue	excellent	good	good	excellent	fair	fair

Figure 2: Relative effectiveness of different predictive technologies on detecting and troubleshooting different failure modes

Step 2: Select Equipment

Sampling location and methodology has perhaps the single biggest influence on the effectiveness of oil analysis in detecting failure modes. Unfortunately, all too many oil analysis users perceive that provided oil from the right machine gets into the sample bottle, they are guaranteed success. A detailed review of sampling location is beyond the scope of this paper, but to illustrate why this is not necessarily true, consider a typical hydraulic system (Figure 3).

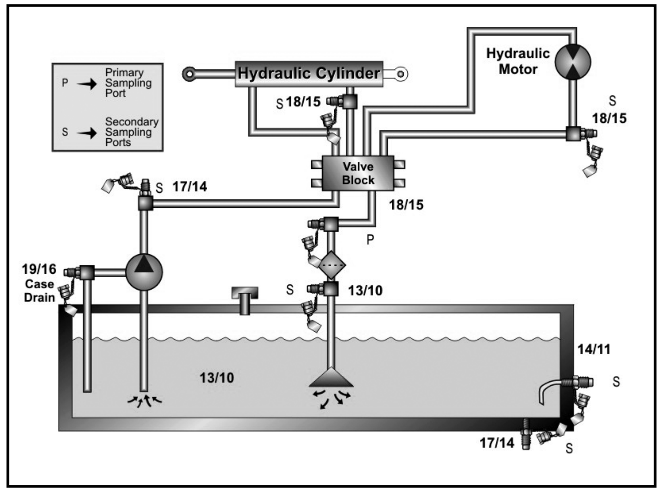

Figure 3: Sampling locations for a typical hydraulic system

In our example a series of 6 and 14 um particle count measurements have been taken at various locations in the system including the reservoir, on the main supply line, on the case drain of the pump, after each of the two actuators (hydraulic cylinder and motor), after the valve block and after the high pressure return line filters. From the figure, it can be seen that the particle counts from the two extremes (case drain versus reservoir) differ by six ISO codes or an average of a sixty-four-fold difference in fluid cleanliness! In this case, by tracing the ISO particle codes through the system using a series of primary and secondary sampling valves, the source of the particle ingress can be traced to the pump. But if the sample is taken from the reservoir – a common mistake in hydraulic systems – the high efficiency return line filter will remove any detectable wear debris from the pump before it enters the reservoir and can be sampled.

Now let's consider the type of pump in use. In some types of hydraulic pumps such as the piston pump shown in Figure 4, the fluid which is used to lubricate the bearings is returned to the reservoir via the case drain, rather than through the main high pressure system supply line. As such, if pump bearing failure is identified as part of the FMEA analysis process, a case drain sample is likely to be the only reliable source in identifying the problem early enough.

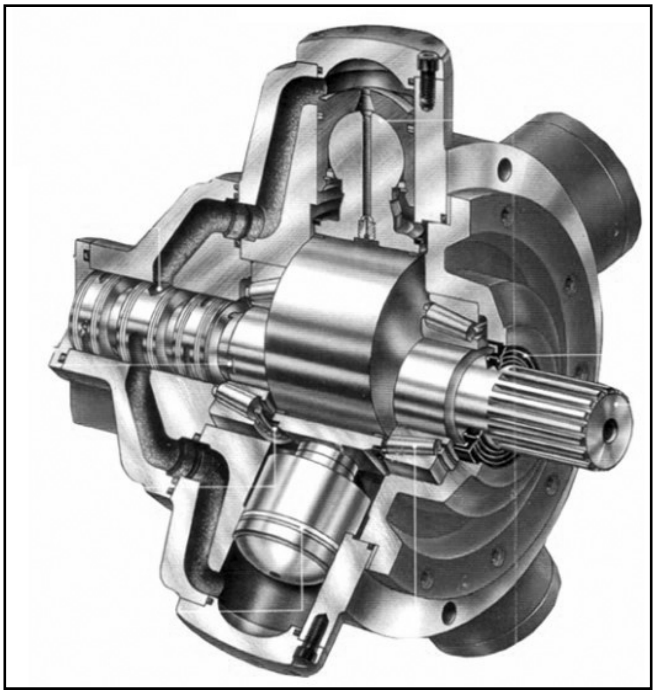

Figure 4: Radial Piston Pump. In this case, the portion of oil used to lubricate the bearings will exit back to the reservoir via the case drain.

Generally speaking, sample valves should be located immediately downstream from the oil-wetted component of interest for maximum effectiveness. In identifying failure modes for various components, those for which we intend to use oil analysis as our primary source of detection (as opposed to say vibration analysis in the case of our radial piston pump), we need to be careful in where we locate our sample valves. Often times, for complex circulating systems such as hydraulics, turbo-machinery or circulating bearing lube systems, multiple sample ports can and should be installed based around our goals and objectives as defined by our FMEA process.

Step 3: Sampling Frequency

In oil analysis, there exists the possibility of taking measurements continuously in real-time using permanently mounted sensors, taking periodic in-line measurements using portable instruments connected to appropriate sample ports on each machine or taking periodic bottle samples for analysis either onsite or offsite – so which is the best option? The answer to this question again is driven by what you're trying to achieve, and how quickly you require validation that a potential problem has occurred.

As part of the RCM process, reliability engineers identify not just failure modes but the time from a potential failure occurring (P) to when a functional failure (F) occurs. By functional failure, we simple mean the machine stops working according to its required design capacity, such as a diminished pumping capacity or cycle time, not necessarily a catastrophic failure which shuts the machine down completely. Figure 5 shows three examples of different possible P-F interval curves for different failure modes.

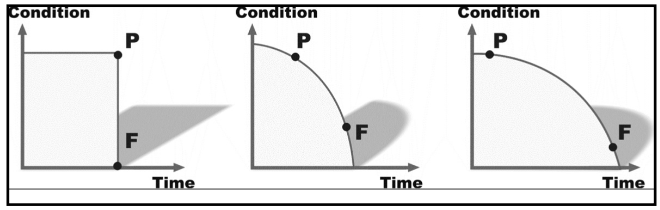

Figure 5: Common shapes of the P-F interval curve

In the first example represented by the step function on the left of Figure 5, a sudden catastrophic failure occurs instantaneously with no advanced warning. A simple example of a failure of this nature would be an electric light bulb – the bulb is either working or it is not. If the P-F interval for a machine failure mode as identified by our FMEA is represented by this simple step function, no amount of predictive maintenance (oil analysis, vibration analysis, etc.) will provide sufficient lead time to prevent an unscheduled functional failure of the machine.

Of course most failure mechanisms do not follow a simple step function, but rather the type of curves shown in the center and right hand side of Figure 5. So in selecting a proposed sampling frequency, it helps to know the anticipated P-F interval for each failure mode so that an appropriate sampling frequency can be selected which should be less than the P-F interval.

As an example, consider two cases: a failure due to misalignment or a contamination-induced failure caused by contamination ingress. For each failure mode, we need to select the technology which provides the earliest lead time (furthest to the left of the P-F curve), and a sampling frequency which is less than the anticipated P-F interval. In the case of the misalignment, the P-F interval may have a fairly steep curve, particularly in high-speed applications, meaning more frequent sampling. Likewise, it is highly probable that vibration analysis will provide a much earlier warning than oil analysis, so for this failure mode, we should select vibration analysis perhaps bi-weekly if this is indeed a high speed machine with a steep P-F curve.

Conversely, in the case of a contamination-induced failure, the P-F interval is likely to be less steep, but oil analysis is going to provide the advanced warning we desire. Again, the steepness of the curve will determine our sampling frequency. For machines which are very sensitive to contamination-induced failure (e.g. servo-controlled hydraulic machines) where we are typically fairly close to our target limits we would choose a fairly frequent sampling frequency (perhaps as often as every two weeks), whereas for a slow turning gearbox where the induction time for failure could be many months or even years, monthly or even quarterly sampling may be adequate.

Again, an understanding of different failure modes and their effects on the machine should drive both our PdM and sampling strategy.

Step 4: Test Slate Selection

In selecting the correct tests for each application, it's important to understand what each oil analysis test can, and more importantly, cannot do. Take, for example, the standard elemental analysis test performed on most oil samples, which provides the parts-per-million (ppm) of various wear metals, contaminants and additive elements. Because the instrumentation (ICP or RDE) which is used to analyze the sample, particles larger than 3-5 um in size cannot be detected by this method.

To understand the impact of this statement, consider three common failure modes of an industrial gearbox: corrosion due to moisture ingress, cutting wear due to particle ingress, and adhesive wear of the gears due to load and/or inadequate lubricant performance. The size distribution for each of these three failure modes is shown in Figure 6.

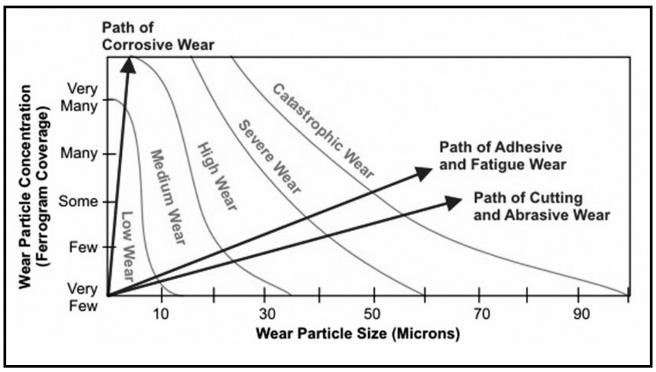

Figure 6: Particle size distribution for corrosive, cutting and adhesive wear

As can be seen from Figure 6, if we are trying to design an oil analysis program to identify corrosive wear, our best option would be to use elemental spectroscopy to look for iron (assuming we're talking about rust). Conversely, if we are interested in an adhesive wear problem, our particle size distribution can grow very rapidly beyond the 3-5 um size limit of ICP or RDE instruments to the point where the failure may be missed completely. In this case our test slate should be supplemented by a test for large particles (either Ferrography, DRII or PQ, again assuming steel/iron wear). Similar limitations apply to other tests in the oil analysis arsenal meaning that a thorough understanding of failure modes, and which tests are best able to detect their problems, is required.

Step 5: Setting alarms and limits

The final step in designing an effective oil analysis program is to set appropriate alarms. Oil analysis alarms can be categorized loosely into three areas: predictive alarms such as wear debris, aging alarms such as oil condition, and goals-based alarms such as cleanliness and dryness targets. In each case, a thorough understanding of the failure mode and what constitutes too high or too low a reading from each oil analysis parameter is required.

Perhaps most significant are the goal-based alarms for cleanliness and dryness. Understanding how much particle or moisture contamination is acceptable without triggering contamination-induced failure modes is an important part of designing effective alarms. But again, test limitations need to be considered. For example, for a typical industrial hydraulic system in a production-critical application, our moisture limits should be set in the 200-400 ppm range. Yet many oil analysis users who perhaps even understand the levels they need to be achieving are relying upon data from FTIR which, when it comes to water detection, is really only capable of detecting water once it exceeds 500-1000 ppm. Oblivious to this test limitation, plant hydraulic systems could be running above the prescribed limit for the plant's reliability objectives and nobody may even know!

Summary

Alongside other technologies such as vibration alignment, thermography, ultrasonics and motor current analysis, oil analysis can be an effective tool in helping plants meet and achieve reliability objectives. But just like any other engineered process, unless the program is properly designed and developed, its effectiveness can be seriously diminished. Oil analysis program design is a stepwise process – select the correct machines to sample, decide where to sample each one, select an appropriate sampling frequency, choose the right tests and get the right alarms and limits in place. But in each case our design should be guided by what we want to achieve, which in turn should be determined by a thorough understanding of all possible failure modes and their effects.