Proactive Maintenance can Yield More than a 10-Fold Savings Over Conventional Predictive/Preventive Maintenance Programs

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Introduction

Plainly stated, the growing cost of maintenance is a serious business problem. According to DuPont, "maintenance is the largest single controllable expenditure in a plant: in many companies it often exceeds annual net profit." One major U.S. automotive manufacturer has a maintenance staff of between 15,000 and 18,000, all plants combined. They say "85% to 90% is crisis work" (breakdown).

While preventive maintenance, when well implemented, has been shown to produce savings in excess of 25 percent, beyond that its benefit quickly approaches a point of diminishing return. According to a Forbes Magazine study, one out of every three dollars spent on preventive maintenance is wasted. A major overhaul facility reports that "60 percent of hydraulic pumps sent in for rebuild had nothing wrong with them." These inefficiencies are the result of maintenance performed in accordance with a schedule (guess work) as opposed to the machine's true condition and need.

Most recently, predictive maintenance (also known as condition monitoring) has been leading the way to additional savings over preventive maintenance. The use of real time or portable instruments such as vibration monitors, thermography, ferrography, etc. has been effective at recognizing the symptoms of impending machine failure. The major benefit is the availability of an earlier warning, from a few hours to a few days, which reduces the number of breakdown "catastrophic" failures.

Predictive maintenance is usually implemented concurrently with preventive maintenance and targets both the warning signs of impending failure and the recognition of small failures that begin the chain reaction that leads to big failures (i.e., damage control).

Proactive "Life Extension" Maintenance

Proactive maintenance has now received worldwide attention as the single most important means of achieving savings unsurpassed by conventional maintenance techniques. The approach supplants the maintenance philosophy of "failure reactive" with "failure proactive" by avoiding the underlying conditions that lead to machine faults and degradation. Unlike predictive/preventive maintenance, proactive maintenance commissions corrective actions aimed at failure root causes, not just symptoms. Its central theme is to extend the life of mechanical machinery as opposed to (1) making repairs when often nothing is broken, (2) accommodating failure as routine and normal, or (3) preempting crises failure maintenance in favor of scheduled failure maintenance.

While the root causes of failure are many, or at least presumed to be, it is generally accepted that 10 percent of the causes of failure are responsible for 90 percent of the occurrences. Most often, the symptoms of failure mask the root cause or they are presumed themselves to be the cause. For example, a sudden bearing failure is often blamed on poor quality or a bad lubricant. The root cause, on the other hand, is often contamination in the lubricant (bad filter) or faulty installation of the bearing.

When a machine is well designed and well manufactured, the causes of failure can generally be reduced to machine misapplication or contamination. And, among these two, contamination is clearly the most common and serious failure culprit.A great deal of laboratory proof and field confirmation now are available to support this fact. Therefore, the logical first-approach to proactive maintenance is the implementation of rigorous contamination control programs for lubrication fluids, hydraulic fluids, coolants, air, and fuel. The appropriateness and veracity of this maintenance strategy is emphasized below.

> **A.** According to the bearings division of TRW, "contamination is the number one cause of bearing damage that leads to premature removal."
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> **B.** Machine Design Magazine reports that "less than 10 percent of all rolling-element bearings

reach the fatigue limit because contamination usually causes wear or spalling failure far earlier."

C. According to Caterpillar, "dirt and contamination are by far the number one cause of hydraulic system failures." J. I. Case states that "one thing holds true about hydraulic systems: the systems must be kept clean -- spotlessly clean -- in order to achieve the productivity they're capable of."

D. Protractive studies by the U.S. Navy show that the cost of contamination on marine and aviation equipment per operating hour exceeds 60 percent of the cost of fuel per hour on the same equipment.

E. Massachusetts Institute of Technology states that "six to seven percent of the gross national product ($240 Billion) is required just to repair the damage caused by mechanical wear." Wear occurs as a result of contamination.

F. Oklahoma State University reports that when fluid is maintained 10 times cleaner hydraulic pump life can be extended by 50 times.

Human Medicine Parallel to Maintenance Strategies

The human body offers many parallels to machine maintenance. In fact, from good observation of advances in human medicine we can gain excellent insight to effective strategies in the maintenance of machinery.

Most machinery are fluid dependent systems, just like the human body. Fluids such as lubricants, hydraulic fluids, coolants, fuels, and air bring contaminants into the system and transport the contaminants within the system. The abnormal presence of contamination in a system can be described as an incipient failure, meaning that, while the machine is not currently experiencing loss of performance or component degradation, the conditions that lead to failure and shortened service life are present and untenable. High contaminant levels are similar to living with high cholesterol and high blood pressure: more sooner than later you die. And similar to cholesterol, high contamination is a correctable condition.

Types of Contaminant-Induced Failures

There are many types of contaminant-induced failures in machinery. The most common are wear, stiction, seizure, erosion, and corrosion. Contaminants involved include solid particles, moisture, air, chemicals, and other materials foreign to the system. However, of the failure types, abrasive wear, caused by solid particles, is substantially the most serious. According to the Vickers division of Trinova/Aeroquip, "abrasive wear accounts for about 90% of failures due to contamination." This abrasive wear is the result of particles (too small to be seen) that cut and plow rolling and sliding surfaces.

The rate at which contamination enters the fluids of hydraulic and lubricating machinery is typically greatly underestimated and understated. Likewise, the effectiveness of filters at removing fluid contaminants in field systems is greatly overstated. According to a study of hydraulic equipment at Oklahoma State University, "it has been demonstrated that apparent ingression rates of 10 million to 100 million particles greater than 10 microns (per minute) characterize field systems".

Hence, the filter, if existent, is challenged with the formidable task of removing particles from the fluid at the same rate at which they are entering (ingression). Tests by machinery manufacturers show that filters have great difficulty achieving this task in the field, where they are subjected to conditions of frequent and large changes in temperature, fluid viscosity, pressure, and flow (surges), plus the effects of shock, vibration, and fatigue. Other common problems are filter bypass valves that get stuck open, damaged or missing filter gaskets, and filters that are installed backwards or crooked. Accordingly, the spoils and vagaries of field-oriented situations are many. As a result, fluid contaminant levels must be frequently monitored to verify filter performance and to provide the essential "feedback" that gives integrity to a contamination control program.

Hydraulic Maintenance Savings

When it comes to proactive contamination control maintenance, the Japanese may be the global leaders. They have clearly taken a "do-it, don't-just-talk-about-it" approach. Evidence of this comes from reports by two of the world's largest steel mills, Nippon Steel and Kawasaki Steel, both in Japan:

> **A.** After Nippon Steel implemented a hydraulic system contamination control program plant-wide, involving both improved filtration and rigorous fluid cleanliness monitoring, pump replacement frequencies were reduced to one fifth and the cumulative frequency of all tribological failures (i.e., failures relating to wear and contamination) was reduced to one tenth.
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> **B.** Likewise, Kawasaki Steel, not to be outdone, implemented a similar contamination control program and achieved an almost unbelievable 97% reduction in hydraulic component failures. Such claims as these spurred the British Hydromechanics Research Association (BHRA) and the U.S. Navy to conduct their own controlled studies to substantiate benefits of proactive contamination control maintenance:
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> 1. The BHRA study covered a three-year period and was based on the carefully monitored field experience of 117 hydraulic machines evenly spread across eight categories (i.e., injection molding, machine tools, material handling, mobile/construction, marine, metal working, test stands, and miscellaneous). The results of the study showed a dramatic relationship between fluid contamination levels and service life. Improved system cleanliness achieved extended actual mean time between failures (MTBF) from 10 to 50 times, depending on cleanliness.
> 2. A study by the Naval Air Development Center in Warminster, Pennsylvania performed on aircraft hydraulic pumps showed nearly a 4-fold wear-life extension with a 66 percent improvement in filtration and a 13-fold wear-life extension with a 93 percent improvement in filtration.

Bearing-Life Savings

According to the Bearing Division of TRW, "contamination is the number one cause of bearing damage... the amount of damage caused by solid contaminants passing between the rolling and sliding surfaces of an anti-friction bearing is proportional to the size and concentration of the contaminants." Unlike subsurface-originated damage commonly associated with fatigue, contamination causes surface-originated damage to bearings. This contaminant-induced wear reduces bearing life to as little as five percent of its rated life, according to Japanese researchers. Other in-plant studies are just as resounding:

1. The contamination control program reported by Nippon Steel included lubricating systems involving both journal and roller bearings. Over the study's three-year period they successfully achieved a 50 percent reduction in bearing purchases plant-wide.
2. International Paper Company reported nearly a 90 percent reduction in bearing failures in just six months after they implemented improved filtration and contamination control in their Pine Bluff paper mill.
3. According to the post-sales research of a well known manufacturer of high-duty thrust and journal bearings, "dirt has been responsible for 85 percent or more of their customers' troubles." This appears to conclude that 85 percent of problems and failures with bearings can be eliminated if contaminant levels are reduced and controlled.

Diesel Engine and Gas Turbine Maintenance Savings

The benefits associated with the proactive contamination control of diesel engine lube oils are great. Historically, there have been many misconceptions regarding the influence of contamination on engine service life. Hence, filters with very poor efficiencies have been and still frequently are specified for engine lube oils. However, from a number of important new field and lab studies we can now conclude that lube oil contamination is the primary cause of engine wear that begins what is referred to as the chain-reaction to failure.

In diesel engines, high local stresses associated with sliding contact wear result in abrasive removal of material surfaces. When loads are concentrated on the effective area of a small particle, the resulting surface stresses can be greater than 500,000 psi, far beyond the elastic limit of substrate materials. Oil film thicknesses, between which particles can reach and attack surfaces, are typically in the 10-micron range. This explains why, according to a wear study by Cummins Engine, particles smaller than 10 microns generated about 3.5 times more wear (rods, rings and main bearings) than particles greater than 10 microns. Other important well documented studies are described below:

1. Pall Corporation, in participation with Detroit Diesel Allison (DDA), investigated the influence of improved lube oil cleanliness on the performance and reliability of 150-ton diesel trucks operating in an open pit mine. The study revealed substantial reductions in wear metal concentrations.
2. AC Delco Division of General Motors also tested DDA engines and found an eight-fold improvement in wear rates and engine life with lower lube oil contaminant levels. In a related study on both diesel and automotive engines, General Motors reports, "compared to a 40-micron filter, engine wear was reduced by 50% with 30 micron filtration. Likewise, wear was reduced by 70% with 15 micron filtration."
3. A study conducted by the supermarket chain Albertson's Inc. on a series of over-the-road Cummins tractor engines found markedly reduced wear rates with greater lube oil cleanliness. After analyzing six engines having 600,000 operating miles, Albertson's reports, "engine crankshaft journals showed only 0.0005 inches of wear. The rod and main bearings hadn't even worn through to the copper layer. Compression-ring and oil-ring wear were negligible."
4. An independent European university study, as published in Lubrication Engineering Magazine, reports a reduction in diesel engine wear by a factor of 14 when better lube oil cleanliness is maintained. The study also equates the resulting friction reduction with a 5 percent increase in fuel economy.

In reference to gas turbine engines, the U.S. Department of Defense states that "approximately 30 percent of all engine failures are caused by metal particulate contamination in lubricating oil systems." More precise studies, if conducted, would likely prove the true percentage to be much higher. After all, the wear processes and failures of gas turbines, by design, should be very similar to diesel engine and bearings failures, as previously reported and well documented.

It is interesting to note that currently an estimated 25 to 50 million lube oil samples are analyzed by commercial and in-house fluid analysis labs in the United States each year. Yet, despite the fact that contamination is the largest contributor to engine failure, fewer than 5 percent of these labs do particle counting on lube oil samples. Wear metal analysis and elemental analysis are too often confused as being indicative of actual particle sizes and concentrations in lube oils. Only accurate particle counting devices can determine this.

Steps to Implementing Proactive Contamination Control Maintenance

Contamination control, being the bedrock of proactive maintenance, can be implemented in three simple steps:

1. Using the Contaminant Life Index, establish the target fluid cleanliness levels for each machine and fluid system.
2. Select and install filtration equipment (or upgrade current filter rating) and contaminant exclusion techniques to achieve target cleanliness levels.
3. Monitor fluid cleanliness at regular intervals to verify that targets are achieved. Adjust filtration and contaminant exclusion techniques, as required, to stabilize target cleanliness.

A thorough explanation for implementing each of these steps can be found in the book Fluid Contamination Control, by Dr. Ernest C. Fitch, which can be obtained by contacting the author of the paper.

It is important to note that a common myth among people responsible for machine maintenance is the belief that the incremental costs outweigh the benefits of achieving improved fluid cleanliness. These costs are assumed to be associated with the addition or upgrading of filters and/or the more frequent changing of fluids. While it is not the intent of this article to detail the host of techniques for implementing fluid contamination control, it should be noted that if program origination costs are required, they are generally very quickly absorbed by maintenance cost savings. Beyond origination costs, incremental operating costs to maintain improved fluid cleanliness would be expected only for certain high contaminant-ingression applications, typically less than 10 percent of the cases. Otherwise, savings usually outweigh costs by great margins.

Generally speaking, fluids and lubricants have indefinite life when protected from excessive heat, moisture, air, and particles. As these are all considered contaminants, their control should be a part of the contamination control program. In fact, some power generation lube oils have achieved service life in excess of ten thyears. Referring to the Nippon Steel report, they state that the influence of rigid contamination control practices contributed to a reduction of oil 83 consumption of 83 percent. Pall Corporation claims that by improving fluid cleanliness, oil change intervals can be extended by a factor of 2 or more.

Due to significantly lower wear rates (particle generation), Pall also claims filter change intervals can be extended up to a factor of 2. This can be extended further by taking steps to restrict the entry of contaminants into the fluid. Additional savings can be achieved by routine monitoring of fluid contaminant levels in order to time filter changes at optimum points.

Contaminant Monitoring is Essential to Successful Contamination Control

Unassailably, fluid contaminant monitoring is the operative element to achieving the goal of extended machine life. Machine contaminant levels, as effected by ingression and filtration, are extremely dynamic. And, it is not unusual for levels to vary two or three orders of magnitude over a period of days or even hours. Accordingly, contaminant monitoring closes the loop by providing the essential feedback and therefore control. Flying an airplane in a storm without an altimeter, or navigating a ship at sea without a direction finder, or driving a car a cross-country without a fuel gage are some of the analogies that could be used for attempting maintenance without monitoring.

Fluid contaminant monitoring can be accomplished in the field or plant by extracting samples of fluid into bottles for lab analysis or by portable instruments used right at the machine. Recently there has been a trend away from bottle sampling and lab analysis for routine contaminant monitoring due to the associated higher cost, reduced accuracy, and time delay. In its place has been the use of portable monitors that receive fluids directly out of machines for on-the-spot analysis.

One instrument, sold by Diagnetics, called digital Contam-Alert (dCA), is battery operated and extremely lightweight. It consists of a sensor attached by cable to a hand-held computer. During a test, the sensor is placed momentarily on a special diagnostic port permanently installed on the machine. A small sample of fluid under pressure passes into the sensor and after a minute or two the particle count is displayed on the computer screen.

The unit can be used with a variety of different fluids, such as lube oils, hydraulic fluids, transmission fluids, gear oils, and coolants. After each test the handle on the sensor is depressed, which expels the sample, making it immediately ready for reuse. Particle count data can be easily stored in the computer, tagged to machine I.D., the date, and user comments. Later, the data can be printed out with a portable printer or it can be down-loaded to a desk-top personal computer.

Use of the portable contaminant monitor provides easy in-the-plant or in-the-field proactive or predictive maintenance. Maintenance operators can simply walk from machine to machine checking fluid contaminant levels and compare them to target baselines. Maintenance work orders can then be issued to correct out-of-specification systems.

Comparison of Contaminant Monitoring to Typical Predictive Maintenance Techniques

Outside of its usefulness as a proactive maintenance tool, contaminant monitoring can be equally effective as a first-alert to impending machine failure, i.e., predictive maintenance. When a machine failure is in progress there is a precipitous generation of wear debris resulting in an abnormal presence of particles in the fluids. This chain-reaction of few particles generating more and more particles is an incontestable indication of progressive failure. Using portable contaminant monitors, distinct shifts in contaminant levels can be easily recognized, usually in plenty of time to schedule maintenance.

This technique has a number of advantages over other predictive maintenance techniques:

VIBRATION MONITORING.

According to the text "Hanbuch der Schadenverhutung," 63% of compressor failures and 78% of turbine failures do not cause a change in vibration. Further, in attempts to detect centrifugal compressor failures using vibration monitoring, Chevron reports, "Many thrust bearing failures occur instantaneously, allowing only seconds from the first indication of trouble to internal contact of rotating and stationary parts." They further state, "the vibration orbits have always 'blossomed' just prior to sudden catastrophic failure, exceeding the shutdown limit in both the X and Y directions."

Wear occurs well ahead of the generation of aberrant vibration signals in most rotating machinery. The resultant accelerated particle levels in the lube oil is therefore the earliest sign of impending failure. Further, there are many types of equipment where the vibration signals are far too complex to monitor without highly sophisticated computer software to decipher the signature. So far, for instance, attempts to use vibration monitoring on hydraulic equipment have not been particularly successful.

FERROGRAPHIC ANALYSIS.

Ferrography describes the process of depositing ferromagnetic particles on a laboratory slide and then viewing them under a microscope. Its use is limited to laboratory analysis from sample bottles due to its lack of portability. More often, owing to the high cost of analytical ferrography equipment, samples are sent to commercial labs where results can take several days to several weeks. Also, analytical ferrography is not a quantitative technique and does not assess the presence of non-magnetic particles, such as aluminum, brass, copper, and chromium. Analytical ferrography can, however, be very useful as a supplemental tool to localize faults and interpret wear processes, once the initial indication is given by contaminant monitoring.

SPECTROGRAPHIC ELEMENTAL ANALYSIS.

Spectrographic analysis has been used since World War II to establish and quantify the presence of wear metals and additives in lube oils and hydraulic fluids. There have been many conflicting studies regarding the usefulness and accuracy of spectrographic analysis. The doubters state that the technique cannot detect particles greater than 10 microns and no quantitative data regarding particle size and count can be determined. One study published in Lubrication Engineering Magazine involved over 150 used oil samples taken from industrial gear boxes, compressors, power transmissions, and hydraulic systems. It concluded that:

1. "High contamination levels in these systems contribute to higher levels of wear, accelerate the process of wear, and results in premature failure."
2. "By the time wear metals analysis alone [as opposed to contaminant monitoring] indicates an increase in wear, the abrasive process may be irreversible and the system may in fact be at the point of catastrophic failure."
3. "It is interesting to note that spectroscopic wear metal analysis results DID NOT CHANGE significantly [despite greatly improved filtration], however an overall reduction in total wear was

> achieved after several months of monitoring the system."

Still, another study showed that "spectrographic analysis did not predict the failure of oil-wetted components on aircraft." Amazingly, after analyzing an oil sample taken from an electric generator in another report, the spectrographic results indicated "no major problems." In fact, the sample had been taken from the engine AFTER catastrophic failure, a point at which exorbitant wear metal levels should have been detected.

System Monitoring Hierarchy

It has been stated that the fundamental purpose for contamination control and contaminant monitoring is to achieve greatly extended mean time between failures (MTBF), not damage control. However, when anomalous conditions are present, as first measured contamimetrically, further analysis using ferrography or vibration can identify the source of the problem.

For each application, three baselines are established. The first baseline is routine contaminant monitoring, which serves the major system monitoring requirements. It establishes the target cleanliness level, within which the desired extended machine life can be accomplished. The second baseline is set above the first on the contaminant level scale and represents abnormal conditions requiring further analysis. The author prefers ferrography as the means to localize and explain the source of the contamination.

In the example, a cylinder wiper seal failure is shown. This type of failure has no immediate operational performance effect but does result in abnormally high particle ingression. Once corrected, contaminant levels return below the first baseline, to normal. The second movement past the first baseline was determined to be a spent filter, which was replaced. In both cases, ferrography failed to confirm unusual wear debris levels, directing the trouble shooting elsewhere.

In some systems where vibration monitoring can be used, a third baseline is established. If contaminant levels proceed into this region and ferrography confirms abrasive or abnormal wear, then vibration analysis can be employed as a damage control technique. Other methods such as volumetric analysis or spectrograph analysis may be helpful as well. Once the problem component is identified, maintenance can be readily scheduled.

This system monitoring hierarchy should be customized to appropriate user and application requirements. It is designed to serve the combined needs of proactive and predictive maintenance to achieve the maximum savings possible. As a guide, the key to effective implementation is 90 percent planning and 10 percent doing. The author plans a follow-up article to fully describe the implementation strategy.

Summary and Conclusions

Proactive maintenance is presented as an important means to cure failure root causes and extend machine life. Fluid contamination control is established as an essential technique to implementing proactive maintenance. Substantial savings are cydraulic, bearing, engine, and gas turbine aponfirmed based on case studies involving hplications. Numerous examples of 10-fold maintenance cost improvements are given.

As opposed to traditional predictive maintenance, contaminant monitoring is cited as being key to achieving contamination control and proactive maintenance. A comparison of contaminant monitoring to other predictive techniques is discussed. It is concluded that contaminant monitoring offers the preferred "first defense" against mechanical failure, followed by ferrography and vibration monitoring.

Finally, it seems inevitable that future machinery include on-board contaminant sensors for real-time proactive maintenance and condition control. Expert system software combined with strategically located sensors and transducers (e.g., pressure, temperature, vibration, viscosity, wear debris, and moisture) will provide comprehensive machine health monitoring for the most sophisticated future machine applications.

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