WHITE PAPER

Condition Based Maintenance and Condition Monitoring

By: Andy Page

Principal Consultant

Contents

INTRODUCTION

When it comes to working on machinery in the plant, the old adage of 'If it ain't broke, don't fix it' comes to mind. Everyone agrees that we should not work on something until it needs to be worked on. The challenge is that everyone has a different definition of 'broke', so everyone has a different idea of when something needs to be worked on. Well, the first step in this process is to understand the current state of the machine. Once the current state is understood, decisions can be made about how to work on the machine and when to do so. This is called Condition Based Maintenance, or CBM. When organizations use CBM, they do not arbitrarily work on machinery just because a certain amount of time has passed. They constantly monitor the machinery and perform maintenance based on the condition of the machinery; which is to say, they perform maintenance when a defect has been detected in the machinery.

The defects are found through the use of inspections. Some inspections are performed via the use of the human senses; what we can see, hear, feel, smell, and even sometimes taste. Some inspections are performed via the use of measurement instruments like dial indicators, snap gages, and calipers. Both of these categories of inspections are called Preventive Maintenance (PM) inspections. Another style of inspection is called condition monitoring inspections, also known as Predictive Maintenance (PdM) inspections. Those in the PdM world prefer the term condition monitoring as this is the most correct term, but as PdM is extremely common, that works as well. The term predictive maintenance refers predominantly to the five technologies of vibration analysis, infrared thermography, oil analysis, motor circuit analysis, and ultrasonics. Each of these will be discussed in detail later in this paper.

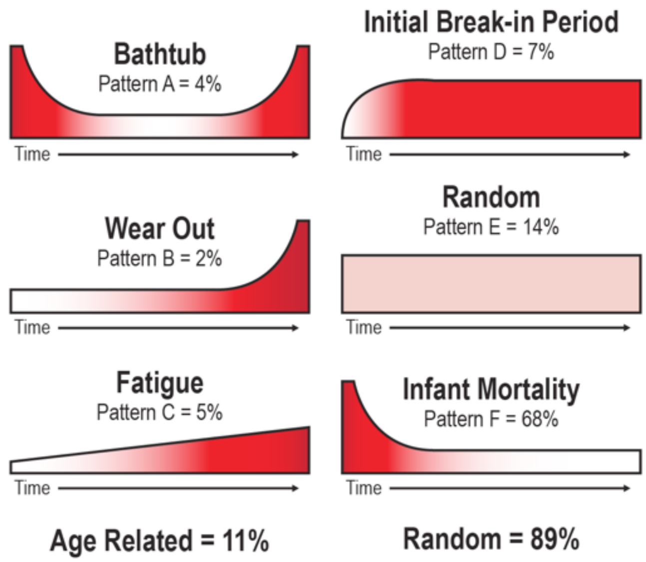
You may have noted in the previous paragraphs the term condition-based monitoring was not used. That is because there is no such term, not officially or correctly anyway. Though the term is used in industry, it is used incorrectly. There is no such thing as monitoring something based on condition. We use the monitoring to determine the condition. Therefore, the term condition-based monitoring is an oxymoron and should not be used.

WHY SHOULD WE PERFORM CONDITION MONITORING?

All maintenance and reliability programs have essentially the same goal: to effectively and efficiently ensure the plant's production capacity. As such, the most preferred way to affect the accomplishment of this is to be proactive about dealing with machinery defects. The reason for this is that we know that left to their own devices, these machinery defects will eventually cause a functional failure of the machine. So, the earlier we can detect the defect, the more time we will have to deal with the situation and not get the organization into an emergency state.

It should be noted that proactive is not binary in nature, meaning it is not an either/or condition. People are not only proactive or not proactive. Proactive should be seen as a continuum. So by their actions, people can be placed along the continuum with some people being more proactive than others. The definition of proactive then is to act before the business necessity of the situation demands it; stated

Figure 1. RCM Failure Curves from Nowlan and Heap



another way, proactive means to act before the cost of doing so increases.

This definition of proactive helps us understand the benefit of early defect identification and early defect elimination. If an organization can find and fix the defects early enough, the number of emergencies, and the number of schedule interruptions, will decrease drastically.

WHAT DO WE KNOW ABOUT MACHINERY FAILURES?

There is plenty of data in the reliability field that indicates the nature of equipment failures. Some of this data is old, but it still aligns with the new data being generated on a daily basis. What we know from the original Nowlan and Heap report (see Figure 1) on Reliability Centered Maintenance (RCM) is that only 11% of the failure modes for equipment are a function of time, while 89% of the failure modes are random. This means that a time-based replacement strategy, like traditional PM programs, is not sufficient to ensure the reliability of the asset base. An inspection-based program is required to combat the random failures.

We know that all inspection methods are not created equal. Some inspections can be done while the machine is running and some require the machine to be down; still others require the machine to be in some state of disassembly. When faced with the choice, inspections that can be done with the machine running are preferred over inspections that require the machine to be off. The running inspections are certainly preferred over those inspections that require some degree of disassembly.

Furthermore, some inspections find the defect low on the P-F Curve, requiring the organization to respond quickly, while other inspections find the same defect very high on the P-F Curve, allowing the organization ample time to respond. When faced with this choice, the organization should choose the inspection method that identifies the defect as high on the P-F Curve as possible. (For more information on the P-F Curve, refer to P-F Curve Thinking.)

The combination of these two parameters means the inspections that can be performed while the machine is running and identify the defect high on the P-F Curve are preferred over the inspections that require the machine to be off and identify the defect very low on the P-F Curve. When given a choice then, this builds a very strong case for the preference of PdM over PM for almost all failure modes.

WHAT ARE THE BENEFITS OF CONDITION MONITORING?

One of the major benefits of condition monitoring is that the technologies offer the organization a plethora of information about the nature of the defect and, to a large extent, information about the physical cause of the defect. This enables the organization to significantly enhance the effectiveness of the root cause analysis process and eliminate the possibility of this same defect occurring in the future. Condition monitoring gets its fame from being able to help the organization prevent unexpected failures. By finding the defects early, the organization can plan and schedule the outage and therefore not experience the surprise of machinery failure when least expected.

Another benefit of condition monitoring is the amount of specific information that the data from the technologies can provide the maintenance technicians about the nature of the problem. By using some of these technologies, specific defects are identified, such as 'inner race defects found on both pump bearing', instead of the general indication of 'pump making strange noise'. By and large, this reduces the troubleshooting time and costs associated with 'parts swapping until the problem is solved'. This also reduces the total amount of downtime for a repair, thus increasing availability and possibly even productivity.

Figure 2. P-F Curve

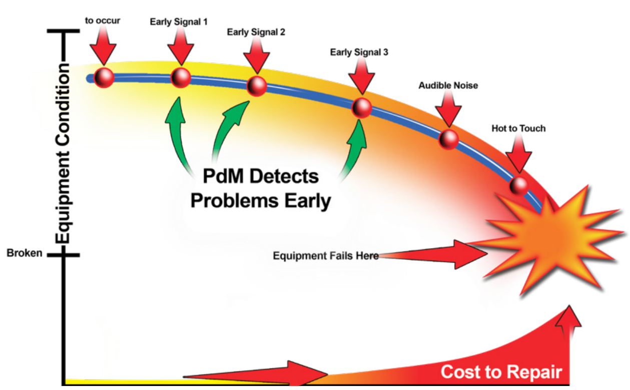
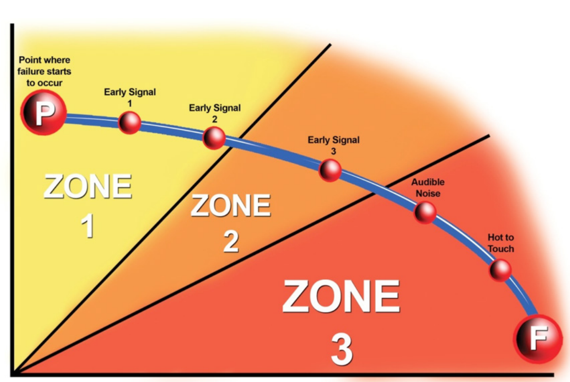


Figure 3. P-F Curve with Zones



Condition monitoring enables the planning and scheduling process in three ways. First, condition monitoring identifies the defects early enough to allow the planning and scheduling process to take its natural flow. Nothing has to be expedited or rushed, and production schedules do not have to be changed at the last minute. Second, it gives the planner something specific to plan. Because of how precise the problem can be pinpointed to, the planner can kit a specific collection of parts and have confidence that the required parts are there and the maintenance technicians will not have to stop the job to go find what they need. Third, the early detection of the fault means that more parts can be ordered and fewer parts have to be kept in stock.

While there are several benchmark case histories and success stories published in industry trade magazines, the specific list of benefits are almost universal. A typical list includes:

- Maintenance costs reduced by 50%
- Unexpected failures reduced by 55%
- Repair and overhaul time reduced by 50%
- Spare parts inventory reduced by 30%
- Mean Time Between Failures (MTBF) increased by 30%
- Machinery availability increased by 30%

P-F CURVE THINKING

The P-F Curve (Figure 2) is an artist's version of the fault progression of a defect. Point P is the point at which the defect enters the system and is detectable. Point F is the point at which the defect has created a functional failure. The nature of the fault progression is that the longer the defect remains, the more quickly it gets worse; thus, it is a curve and not a straight line. The defect gives off different signals along the way, and the

different PdM technologies are well suited to identify these signals as they change. As such, these signals help us identify the general location of the defect along its progression path. Knowing the location of the defect along its progression path helps the organization understand the severity of the defect and allows the organization to schedule their maintenance accordingly. While the specific location of the defect along the curve is next to impossible to determine, it is generally accepted that the defect severity can be placed into one of three zones, as shown in Figure 3.

CONDITION MONITORING TECHNOLOGIES

INFRARED THERMOGRAPHY

When it comes to implementing the PdM technologies, the first technology that should be implemented is infrared thermography. This technology is capable of finding both electrical and mechanical defects and it is very easy to understand and accept. Manufacturers of infrared cameras are now making low-cost solutions of adequate image quality that work great for infrared programs that are just getting started.

Just about any defect in electrical apparatus creates localized heating. This localized heating is easily detected with an infrared camera. For the most part, problems with electrical apparatus are almost always loose and/or dirty connections. Examples of this can be seen in Figure 4.

Infrared thermography is also very applicable for many mechanical defects as well. Defects like misalignment, v-belt and sheave problems, bearing defects, and lubrication problems all produce heat within the components. This heat is easily detected by the infrared camera. It should be noted though that infrared thermography is not the most preferred method for detecting mechanical defects as the defect is already significantly down the defect progression path before the localized heating begins to occur. Figure 5 shows some typical examples of mechanical defects detected by infrared thermography.

Figure 4. Infrared Thermography (Electrical) Example Images

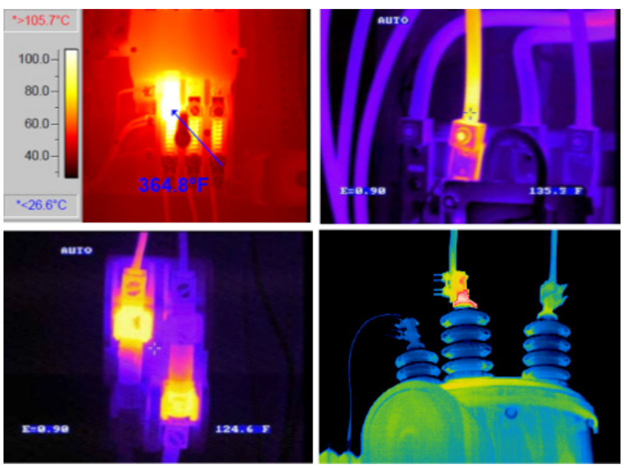
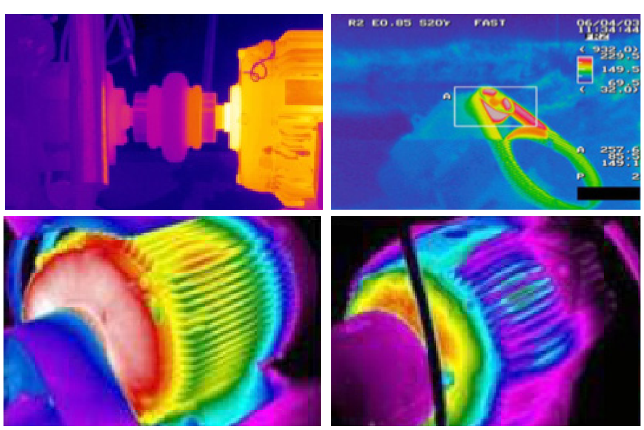


Figure 5. Infrared Thermography (Mechanical) Example Images



ULTRASOUND

The second PdM technology that should be implemented is ultrasound. This inspection method is both powerful and inexpensive.

Ultrasonic devices (Figure 6) are used to listen to rotating machinery, electrical apparatus, and stationary components. In rotating machinery, ultrasound can detect bearing faults, gear problems, electrical problems in motors, lubrication issues, and cavitation in pumps. In electrical apparatus, ultrasound can detect the presence of arcing, tracking, and corona. Arcing and tracking are both damaging to the electrical equipment and increase the potential for arc-flash. For stationary equipment, ultrasound is used to find defects in valves and steam traps. As mechanical inspection technologies go, ultrasound is the biggest bang for the smallest buck in the group of PdM technologies.

The device takes sounds that are above the range of human hearing and transforms those sounds into something we can hear. The main challenge with ultrasound is that the analysis is qualitative and is based on the trained ear of someone familiar with the ultrasonic signatures of healthy and unhealthy equipment. Another challenge with ultrasound is that while it is powerful in finding the high frequency problems, it is powerless against the low frequency problems like imbalance, misalignment, and looseness. So, ultrasound is not a like-for-like replacement for vibration analysis.

Figure 6. Ultrasonic Devices

Figure 7. Ultrasonic Assisted Lubrication

However, given its price, it is a very powerful addition to any PdM program, most especially when the organization wants operators, mechanics, and electricians to participate in the PdM program. These units cost between $2,000 and $20,000 depending on the options you select.

Perhaps the most powerful aspect of ultrasound is its ability to help improve the lubrication program. One of the most common problems with lubrication is the over/under lubrication of bearings. Ultrasound helps eliminate this problem. The ultrasonic energy coming from a bearing can help us determine whether the right amount of grease has been added to the bearing. See Figure 7 for some images of this device at work.

OIL ANALYSIS

Oil analysis is a very common PdM technology and one of the most commonly used as well. Oil analysis was originally used in the manufacturing world to detect water and the depletion rate of additive packages in the lubricant. Its use has since been expanded to include the detection of wear particles in the lubricant, as well as the presence of outside contaminants.

Oil analysis should be thought of as a three-pronged technique. One aspect of oil analysis is tests that detect changes in the lubricant chemistry. Another aspect of oil analysis is the detection of wear particles that indicate defects in the components that the lubricant is there to service. The final aspect of oil analysis is the detection of contaminants from outside of the lubrication system, indicating a sealing problem or poor storage and handling practices.

There are several tests for each of the aspects. The best oil analysis program identifies the reasonable and likely failure modes for each of the machines that qualify for the oil analysis program and then specifies to the oil lab which tests are to be run for which samples. This declaration of tests for a given sample is called a test slate. The test slate will vary not only based on the asset/component type, but also depending on the operating environment and operating context specific to the asset/component. For example, the test slates are not the same for all pumps as some pumps operate in different environments and under different running conditions.

Figure 8. Vibration Data

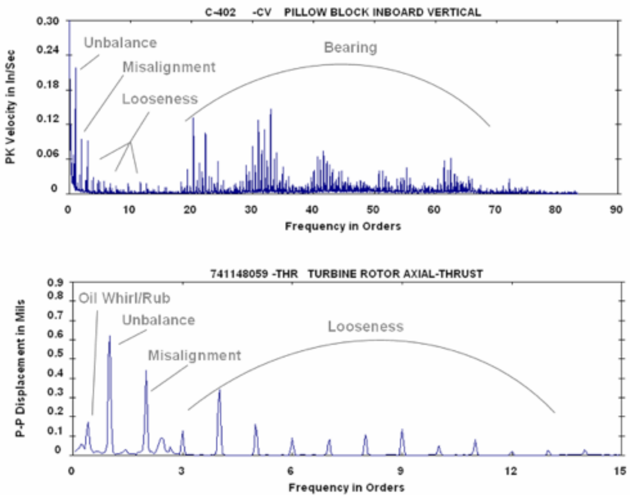
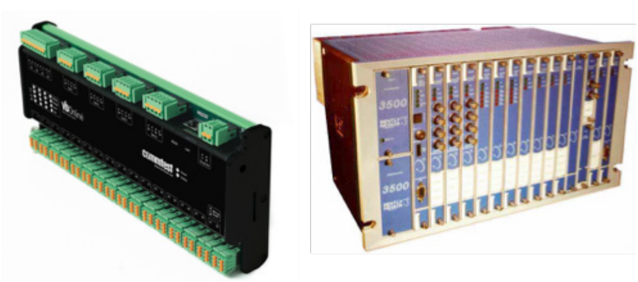


Figure 9. Portable Vibration Data Collectors

Figure 10. Continuous Vibration Data Collection Systems



VIBRATION ANALYSIS

By far, the most powerful PdM technology for rotating equipment is vibration analysis. While there are some problems with rotating equipment that vibration analysis cannot detect, it stands alone as the most comprehensive method for detecting defects in rotating equipment.

The vibration signature (Figure 8) is collected from a rotating machine and then analyzed by a person. The signature is a collection of spikes called peaks. These peaks represent different forces at play on the rotating drive train. The analysis of the peaks is the linking of their frequency to the known frequency of rotating drive train defects. For example, shaft misalignment happens at a different frequency than gear problems do, or bearing faults, or even electrical problems in motors. Each of these has their frequencies, and each has their own patterns in the vibration signature.

The data can be collected via different devices. Some are hand-held devices (Figure 9) that are carried from machine to machine during data collection, while some are permanently installed devices that connect to the PLC network in the plant and provide continuous monitoring (Figure 10).

MOTOR CIRCUIT ANALYSIS

The motor circuit includes the motor windings as well as the wires that connect the motor to the starter. The entire circuit is tested to detect the presence of insulation problems, contamination problems, and other mechanical issues with the motor.

Motor Circuit Analysis (MCA) falls into two categories: offline and online. Offline MCA is performed when the motor is off and the rotor is secured in place. These offline tests help the analysts detect any insulation issues between the three phases of the motor, as well as any issues between the phases and the electrical ground of the motor. Online MCA tests for the presence on any torsional loading on the motor. Most torsional loading on the motor comes from inside the motor due to loose or broken rotor bars or broken welds on the end ring of the rotor. However, some torsional loading can come from outside the motor, such as misalignment, coupling problems, or in extreme cases, even bearing faults.

COMBINING TECHNIQUES USING CRITICALITY RANKING

It is a common misconception that the criticality of the machine in some way influences the inspection frequency of the machine. This is not the case. The inspection frequency is a factor of the length of the P-F Curve for the failure mode in question. However, the criticality of the machine does affect the number of technologies that are applied to a given failure mode. The technologies are inspections for certain failure modes. The more critical the machine and the more critical the failure mode, the more redundancy the organization will want in the inspections. For the most critical machines, the organization may elect to have as much redundancy as they can get. This style of thinking means that for the top 20% of the machines on the criticality list, there may be four or five different PdM technologies covering the machine. For the next 30%, the organization may elect to have the two best PdM technologies for each failure mode. For the balance of the list for PdM coverage, the organization may elect to have only one PdM technology for each failure mode.

PROACTIVE WORKFLOW MODEL – HOW MUCH CONDITION MONITORING SHOULD WE BE USING?

The Proactive Workflow Model (Figure 11) helps an organization understand how much PdM the group should be doing and how PdM should balance with PM. For the organization to effectively be ahead of the emergencies created by machinery failures, 80% of the work conducted by the maintenance department should come from the PM and PdM programs.

The PM program should consume about 15% of the maintenance labor. This does not mean that 25% is better than 15%. No, PM should be 15%, +/- 3% only. The corrective work that is generated by the PM inspections should consume another 15% of the maintenance labor. An additional 15% of the maintenance labor should be consumed by the PdM inspections. The corrective work that comes from the PdM inspections should consume 35% of the maintenance labor.

These percentages represent a healthy balance of PM and PdM and ensure that the organization is identifying the work correctly and early enough to make a difference.

KEY PERFORMANCE INDICATORS FOR CONDITION MONITORING

The PdM Program Design infographic (Figure 12) provides the essential key performance indicators for any PdM program.

COVERAGE MODEL

First, the organization has to ensure that enough machinery is being monitored with PdM to actually

Figure 11. Proactive Workflow Model

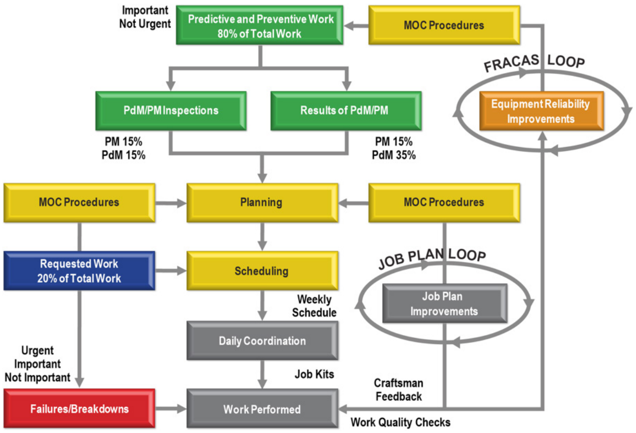
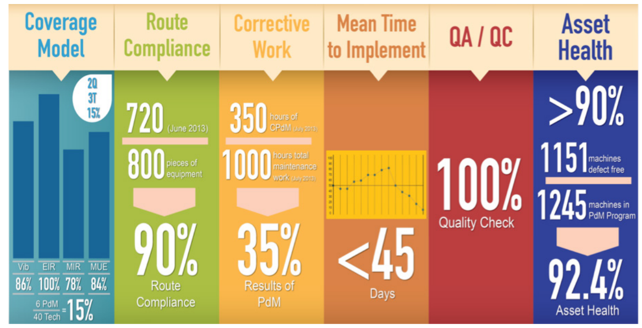


Figure 11. PdM Infographic



create a shift in machinery availability. The organization should be targeting 2nd quartile coverage on at least three technologies, and this level of effort should consume about 15% of the maintenance labor.

Second, quartile coverage should be greater than the following numbers for each technology:

- 60% - Vibration analysis and mechanical ultrasound
- 52% - Infrared thermography (mechanical)
- 86% - Infrared thermography (electrical) and electrical ultrasound
- 30% - Oil analysis
- 30% - Motor circuit analysis

For example, a facility has 1,845 rotating machine trains, and vibration analysis could be applied to all of them. The organization wants to employ vibration analysis, so they should cover at least 60% of those 1,845 rotating machine trains with vibration, or 1,107 machine trains. The selection of which rotating machine trains are to comprise the 60% is based on the machinery criticality ranking index, which is to say, the most critical machines first.

The organization also wants to use infrared (electrical) and MCA as their other two technologies to satisfy the three-technology requirement. An assessment revealed the plant has 4,613 electrical items such as breakers, starters, fused disconnects, transformers, etc., so the infrared (electrical) program should cover 3,967 of those items, all selected in criticality order. The site has 1,845 motors, so the MCA program should have 554 motors on route for quarterly and semi-annual inspections, also selected based on the criticality ranking.

ROUTE COMPLIANCE

Now that the routes have been created, the data must be collected. The metric to ensure that this is being done is route compliance. Route compliance is the number of components that had data collected and analyzed divided by the number of components that were scheduled for data collection and analysis. This number should always be greater than 90%.

CORRECTIVE WORK

The analysis of the collected data should produce corrective work. If the organization is spending 35% of its maintenance labor correcting the defects identified on the PdM routes, there should be a significant decrease in the amount of emergency work.

MEAN TIME TO IMPLEMENT

It is not enough that the work is being completed; the work has to be completed quickly enough to make the proactive difference. As such, the average time for a defect to be corrected should be less than 45 days since it was first detected. This will ensure that the organization is being proactive enough to make the difference that the program is intended to make.

QA/QC

The work is not complete until the PdM technician that found the defect says it is complete. Just because the maintenance technicians say they fixed it does not ensure that the defect has been removed and there are no other problems.

With this in mind, anytime maintenance technicians say a job is complete, the defect should not be retired until the PdM technology that found the defect originally verifies the elimination of the defect. This workflow process ensures that the defects are being effectively eliminated; it also ensures that any craft skills issues are brought to light.

ASSET HEALTH

No program is successful unless it produces the desired effect. No PdM program is successful unless the number of machines in the plant running defect free gets over 90% and stays there.

This is where the metric of Asset Health enters the picture. Asset Health is a leading indicator of both maintenance costs and equipment availability. A plant with an Asset Health of 54% will have higher maintenance costs and lower equipment availability next month than a similar plant with an Asset Health of 92%, guaranteed. Asset Health is the goal of the PdM program; everything else is icing on the proverbial cake.

WHY MOST CONDITION MONITORING PROGRAMS FAIL

There are many reasons why condition monitoring programs fail. Most immediately, we can look at the metrics in the previous section; when these metrics are not enforced, failure is a definite possibility. But, to be more specific, we can discuss other reasons as well.

LACK OF STANDARDS:

To be effective and efficient, PdM should be the full-time job of the PdM technicians. As such, they should be both certified and qualified.

Certified means they attended a series of classes and passed a written and practical test to demonstrate their expertise.

Qualified means they have an adequate amount of practical experience. Asking people to perform PdM part time is like asking a professional chef to work on your car – while they may know a little, it is not their area of expertise.

INCORRECT HARDWARE AND SOFTWARE:

Software and hardware have to be up-to-date. Many programs have gear that was purchased 15-20 years ago and it is antique by modern standards. The technology progresses as the years pass. Good programs stay up-to-date on both the hardware and the software, as well as the training that goes with them.

SUCCESS NOT TRACKED AND BROADCASTED:

Like any change, the successes at first are hard fought. These successes, if tracked and broadcasted, can provide positive press within the organization. This positive press makes the next technical or political battle that much easier to fight. Enough successes and the change effort begins to develop its own momentum.

PDM NOT USED FOR TROUBLESHOOTING OR TO COMMISSION REPAIRS:

These technologies are very powerful. They are applicable not just for route-based inspections. They are applicable for troubleshooting and for commissioning repairs. Organizations that embrace the power of these technologies begin to find new and inventive ways to apply them. These technologies can drastically improve the troubleshooting process and cut the total repair time down significantly. Errors made during maintenance can be caught before the machine is given back to operations, which tends to make everyone happy at the same time.

SUMMARY AND CONCLUSIONS

Predictive maintenance is the use of vibration analysis, ultrasound, oil analysis, infrared thermography, and motor circuit analysis to identify the presence of defects in industrial equipment. This identification makes condition based maintenance more easily attainable. By using the technologies to identify the defects, the organization can make better decisions on what to fix and when.

Predictive maintenance inspections help the organization become proactive. The PdM technologies identify defects early in their fault progression cycle. This early identification empowers the planning and scheduling process by providing specific information about the defect early enough to make the planning process easy, and the scheduling process even easier. The PdM technologies help eliminate unnecessary troubleshooting by providing the maintenance technicians with specific information about the nature of the defect.

If an organization wants to see a step change in machinery availability, the use of the PdM technologies can go a long way in making that goal a reality.

Contact us

Global Headquarters

10344 Sam Houston Park Drive, Suite 110

Houston, TX 77064

www.alliedreliability.com