EFFECTIVE CONDITION MONITORING

AN INTRODUCTION TO DESIGNING, IMPLEMENTING, AND MEASURING A SUCCESSFUL CONDITION MONITORING PROGRAM

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INTRODUCTION

When it comes to working on machinery in the plant, the saying 'If it ain't broke, don't fix it' comes to mind. In other words, don't 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. From the perspective of reliability, a machine is broken as soon as a defect enters the system that will lead to a functional failure and potentially a catastrophic failure.

A process is needed to understand the current state of the machine and to detect the presence of a defect in a system. Once the current state is understood, decisions can be made about how to work on the machine and when to perform this work. This approach is called predictive maintenance (PdM). When organizations use CBM, they monitor the machinery and perform maintenance based on its condition, which is to say, they perform maintenance when a defect has been detected in the machinery.

The defects are found using various inspection techniques. Some inspections are performed via the use of the human senses; what one can see, hear, feel, smell, and even sometimes taste. Some inspections require the use of measurement instruments like dial indicators, snap gages, and calipers. Both of these types of inspections are part of an interval-based or preventive maintenance (PM) program. Another style of inspection uses condition monitoring technologies, which refers primarily to vibration analysis, infrared thermography, oil analysis, electric motor testing, and ultrasound. Each of these five methods will be discussed in detail later in this paper.

WHY PERFORM CONDITION MONITORING?

All maintenance and reliability programs have essentially the same goal: to maximize the value of a plant's equipment and processes. The best way to do this is to be proactive in dealing with machinery defects because, if left alone, defects will eventually cause a functional failure of greater proportion. The earlier a defect is detected, the more opportunity there is to deal with the situation and avoid any disruption in normal plant operations.

Condition monitoring technologies are a proven way to identify machinery defects at a very early stage. This provides the benefit of time, making it possible to plan, obtain spare parts, organize, and address the situation when it is most convenient for the organization. Early defect identification not only allows early repair of equipment, but it also reduces the number of emergencies, breakdowns, and schedule interruptions encountered.

It should be noted that condition monitoring alone will not improve reliability. Condition monitoring is the process of *testing and analyzing* data that pertains to the condition of a system or machine. The data must be acted on to receive the full benefits of condition monitoring – ultimately achieving better reliability and improving the plant's overall performance.

WHAT ARE THE BENEFITS OF CONDITION MONITORING?

Condition monitoring technologies offer a plethora of information about the nature and physical root cause of a defect. This information significantly enhances the effectiveness of the root cause analysis process and eliminates the possibility of the same defect occurring in the future. Condition monitoring gets its recognition from helping to 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.

Condition monitoring also provides specific information about the problem. such as 'inner race defect found on the pump bearing,' instead of the general indication of 'pump making strange noise.' This reduces the troubleshooting time and costs associated with traditional parts swapping until the problem is solved. It also reduces the total amount of downtime for a repair, thus, increasing availability and possibly even productivity.

Condition monitoring improves the planning and scheduling process in three ways. First, it identifies the defects early enough to allow the planning and scheduling process to take its natural flow. Nothing needs 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 the problem can be precisely pinpointed, the planner can kit a specific collection of parts and have confidence that the required parts are present, and the maintenance technicians will not have to stop the job to go find what they need. Third, early detection of the fault means that more parts can be ordered, and fewer parts need to be kept in stock.

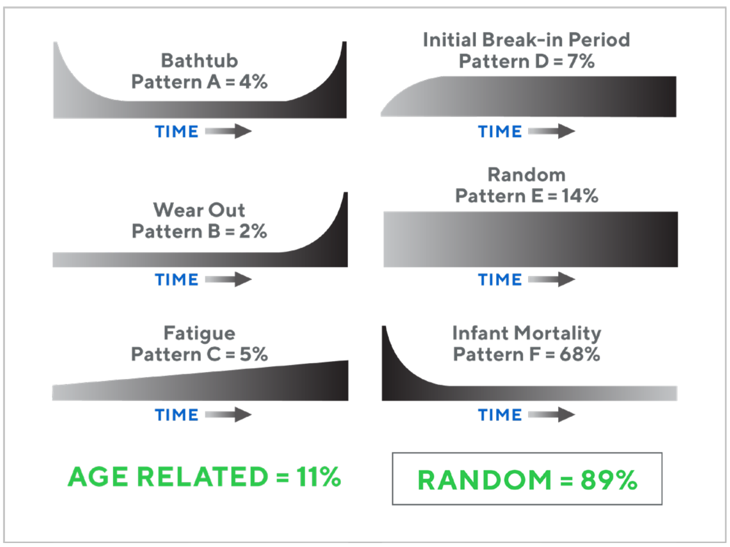
While there are several benchmark case studies and success stories published in industry trade magazines, the list of benefits is almost universal. A typical list includes the following claims:

- 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%

WHAT IS KNOWN ABOUT MACHINERY FAILURES?

There is plenty of data in the reliability field that indicates the nature of equipment failures. Experience and analytics prove that the nature of failures has not really changed much over the last several decades. The original Nowlan and Heap report on failure modes and probability of failure illustrates this point precisely. After studying failure modes and comparing the age of parts with the probability of failure, Nowlan and Heap came up with the six different failure patterns, shown below.

FAILURE PATTERNS

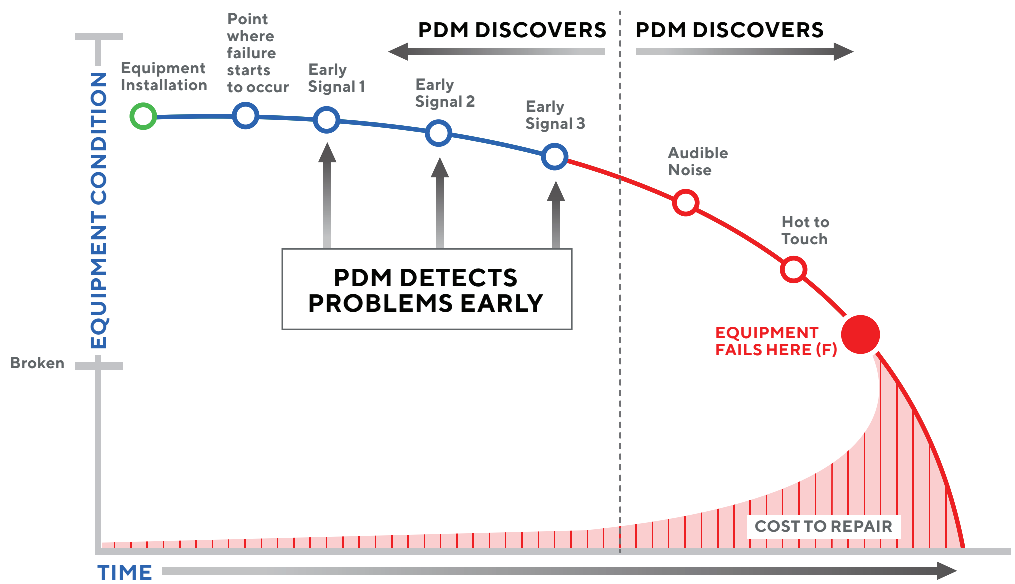


AGE VERSUS PROBABILITY FAILURE CURVES FROM NOWLAN AND HEAP

The biggest takeaway from this study is that only 11% of the failure modes for equipment are a function of time, while 89% of the failure modes do not have any relationship to the age of the component or part. This means the bulk of the failure modes that occur are random in nature and a time-based replacement strategy, like traditional PM programs, is not sufficient to ensure the reliability of the asset base. In fact, using a traditional PM program to address random failures can often lead to over-maintaining a machine, reduced reliability due to infant mortality failures, and excessive costs as parts are used at a higher rate and good parts are often discarded. This builds a very strong case to deploy condition monitoring over a traditional PM program to combat random failure modes.

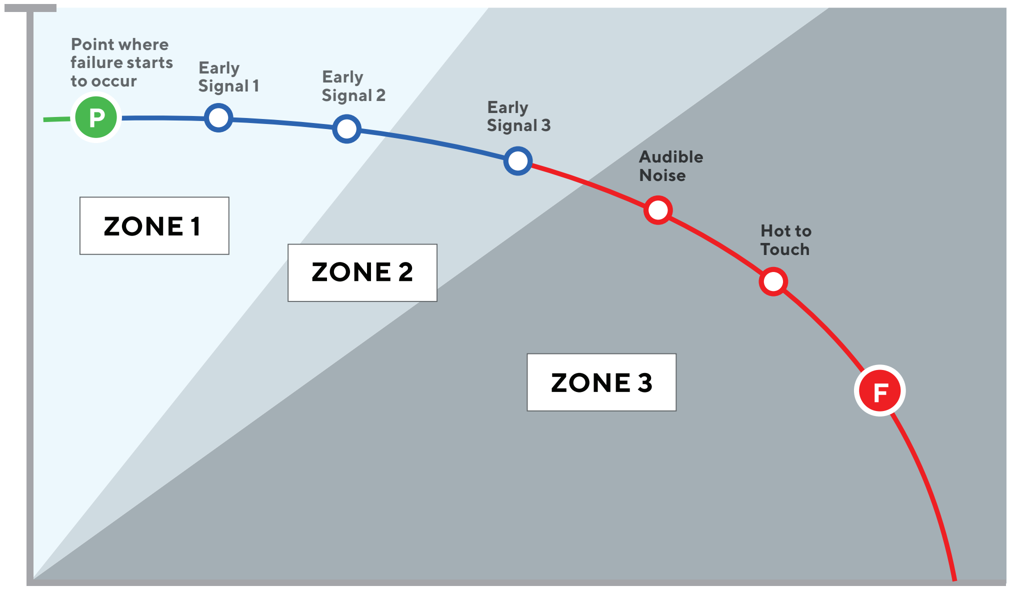
P-F CURVE THINKING

The P-F Curve is the foundation of a condition monitoring program, showing the fault progression of a defect. Allied Reliability's version of the P-F Curve is expanded to include Point I – the point at which the equipment is installed or returned to service after a repair. The distance from Point I to Point P represents long and trouble-free operation of the equipment. Point P is the moment in time when a defect has entered the system and damage has started to occur to a piece of machinery. Once Point P is passed, there is no going back; the equipment will start its march to the point of functional failure (Point F). During this time, the condition of the machine will start to degrade, and the rate of degradation will accelerate the longer the equipment continues to operate. Fortunately, equipment will give off warning signs that there is a problem, and the condition monitoring technologies are designed to measure these early signals so that the defect can be identified as soon as possible.



I-P-F CURVE

As the condition worsens, additional signals will be generated, helping to identify the general location of the defect along its progression path. Knowing the location of a defect along this path helps the organization understand its severity and allows maintenance to be scheduled accordingly. While the exact 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.



P-F CURVE WITH DEFECT SEVERITY ZONES

Thus, condition monitoring data can be used to determine not just the severity of the defect, but the priority that should be given to the work request for repair.

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 ample time to respond. When faced with this choice, the inspection method that identifies the defect as high on the P-F Curve as possible would be recommended.

Finally, as the machine degrades, there is secondary damage to the equipment and systems, which means that the longer one waits to perform maintenance, the higher the cost of the repair will be due to the need to replace or rebuild additional parts.

A good example of this is misalignment. If a misalignment is detected and repaired early, the cost to repair is about two hours of craftsperson time and a handful of shims, and it can be performed on a scheduled downturn so that production is not interrupted. If the machine continues to operate in a misaligned condition, it will put additional stresses on bearings, couplings, shafts, and seals, resulting in premature failure of these parts. Now the repairs involve replacing motors, couplings, and driven components, which will take much longer and often cause a catastrophic failure in the middle of a production run, resulting in unplanned downtime and lost production.

Therefore, the goal should be, “Find it early. Fix it early.”

CONDITION MONITORING PROGRAM OVERVIEW

While the focus of this paper is on condition monitoring technologies, it is important to note that technology alone will not improve reliability. There are several elements that need to be addressed before starting a condition monitoring program to ensure its success.

These foundational elements include a complete asset catalog, meaning that everything that is out on the plant floor is also listed in a database. There are several Computerized Maintenance Management Systems (CMMS) available on the market that can house this database, but the key thing to remember is that the list of equipment in the system must match the actual equipment in the plant.

Second, a criticality ranking needs to be performed according to:

- What equipment is most important to the process
- What equipment will cause the greatest disruption
- What equipment has the potential to adversely affect safety or the environment
- What equipment could delay delivery of goods or services to the customer

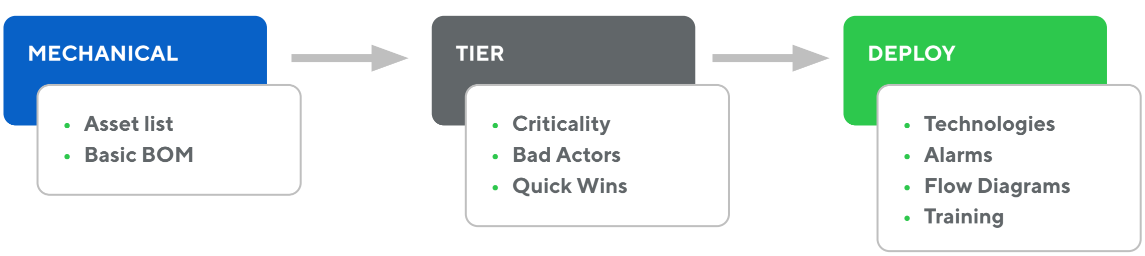
Utilizing this ranking will ensure that condition monitoring technologies are deployed to the correct pieces of equipment to provide the greatest benefit to the organization.

Third, inspections must be deployed to detect or prevent a failure mode. A reliability tool that produces an optimized asset strategy, such as Reliability Centered Maintenance (RCM) or Failure Mode, Effects, and Criticality Analysis (FMECA), will need to be used to identify machinery failure modes and the proper technology to detect those failure modes at the earliest stage on the P-F Curve.

EQUIPMENT TYPE VS. TECHNOLOGY APPLICATION(S)	MECHANICAL				ELECTRICAL					
	Vibration	Mechanical IR	Mechanical Ultrasound	Lubrication Analysis	Electrical IR	Electrical Ultrasound	MCA On-Line	MCA Off-Line	Partial Discharge Testing	SF_6 Testing
	273	276	300	263	269	269	406	137		
Substation Grounding Grid System						X			X	
LV MCC					X	X	X	X		
MV Motor Starter					X	X	X	X	X	
MV Cable					X	X	X	X	X	
MV Vacuum Circuit Breaker					X	X	X	X	X	
751A Protection Relay					X	X				
HV SF6 Circuit Breaker					X	X		X	X	X
HV SF6 Circuit Switcher					X	X		X	X	X
Rotary Controlled Ball Valve			X				X	X		
MV Switchgear with Vacuum and Contact Breakers				X	X	X	X	X	X	
Sump System			X	X	X		X	X		
138KV-4KV Oil Transformer				X	X	X	X	X	X	
MV Oil Transformer				X	X	X	X	X	X	
Tanker Mixer	X		X	X	X	X	X	X		
Uninterruptible Power Supply					X	X	X	X		
VFD	X				X	X	X	X	X	
Building Fan	X	X	X		X	X	X	X		
Declassification Fan	X	X	X		X	X	X	X		
Emergency Diesel Generator	X	X	X	X	X	X	X	X		

EXAMPLE OF EQUIPMENT TO CONDITION MONITORING INSPECTION MATRIX

Pareto Analysis can also be used at this junction to identify bad actors as a starting point for a condition monitoring program.



PROGRAM DEVELOPMENT FLOWCHART

Reliability programs also need people to be successful. Training and communication of program goals are essential to attain buy-in for applying these technologies. Analysts also need to be properly certified in their respective technologies.

It is important to also have a Work Execution Management (WEM) process in place to deal with the new work requests that will be generated from the implementation of condition monitoring. An organization needs to be able to perform repairs in a timely manner, so that the defect identified today does not end up as tomorrow's catastrophic failure.

Deployment of the technologies should not be done all at once. Experience has shown that condition monitoring is better when deployed in stages. These stages are called quartiles and help prevent overloading the WEM process as defects are identified and work requests are generated.

EXAMPLE OF QUARTILE COVERAGE MODEL

COVERAGE	VIBRATION	UE	ELECT IR	MCA OFFLINE	MCA ONLINE	OIL ANALYSIS	IR MECH	UE ELECT	PARTIAL DISCHARGE
100% Theoritical	100%	100%	100%	100%	100%	100%	100%	100%	100%
"Best Practice" 1st Quartile	92%	64%	100%	64%	64%	38%	71%	100%	100%
2nd Quartile	69%	50%	88%	50%	50%	30%	52%	88%	88%
3rd Quartile	42%	36%	80%	36%	36%	20%	35%	80%	80%
4th Quartile	26%	22%	69%	22%	22%	11%	15%	69%	69%

Mech – Mechanical UE – Ultrasound Emissions IR – Infrared Thermography
Elec – Electrical MCA – Motor Circuit Analysis

Note that most condition monitoring technologies do not reach 100% coverage to attain what is considered "best practice." The reason for this is that during the criticality assessment, there will be equipment deemed as not critical enough to justify the cost of monitoring. These assets will then be shifted into a strategy called "run to failure." It is important to differentiate "run to failure" from "reactive maintenance." Reactive maintenance means that when a failure occurs, the equipment needs to be restored to operational function as fast as possible, and it is considered an emergency in the plant. A run to failure strategy means due diligence was done, and a failure was found that does not warrant an emergency because it does not pose a significant consequence to the facility.

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 designed for certain failure modes. The more critical the machine and the more critical the failure mode, the more redundancy the organization will want in their inspections. For the most critical machines, the organization may elect to have as many redundancies 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 condition monitoring technologies covering the machine. For the next 30%, the organization may elect to have the two best technologies for each failure mode. For the balance of the list, the organization may elect to have only one condition monitoring technology for each failure mode.

CONDITION MONITORING TECHNOLOGIES

INFRARED THERMOGRAPHY

Infrared (IR) thermography is used for both mechanical and electrical applications and is one of the most diverse and widely accepted condition monitoring technologies in the market today. Thermography is the study of radiated thermal energy, and these tools measure that energy. Thermal detection devices do not measure temperature, rather they calculate temperature based on the detected thermal energy and several other factors. Therefore, absolute temperature readings are not as important as relative or comparison temperature measurements.

IR Thermography Inspection Applications

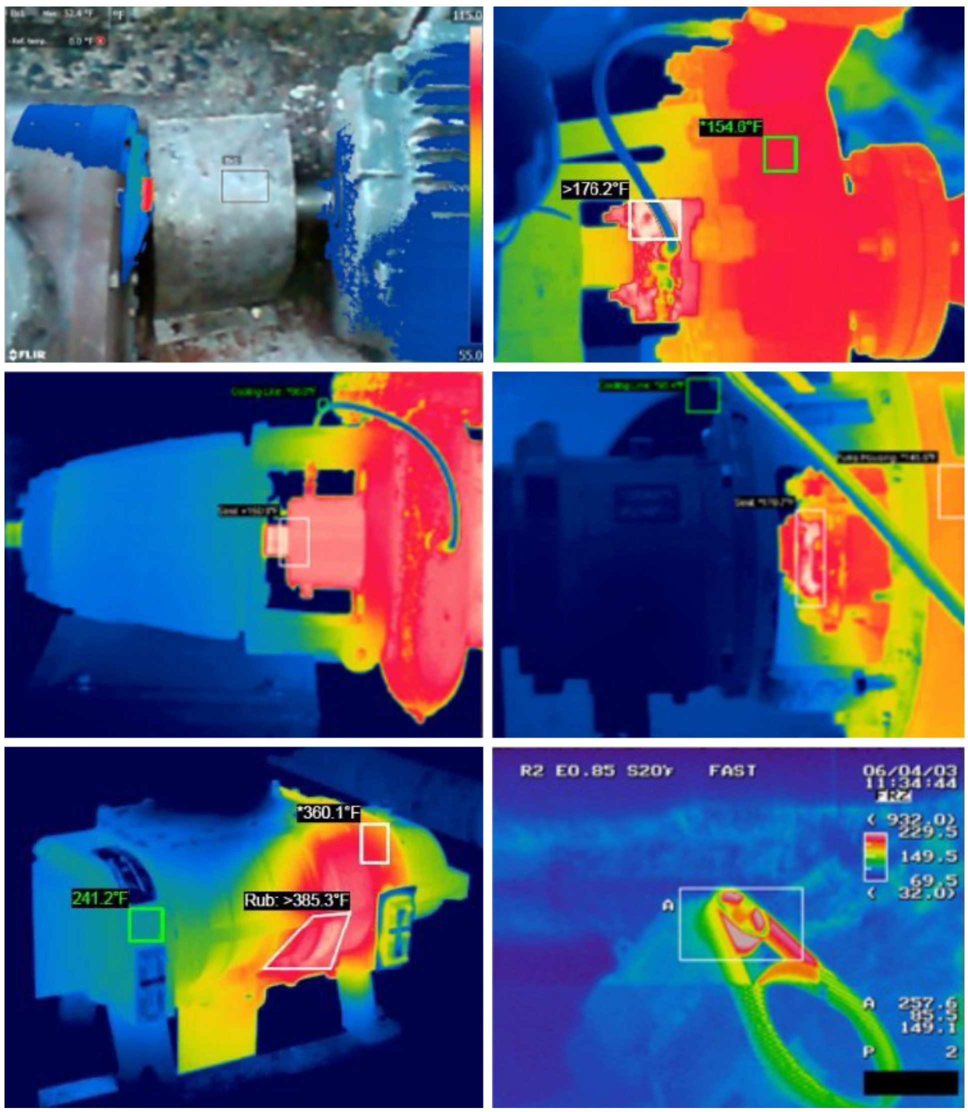
MECHANICAL IR THERMOGRAPHY

When using thermography on mechanical systems, an effective approach is to focus on elements of the systems, such as seals, lubrication points, cooling systems, and powertrain systems (belts, chains, and couplings). Understanding the inherent operational ranges of the parts, as well as the basic principles of thermodynamics, allows for a quantitative, trending approach based on a visual display of each system. Monitoring the assemblies/parts of a mechanical system that can lead to conditions that produce the widest range of faults can be utilized to support a "whole machine" maintenance reliability approach.

Mechanical IR thermography is assessed via a difference in thermal profiles and/or a concentrated heat differential, defined as a difference in temperature compared to a 'normal' baseline or to 'adjacent' parts of the same or other components.

- **Normal** – This is the normal operating thermal profile of the machine, a.k.a. baseline. The baseline temperature is defined as the measured thermal profile of the machine while operating within its design parameters.
- **Adjacent** – Thermal anomalies may also be defined as differences in thermal profiles:
    - Across the same component, for example:
        - A double spherical roller bearing in a non-fixed (floating) application may be experiencing a high thrust load and will, therefore, have a temperature change across the bearing housing.
        - Shaft misalignment can manifest itself in the thermal profile of the coupling. One side of the coupling may be hotter than the other, or there may be a localized hot spot in the middle of the coupling.
    - Between components on the same machine train, for example:
        - In a shaft misalignment condition, it is reasonable to expect the shaft end motor bearing and the coupling side pump bearing to both show elevated temperatures.
        - Sheave misalignment can often be seen across a multi-belt drive as the belts on one side being hotter than the belts on the other side.

- Between like components in similar applications, for example:
  - Identical motors in similar loading conditions in the same ambient conditions should both show the same thermal profile. A difference in profiles is an indication of the presence of an unacceptable condition or a component defect.
  - For a bank of pumps with identical seal designs, the temperature of the seals should be uniform. One seal being hotter than its counterparts would be an indication of a problem.



IR THERMOGRAPHY EXAMPLES

ELECTRICAL IR THERMOGRAPHY

Electrical IR thermography is utilized on all accessible power control or switching equipment. The nature of an electrical connection, whether a termination, contact closure point, or joining splice, is that heat generation is a function of the amount of resistance across such connection. As the resistance increases, the overall temperature increases. The resulting temperature increase will result in decreased operational life on parts, such as starter contacts and springs, disconnect switch assemblies, circuit breaker trip mechanisms, and fuse holders. Utilizing thermography to assess both the source of the elevated thermal pattern and the associated parts or circuits presents the opportunity for proper planned and scheduled maintenance activities and greatly reduces the risk for any operational disruptions.

Electrical IR thermography can be used to inspect the following areas and components:

- Overhead Cutout Switches
- SF6 Switches or Breakers
- Bolted or Compression Line Connections
- Stress Cone Connections
- Oil-filled Transformers
- Dry Transformers
- Potential Transformers
- Isophase Bus
- Tubular Bus
- Oil-filled Circuit Breakers and Voltage Regulators
- Switchgear
- Motor Control Cabinets (MCC)
- Station Surge Protection
- Distribution and Lighting Panels
- Disconnect Switches
- Batteries

Frequency

MECHANICAL IR

Best practice frequency for mechanical IR is quarterly if combined with vibration analysis, or monthly if used as a standalone monitoring technology.

ELECTRICAL IR

Best practice frequency for electrical IR is quarterly.

ULTRASOUND

Airborne/structureborne ultrasound is a predictive maintenance/energy conservation technology used to locate leaks, detect electrical emissions, and inspect mechanical conditions in operating equipment. Ultrasound inspections detect sound emitted from mechanical and electrical sources above 20 kHz. The short-wave period component (20,000 cycles per second) from high-frequency emissions of ultrasonic waves tends to be directional and localized, allowing them to be easily separated from noisy background plant noises. The separation of sound wave is made possible due to the limits of the human ear, which has a high-frequency threshold of 16.5 kHz. The most utilized component of ultrasonic detection is through air leak surveys, and this strategy can pay for itself quickly (i.e. a single ¼" dia. leak in a 100-psig compressed air system running 24/7 can cost a plant $16,744 annually in added electrical costs), but there are additional ways to utilize this technology to compound cost savings.

Ultrasound Inspection Applications

MECHANICAL

Defects on rotating machines produce a broad sound spectrum and are usually monitored by vibration in low frequency. However, some specific defects actually produce high-frequency vibration and sounds in their early stages, such as: impacting for bearings and gearboxes, friction or rubbing for lubrication, and cavitation for pumps. The use of ultrasonics allows one to hear these high mechanical frequencies. Since ultrasonic detection systems only 'hear' sounds above 20 kHz, it is very easy to detect these high-frequency sounds, even in a noisy environment. This makes ultrasound technology an excellent and sensitive method to highlight these defects at an early stage.

Ultrasound acoustical emissions technology is capable of detecting defects in both low- and high-speed equipment at an early stage.

Typical mechanical equipment/components to be inspected include:

- Drive Belts
- Couplings
- Bearings
- Gearboxes
- Chains
- Valves
- Pumps
- Tube Condensers
- Heat Exchangers

When performing mechanical inspections, depending on the application (equipment/component being inspected), a scanning module or a contact module can be used for the survey. Analysis of wave data in Fast Fourier Transform (FFT) and time domain spectrums offer failure mode identification and trending.

LUBRICATION

Lubrication is often a cause of failure in plant facilities, and in fact over lubrication is responsible for more faults than under lubrication. This is due to the incorrect assumption that if a little grease is good, then more grease must be better.

Ultrasound provides the ability to 'hear' friction, which has launched reliability centered lubrication. Using this technology and trending the sounds from a rolling element bearing, it is now possible to detect when a bearing is in need of lubrication and exactly how much lubricant to add to the bearing.

ULTRASONIC-ASSISTED LUBRICATION

STATIONARY

One of the most common applications for airborne ultrasound is compressed gas leak detection. Leaks are often heard with the naked ear but are difficult to pinpoint because of background noise. An ultrasonic detector can differentiate leak turbulence through ambient noise. While slightly more difficult to detect, ultrasound can also be deployed in a similar manner to find leaks in vacuum systems.

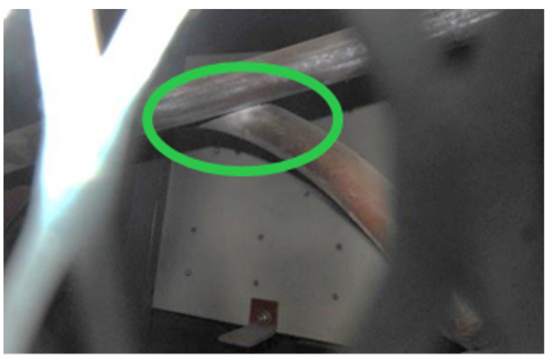
Ultrasonic inspections of the entire steam system will reveal system leaks, blockages, stuck valves, and failed traps. When performing steam system inspections, the contact module should be used for data collection.

ELECTRICAL

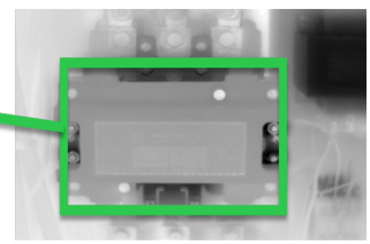
Arcing, tracking, and corona discharge emit ultrasound at the source of the defect/problem. The use of ultrasound detection instrumentation is ideal for identifying the presence and location of such discharge. High-, medium-, and low-voltage electrical equipment all benefit from ultrasound inspection. Within high- and medium-voltage equipment, a greater potential for catastrophic failure occurs in equipment of 1000V or greater. In equipment below 1000V (low voltage), arcing is the main concern. Although arcing is usually accompanied by heat, an IR thermography inspection will not always detect arcing in covered equipment. In these cases, arcing can be heard through air vents and other enclosure cover openings, making the combination of ultrasound and IR inspections very effective.

Electrical ultrasound inspections can detect and identify anomaly conditions and general safe access concerns. Typical electrical equipment/components to be inspected include:

- Transformers, Oil and Dry
- Substations
- Switchgear (Primarily >1000V)
- MCCs (Primarily >1000V)
- Power Distribution Enclosures
- Control Cabinets
- High-voltage Transmission and Distribution Lines
- Inaccessible <1000V Equipment



EXAMPLE OF POST FAILURE, NEW INSTALL FINDING



CONTACTOR ARCING NOT SEEN WITH THERMOGRAPHY

Frequency

MECHANICAL IR

Best practice frequency for mechanical ultrasound is quarterly if combined with vibration analysis, or monthly if used as a standalone monitoring technology.

ELECTRICAL IR

Best practice frequency for electrical ultrasound is quarterly.

VIBRATION ANALYSIS

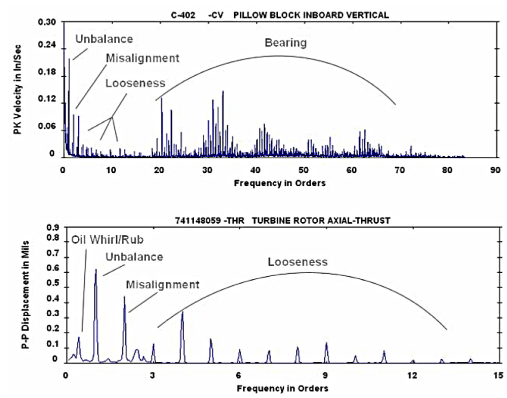
By far, the most widely used condition monitoring technology for rotating equipment is vibration analysis. Vibration analysis stands alone as the most comprehensive method for detecting defects in rotating equipment.

The vibration signature is collected from a rotating machine and then analyzed. The raw data that is collected from the equipment is the time waveform, and the software converts this to a vibration spectrum.

The pattern of the signature provides evidence of the nature of the defect, and the amplitude of these peaks indicate the severity. The components in a machine train will vibrate at unique frequencies, and defects can be detected by linking the measured fault frequency to the forcing frequency of the component. For example, shaft misalignment happens at a different frequency than gear problems, or bearing faults, or even electrical problems in motors. Each of these has their unique frequencies, and each has their own patterns in the vibration signature.

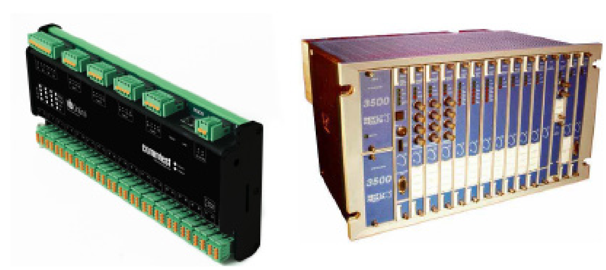
Vibration analysis can be deployed on any rotating equipment and provides an excellent indication of the health of rotating components. This technology can also be very helpful in troubleshooting and root cause analysis studies, as the vibration data can show a specific defect and very quickly provide evidence of the physical root cause of a problem.

Portable data collectors, online systems, and remote systems using wireless sensors can be used depending on the location, application, and environment of the equipment.



VIBRATION DATA

PORTABLE VIBRATION DATA COLLECTORS



CONTINUOUS VIBRATION DATA COLLECTION SYSTEMS

Frequency

Best practice frequency for vibration analysis is monthly.

OIL ANALYSIS

Oil analysis is a very common, widely used condition monitoring technology. 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 is the tests that detect changes in the lubricant chemistry. Another aspect is the detection of wear particles that indicate defects in the components the lubricant is there to service. The final aspect 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.

Frequency

Best practice frequency for oil analysis is quarterly. Equipment that is high on the criticality scale or subject to high contamination levels can be sampled on a monthly basis.

ELECTRIC MOTOR TESTING

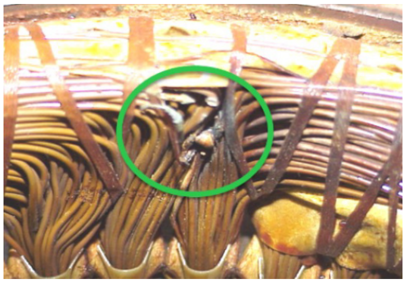
Electric motor testing provides a look inside electrical equipment and measures the electrical health of motors. In the hands of a capable analyst, motor testing effectively identifies defects within an electric motor's stator and rotor. This technology can deliver desired returns on energy savings, while improving equipment reliability and production capacity.

The motor circuit evaluation (MCE) is done on a motor in two different states – offline and online – and is performed at the motor control center (MCC) bucket for the equipment, allowing tests to be performed even if the equipment is inaccessible to other technologies. MCE offline testing evaluates conditions like rotor health and stator insulation condition; MCE online testing shows a more complete picture of how the motor is operating (e.g. power quality, load conditions, operating efficiency, etc.). A third testing option is electric current monitoring (ECM), also known as electrical signature analysis (ESA). ECM is an invasive, remote test that provides insight into the health of rotating equipment, such as motors or generators, and their components.

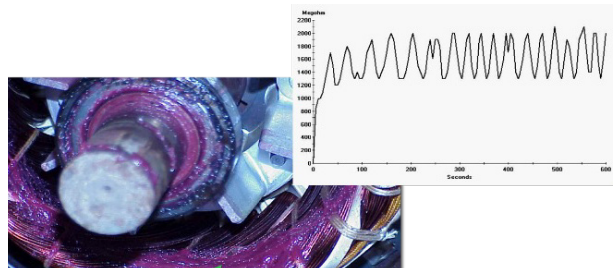
MOTOR CIRCUIT EVALUATION (MCE) – OFFLINE

Static or offline testing is performed while the motor is not running or shut down. This offline evaluation is commonly used as a quality assurance (QA) tool for acceptance testing of new, reconditioned, or rewound motors prior to their being accepted, stored, or put into service. Not only does it ensure that new or repaired motors meet standards, but it also becomes the baseline for future trending. Additionally, MCE offline testing is commonly used as a troubleshooting tool to test the integrity of the motor's insulation system, as overload situations, contamination, and voltage issues can compromise the insulation.

The MCE test equipment used today is capable of adequately reproducing real-world experiences without causing damage to the motor's insulation system. Defects such as turn-to-turn or phase-to-phase shorts, poor internal or lead wire connections, and contamination in the windings can be detected using these tests. Most importantly, offline testing is the only way to measure electrical insulation quality. This measurement must be done while the unit is turned off and locked out.



OFFLINE DATA IDENTIFIES PHASE-TO-PHASE SHORT THAT HAD NOT YET FAILED



POLARIZATION INDEX INDICATIVE OF CONTAMINATION (GREASE ON WINDINGS)

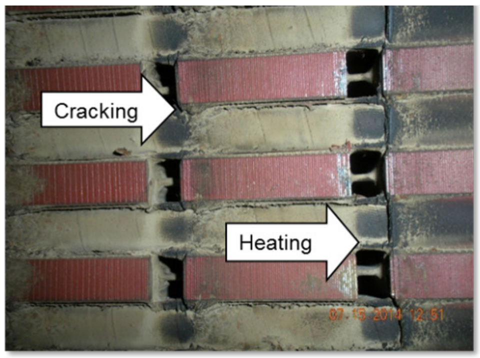
MOTOR CIRCUIT EVALUATION (MCE) – ONLINE

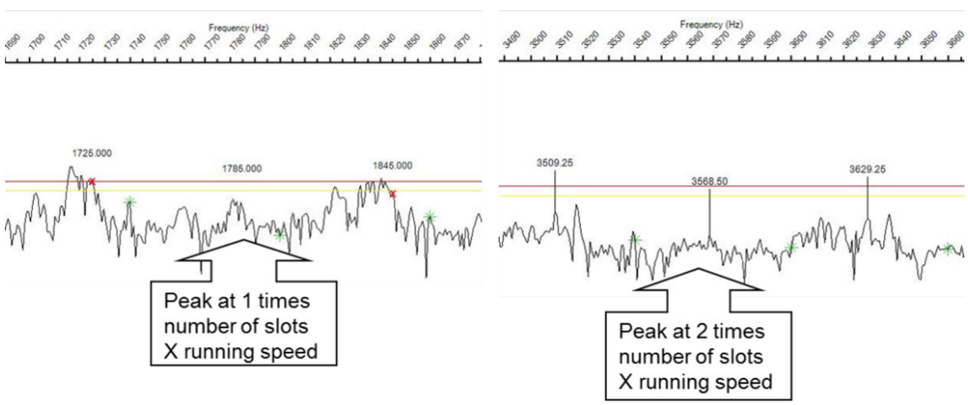
Online testing is performed while the motor is operating within its normal environment and operating conditions. A motor is part of a machine system with three links: incoming power, load, and the motor itself. The MCE online test equipment available today provides insight into all three of these areas. Many motor problems are created by the load or by poor supply power, and many times, the root cause of the failure goes undetected. The most modern online test equipment can calculate speed and torque, define rotor bar problems, and measure distortion. The ability to capture and analyze the components of torque allows the technician a means to separate mechanical and electrical issues. Torque and current spectra have proven useful in determining numerous mechanical issues, including bearing problems, mechanical looseness, eccentricity, gear mesh, pinion impacting, belt frequencies, vane and blade pass, misalignment, soft foot, and coupling defects, as well as other concerns. This ability provides critical information regarding the root cause of motor defects and can assist in eliminating repeat incidents.

Online testing provides insight regarding power quality and conditions, such as voltage levels, unbalances, and distortion. Capturing voltage and current allows for analysis of the power distribution system while monitoring the motor circuit for individual anomalies. With the increased usage of solid-state controls, such as VFDs and soft starters, in a variety of distribution systems, issues such as harmonics, ineffective grounding, and improper power factor correction have become a real possibility, and a reality in many aged facilities. Monitoring systems for internal and external sources of disruption to the overall power distribution system will preserve the motor systems, as well as auxiliary systems such as PLCs, instrumentation, UPSs, and powered sensors. In addition, the ability to monitor potential ignition sources for hazardous rated locations is of added value. A small amount of voltage unbalance coupled with minor harmonic voltage distortion may result in a NEMA de-rating of motors that will not be seen with simple multimeters and amp probes.

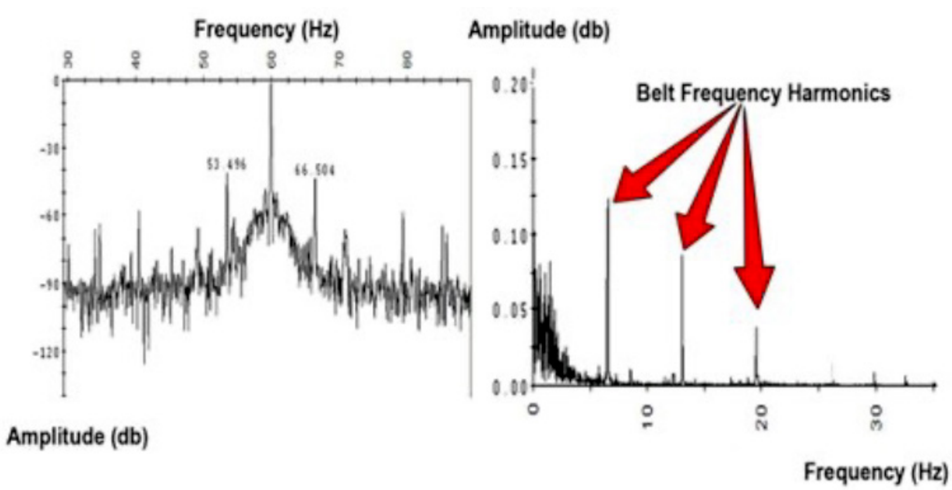
Another major issue with electric motors is the condition of their rotors. Online testing will enable a Technician to identify rotor bar failures or potential failures if the load is relatively steady. A pump, fan, or blower operating at a steady frequency will show very clear rotor bar signatures, making diagnosis fairly easy. During normal operation, a motor's rotor is stressed by its load. The 'torque ripple' provides a picture of those stresses and is an indicator of many mechanical defects. Cavitation and belt flapping are also easily identifiable in the torque ripple signature.

In addition, online testing provides efficiency information, allowing the maintenance technician to make wise and practical decisions when it is time to repair or replace a motor. Improving efficiency by just 2% has the potential to result in thousands of dollars in energy cost every year.





STATOR WINDING ANALYSIS



MECHANICAL FAULTS, MODULATION AND DEMODULATED SPECTRA

ELECTRICAL CURRENT MONITORING (ECM)

Current levels and current unbalances also affect motor performance. The ability to monitor this data is essential when trending motor health, as many of these fluctuations can be linked directly to the onset of defects within the machine system. This data can also be a great trigger for engineering evaluation of affected systems.

The state-of-the-art ECM technology is used to acquire and analyze motor current data. It is a versatile, powerful, and non-intrusive tool originally developed to evaluate motor-operated valve components located in inaccessible nuclear power containment areas.

ECM provides the ability to detect and quantify mechanical defects and degradations in electro-mechanical equipment. It senses load and speed variations, while correlating with minute current and voltage changes, and then analyzes the tiny fluctuations with an ability to match with their source. The result is frequency signatures that reflect loading, stresses, and wear throughout the motor-driven mechanical train. Wears that are detected include bearing defects, gearbox gearing issues, driven belt alignment and slippage, misalignment and unbalanced conditions, static and dynamic eccentricity, motor mechanical issues, motor stator shorts, and rotor condition grading. This extensive range of mechanical diagnostic information, and more, is obtained by a single, 1-minute test.

The ECM test can be used on the following types of equipment: AC induction motors, AC synchronous motor, transformers, generators, DC motors/equipment, and asynchronous generators. It can analyze all mechanical components connected to this equipment, such as: gearboxes, belt-driven equipment, pumps, fans, bearings, blowers, drive rolls, sprockets/chains,

A benefit of ECM is its ability to provide a true picture of electrical reliability throughout a facility's electrical distribution, by providing the following electrical information at each collection point (primary and secondary) of each transformer with the capability to report and trend: voltage, amperage, power (KW, KVA, KVAR), power factor, load, and voltage and current harmonic distortion.

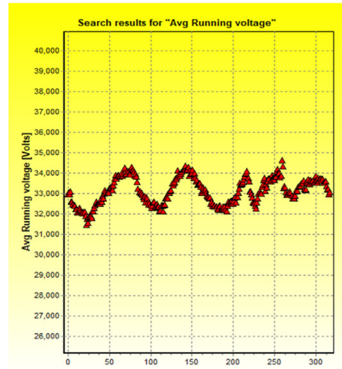
ECM has the unique capability to quantify detected defects as 'wasted power usage.' Each defect in the equipment train affects the electrical motor by adding demand to the motor. The added electrical demand is measured and converted into electrical cost and environmental impact.

Versatility is another plus, whereby ECM can be used as a route-based, manually conducted test or via permanently installed non-intrusive current and voltage probes. Route-based testing is performed using the Ultracheck EMPATH system, requiring an escort to connect and disconnect current and voltage probes similar to testing performed with PdMA® MCE Max equipment. Collection time per test is only 46 seconds. Permanently installed testing is performed via the ECMS-E1 (single channel) or ECMS-32 (32 channel) system.

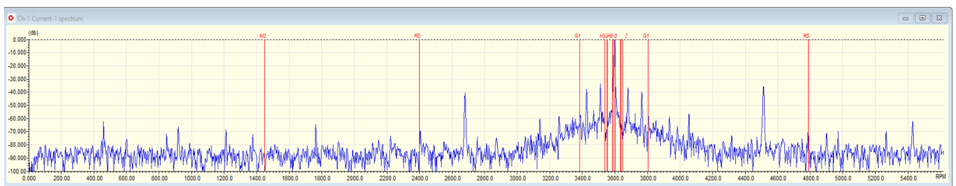
- The **ECMS-E1** system is an analog-to-digital converter that takes incoming voltage and current data and converts it to a digital signal that is sent to the processing computer via ethernet. This system is installed at the source (MCC Bucket or Control Cabinet) and has the capacity to test a single motor at a 5-minute interval.
- The **ECMS-32** system contains a central hub with 32 associated E-plugs. Each E-plug is installed at the source (MCC Bucket or Control Cabinet) and takes incoming voltage and current data and transmits it back to the ECMS-32 unit, where it is converted to a digital signal and sent to the processing computer via ethernet. This system has the capacity to test each channel (each motor) once per hour.

ECM ANALYSIS EXAMPLES:

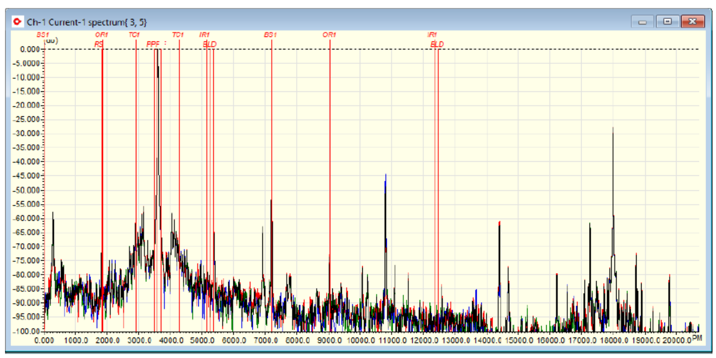
	Phs-1	Phs-2	Phs-3	Total	Units
Power factor	0.830	0.812	0.860	0.834	
Real Pwr.	5106.0	4764.5	5105.9	14976.0	KW
Reactive Pwr.	3434.4	3420.5	3029.4	9884.3	KVAR
Apparent Pwr.	6153.6	5865.2	5937.0	17956.0	KVA
Running Cnt.	309.4	318.6	314.3	314.1	Amp
Line Voltage	32993	32964	32984	32980	Volt



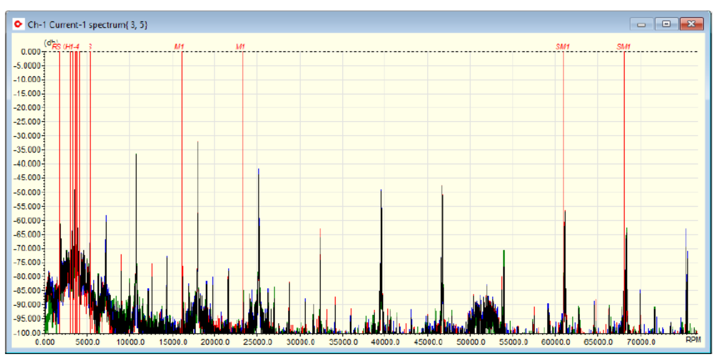
MECHANICAL FAULTS, MODULATION AND DEMODULATED SPECTRA



GEARBOX ISSUE, IDENTIFIED ON THE INPUT SHAFT GEARING



BEARING DEFECT



MECHANICAL DAMAGE OF A MOTOR STATOR

Frequency

MOTOR CIRCUIT EVALUATION

Best practice frequency for MCE (both online and offline) is testing twice per year.

ELECTRICAL CURRENT MONITORING

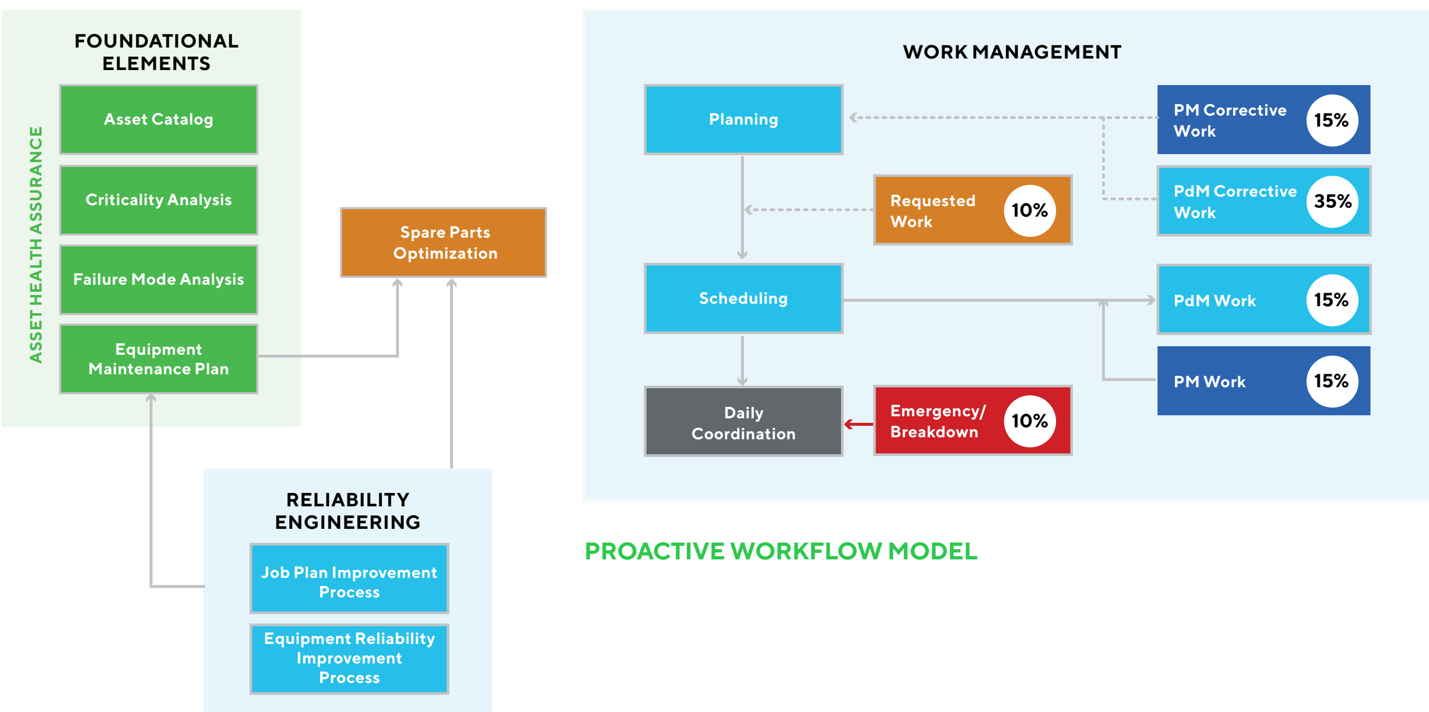
Best practice for ECM varies depending on the equipment maintenance plan and equipment criticality. It may range from monthly for route-based ECM collection to daily in permanently installed remote applications.

PROACTIVE WORKFLOW MODEL – HOW MUCH CONDITION MONITORING SHOULD BE USED?

The Proactive Workflow Model helps an organization understand how much condition monitoring the group should be doing and how condition monitoring 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 condition monitoring programs.

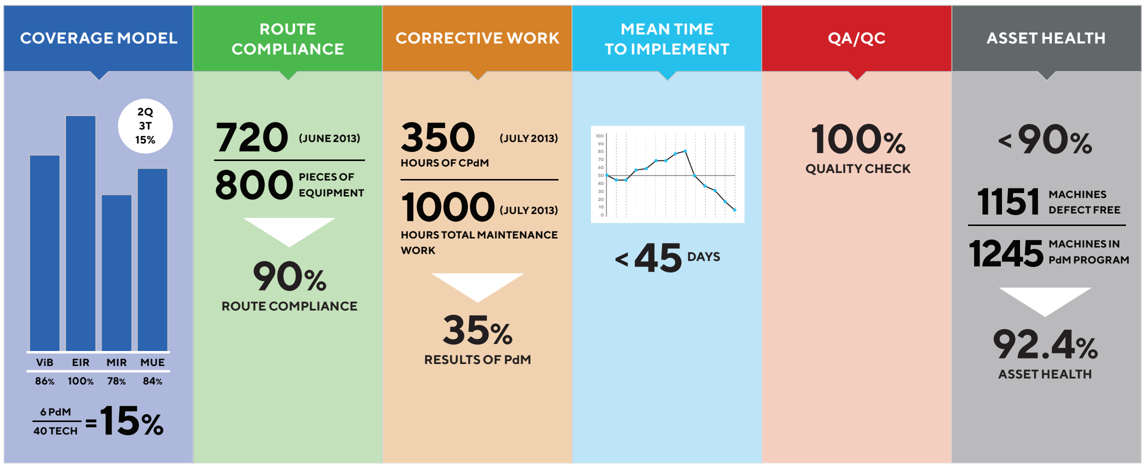
The PM program should consume about 15% of the maintenance labor. This does not mean that 25% is better than 15%. No, PM should be 15%, +/- 3% only. The corrective work that is generated by the PM inspections should consume another 15% of the maintenance labor. An additional 15% of the maintenance labor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



PROACTIVE WORKFLOW MODEL

KEY PERFORMANCE INDICATORS FOR CONDITION MONITORING



ESSENTIAL METRICS FOR ANY CONDITION MONITORING PROGRAM

COVERAGE MODEL

First, the organization must ensure that enough machinery is being monitored with condition monitoring to create a shift in machinery availability. This means 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

ROUTE COMPLIANCE

Now that the routes have been created, the data must be collected. The metric to ensure that this is being done is called '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 condition monitoring 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 must be completed quickly enough to have a proactive impact. 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.

QUALITY ASSURANCE (QA) / QUALITY CONTROL (QC)

The work is not complete until the condition monitoring technician who found the defect says it is complete. Just because the technician says they fixed it does not ensure that the defect has been removed and there are no other problems. Anytime technicians say a job is complete, the work order should not be closed until the condition monitoring 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. It follows that no condition monitoring program is successful unless the number of machines in the plant running defect free reaches 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 primary goal of the condition monitoring program; everything else is icing on the proverbial cake.

WHY MOST CONDITION MONITORING PROGRAMS FAIL

There are many reasons why condition monitoring programs fail: lack of support, lack of acceptance, lack of funding, lack of foundational elements, etc. Below are four of the most common reasons why Allied Reliability has seen programs fail.

LACK OF STANDARDS

To be effective and efficient, condition monitoring should be carried out by certified and qualified personnel.

- **Certified** means the technician attended a series of classes and passed a written and practical test to demonstrate their expertise.
- **Qualified** means the technician has 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.

LEADERSHIP SUPPORT/CHANGE

Condition monitoring programs need to be invested in, and without support from senior leadership, the equipment, manpower, and training are not valued and not purchased. Often, when there is a change in leadership, this program is seen as a cost instead of a value, running the risk of being defunded.

SUCCESS NOT TRACKED AND BROADCASTED

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

CONDITION MONITORING NOT USED FOR TROUBLESHOOTING OR TO COMMISSION REPAIRS

These technologies are very powerful. They are applicable not just for route-based inspections, but also for troubleshooting and for commissioning repairs. Organizations that embrace the power of these technologies begin to find new and inventive ways to apply them. They can drastically improve the troubleshooting process and cut the total repair time 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

Condition monitoring is the use of technologies, including vibration analysis, ultrasound, oil analysis, IR thermography, and electric motor testing, to identify the presence of defects in industrial equipment. This identification facilitates maintenance activities by using the data to drive the decisions on what to fix, and when to fix it.

Condition monitoring inspections help the organization become more proactive. The early identification empowers the maintenance department by providing specific information about the defect early enough to take full advantage of the planning and scheduling process and allow enough time to order parts and materials without having to expedite deliveries. The condition monitoring 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, and therefore an increase in productivity, an effective condition monitoring program can go a long way in making that goal a reality.

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From Insight to Execution

For decades, we have partnered with industrial organizations to optimize their asset performance through the application of reliability and maintenance solutions. From maintenance strategy design to execution, our experts are with you where you need us, when you need us.

We have a proven asset management methodology to help you manage your assets across their entire lifecycle. The approach ensures that business strategy is connected to asset strategy, facilitates continuous improvement, and allows for entry into the process at any point, regardless of where you are on your reliability journey. We are the only provider with an end-to-end solution.

Visit www.alliedreliability.com to learn more about our offerings.

Allied® RELIABILITY

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