MOTORS@WORK

Maximizing motor life through condition monitoring

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Motors fail — it's a fact of life that's nearly as certain as death and taxes.

Until now, preventing motor failure required early retirement — i.e., repairing or replacing your rotating equipment on a schedule possibly years before it would fail. Fortunately, the declining cost of sensors and sub-meters, together with the growing big data industry, have made condition monitoring increasingly accurate and affordable. The net result: condition monitoring can decrease your motor operations and maintenance (O&M) expenses by up to 25%.[1]

This white paper describes how condition monitoring detects motor-damaging situations and uses that information to maximize the life of your rotating equipment: First we describe how motors fail; then, we outline how these failure modes help us to detect declining motor health. The third section summarizes how condition monitoring benefits your bottom line. To conclude, we explain how condition monitoring and the Industrial Internet of Things will lead to truly predictive maintenance within 10 years.

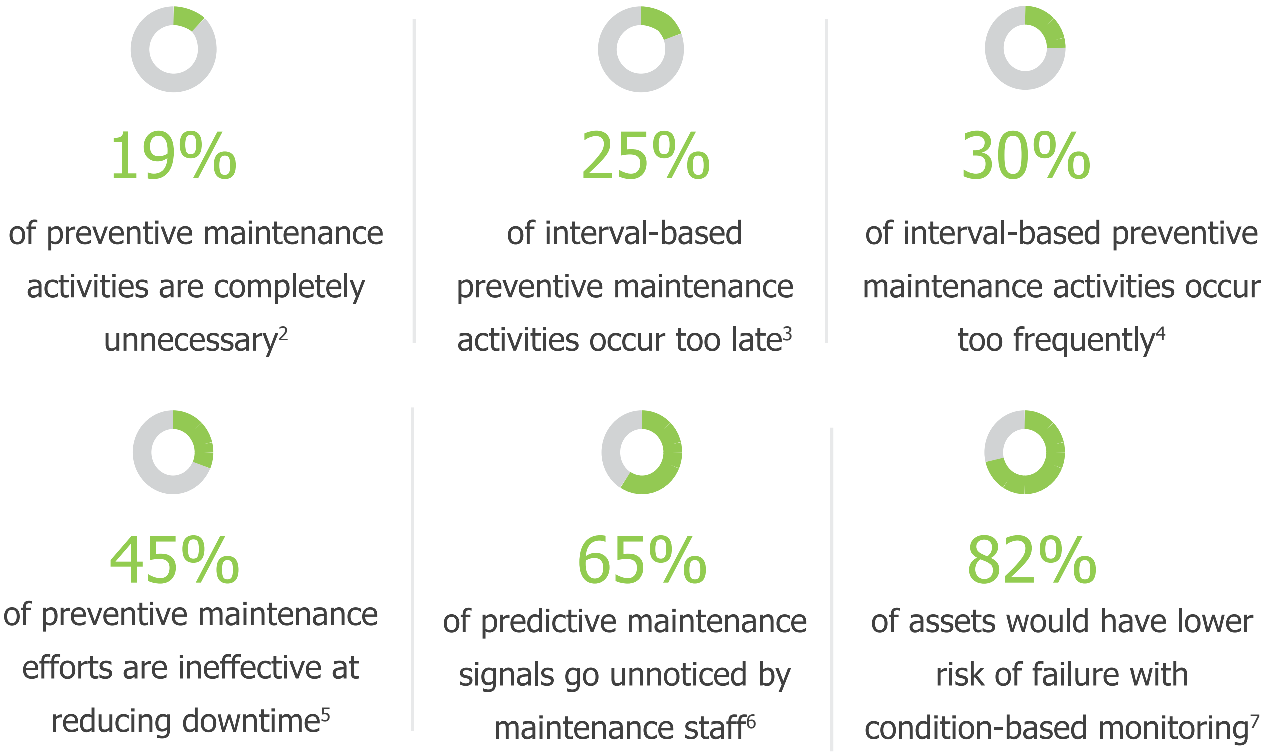

FIGURE 1 The high cost of preventive (PM) — versus condition-based and predictive — maintenance. Condition-based maintenance reduces your maintenance expenses by eliminating unnecessary maintenance activities and helping your maintenance staff work smarter.

WHY MOTORS FAIL

In the 1970s, Nowlan and Heap characterized asset failure patterns into six general models; then, the researchers categorized these failure curves as either age-related (Types A, E, & F) or "random" (not age-related; Types B, C, & D) [Figure 2].[8]

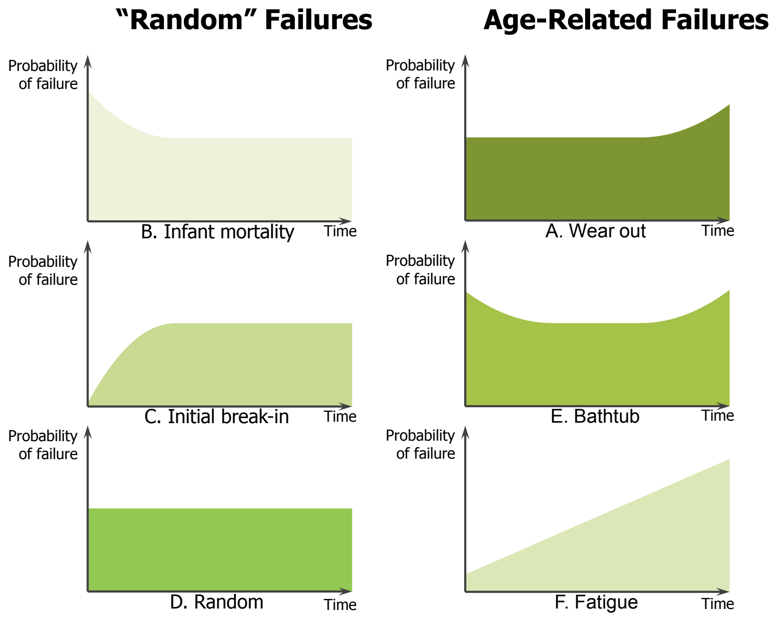

FIGURE 2 Nowlan & Heap's seminal research identified six asset failure patterns and classified these curves as either "random" or age-related.

At the time, Nowlan & Heap classified 11% of equipment failures as age-related.[9] While better manufacturing practices have reduced the number of "random" failures and increased the share of age-related failures since the 1970s, age-related degradation still causes a minority (18%) of equipment failures [Figure 3].[10]

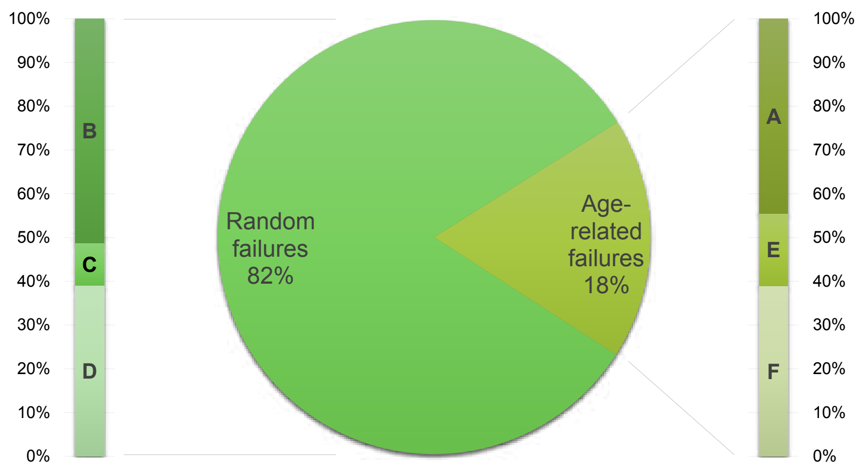

FIGURE 3 Researchers in the 1960s and 1970s characterized asset failure patterns and recognized that few failures occur due to asset age. Motors follow a similar pattern to other asset classes, with only 10% of failures attributable to age-related degradation

Motor failures follow a similar distribution to other asset classes, with age-related degradation causing a relatively small number of failures (10%).[11, 12] While age plays a limited role in motor failures, motors don't fail randomly either: we can identify the root cause.

According to several surveys compiled by EASA and other motor experts,[13, 14] here are the five reasons why motors fail [Figure 4]:

1. Bearings. With 51% of motor failures attributed to bearing issues, bearing failure is the most common root cause for motor failure.[15, 16] Triggers for bearing failure include over- and under-lubrication; inappropriate mechanical loads (e.g., over-loading, radial misalignment, axial thrusting, belt tension issues); shaft currents; excess heat (leads to loss of lubrication); and contamination (e.g., using incompatible greases, water condensation, dust/dirt contamination).[17, 18, 19]

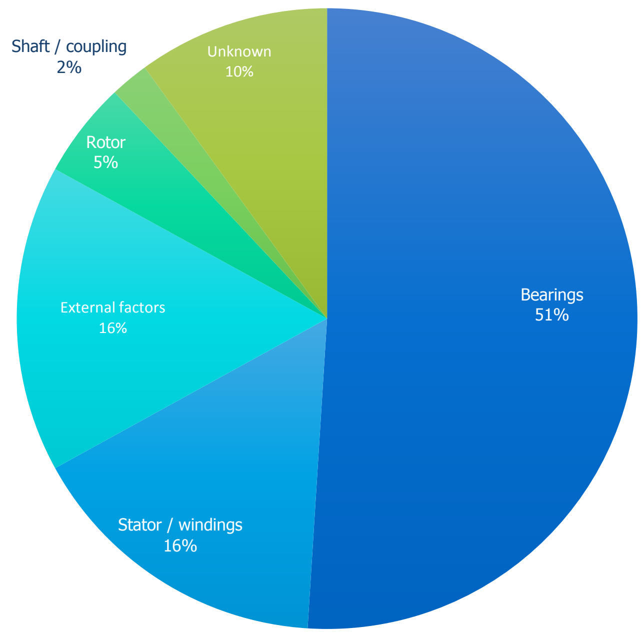

FIGURE 4 Nowlan & Heap's seminal research identified six asset failure patterns and classified these curves as either "random" or age-related.

2. Stator & windings. At 16%, winding issues represent the second most common root cause of motor failure.[20, 21] When windings fail, electricity arcs from one part of the motor to another, causing a short inside the motor. Potential causes of winding failure include over-voltage operation, (e.g., surges, transients); excessive current (e.g., single-phase, under-voltage, over-loaded, or locked rotor operation); high ambient temperature or loss of cooling (degrades epoxy insulation); an excessive number of motor starts or full reverses (see the manufacturer's specifications for the maximum number of starts and reverses per hour); physical damage (e.g., a scratch in the epoxy); and penetration of contaminants.[22]

3. External factors. Causing 16% of motor failures, external factors cover environmental and load-related failures, such as inappropriate mechanical loads (e.g., over-loading, radial misalignment, axial thrusting, belt tension issues); contamination (e.g., water, dust, dirt); ineffective maintenance practices (e.g., under-/over-lubrication); and Acts of God or War (e.g., flooding, excessive heat, bomb damage).[23, 24]

4. Rotor. Rotor issues — such as broken rotor bars, broken end-rings, and core delamination[25] — cause approximately 5% of motor failures.[26, 27] Potential causes include excess vibration (e.g., radial misalignment, axial thrusting, highly variable duty-cycles); an excessive number of starts or reverses, or too-short of an interval between starts/reverses; long starting times; physical damage to the rotor; and excess heat (e.g., high ambient temperatures, over-load, or locked rotor operation).[28]

5. Shaft/Coupling. In 2% of motor failures, the shaft or coupling fails. Causes of shaft failure include improper installation (e.g., radial misalignment, belt tension issues); excessive loading; corrosion; and physical damage to the shaft.

In the remaining 10% of motor failures surveyed, the root cause either was not investigated or was listed as undeterminable.

HOW CONDITION MONITORING SAVES YOUR MOTORS

Now that we understand how motors fail, let's talk about how we can use this information to preserve the health of your motors and motor-driven equipment.

In the 1990s, Austin Bonnett realized that — regardless of which component fails first — a handful of mechanisms cause multiple motor components to fail.[29] Bonnett identified these mechanisms as thermal, electrical, mechanical, and environmental stresses. Electrical stress relates to incoming power quality and equipment grounding. Mechanical stress includes the motor's application, load, duty-cycle and mounting — and particularly the vibration that the motor experiences and produces in this application. Ambient conditions and contamination fall under environmental stresses.

While each of these stresses cause multiple motor components to fail, not all stresses trigger all motor components to fail.[30]

For example, thermal stress — i.e., heat — affects all five motor components; it causes bearing grease to lose lubrosity, degrades winding epoxy, inhibits cooling, initiates rotor core delamination, and even deforms a motor's shaft. Figure 5 maps which stresses cause each motor component to fail.

	THERMAL	ELECTRICAL	MECHANICAL	ENVIRONMENTAL
Bearings	✓	✓	✓	✓
Stator & windings	✓	✓	✓	✓
External factors	✓		✓	✓
Rotor	✓	✓	✓	✓
Shaft/coupling	✓		✓	✓

FIGURE 5 Four cross-cutting stressors ultimately cause motor failures, but not all stressors cause all motor components to fail. Condition monitoring protects motors' health by detecting these stressors and providing you with the information needed to correct them before your motors experience irreparable damage.

Your motor's health is proportionate to the total level of stress it's experiencing. Common motor health diagnostics measure the level of one stressor on your motors; for example, thermography measures thermal stress, while vibration detects mechanical stress. Much like your doctor tracks your temperature and blood pressure, monitoring your motor's vital statistics — i.e., it's normal operating parameters and stress levels — can indicate an issue long before it's symptomatic of a problem.

Energy-based condition monitoring offers three advantages over more common condition-monitoring techniques, like vibration and thermography. First, it's difficult and expensive to monitor vibration, thermography, and ultrasound remotely so these tools tend to be interval based — e.g., quarterly or annually. With the Internet of Things and rapidly declining sub-metering costs, energy monitoring is an increasingly affordable method for providing continuous, remote monitoring.

Second, ultrasound, vibration, and thermography only identify whether your motor is operating normally or not. These diagnostics identify an issue if there is one or, in the absence of an issue, consider a motor healthy. But, energy-based condition monitoring can detect motor-damaging electrical stressors, such as voltage unbalance, before they damage your asset [Figure 6, next page]. With that knowledge, you have a chance to intervene and correct the issue before it harms your asset.

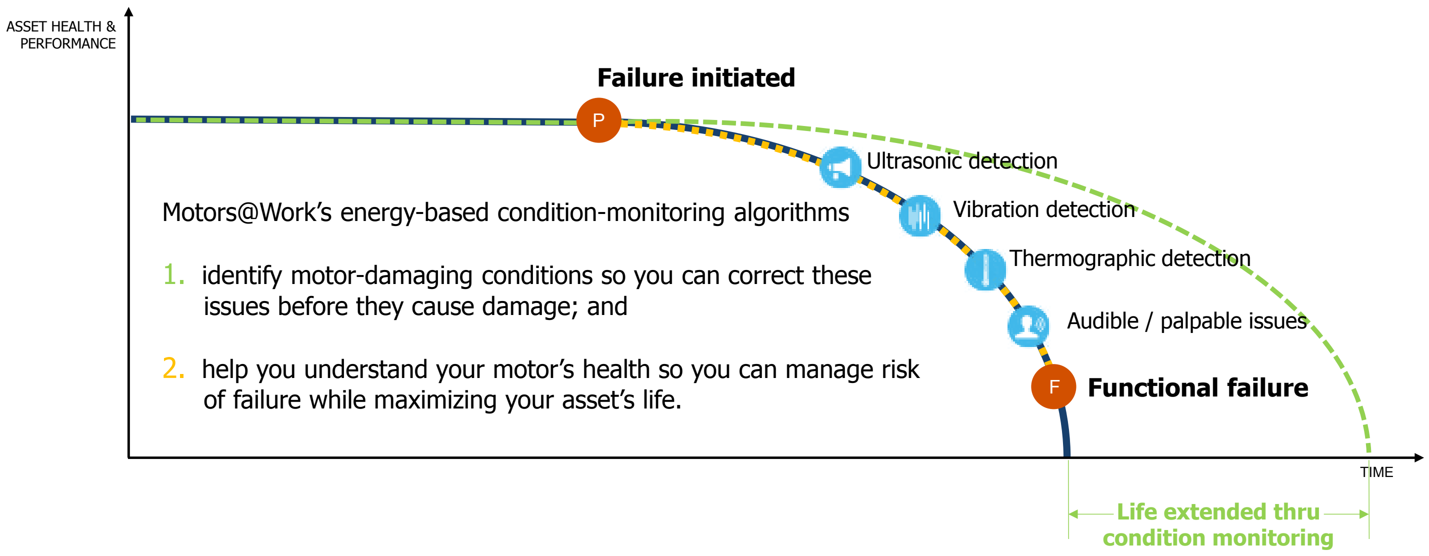

FIGURE 6 Energy-based condition monitoring continuously watches for motor-damaging stresses, such as voltage unbalance, and alerts you when these conditions occur. Taking actions on these alerts prevents damage and extends the life of your asset. Or, if your motor is already damaged, then energy-based condition monitoring supplements other diagnostics to provide insight on the motor's performance so that you can balance operating costs, remediation costs, and risk of failure in an informed manner.

If damage has already occurred, then energy-based condition monitoring provides intelligence that helps you understand your motor's current performance and health. With this information, you can make an educated decision that balances this motor's performance, operating costs, and remediation costs with the risk and consequences of failure.

Third, energy-based condition monitoring uses energy efficiency as a leading indicator of motor failure. Whether a motor is just beginning to arc between windings or has a bearing issue emerging, the motor consumes more energy to generate the same output. That means its efficiency has declined. These slight efficiency changes signal that your motor is stressed. Because energy-based condition monitoring platforms, such as Motors@Work, continuously monitor your motors and compare new to historical measurements, these platforms detect that your motor needs attention — often before ultrasound, vibration, and thermography.

Energy-based condition monitoring effectively detects thermal, mechanical, and environmental stressors — not just electrical stressors. For example, imagine a motor that's thermally stressed because it's outdoors on a 99°F day, effectively reducing its ability to cool itself. As the motor's temperature increases, its electrical resistance (in Ohms) increases. In turn, the higher resistance converts a greater percentage of the motor's electrical input into heat. The hotter the motor becomes, the more electrical power input it requires to deliver the same output.

In other words, its efficiency declines. Similarly, a motor with a bad bearing requires greater electrical input to overcome the increased bearing friction and deliver the required output — even before the bad bearing hits detectable vibration and thermal levels.[31, 32]

HOW CONDITION MONITORING WORKS

Condition monitoring works by collecting, sorting, and analyzing streaming data from sensors on your equipment [Figure 7]. Then, data analysis platforms, such as Motors@Work, apply complex algorithms to the incoming values to detect problematic conditions and update the virtual model — also known as a "digital twin"[33] — of how your equipment operates. The platform compares your equipment's current performance to its manufacturer specifications and historical readings to identify performance "non-conformities," or items that require action. Finally, the platform generates a report with asset history and sensor data and alerts you to these non-conformities, enabling you to determine the proper intervention — such as correcting a potentially motor-damaging stress before it creates a bigger issue or scheduling downtime to replace equipment.

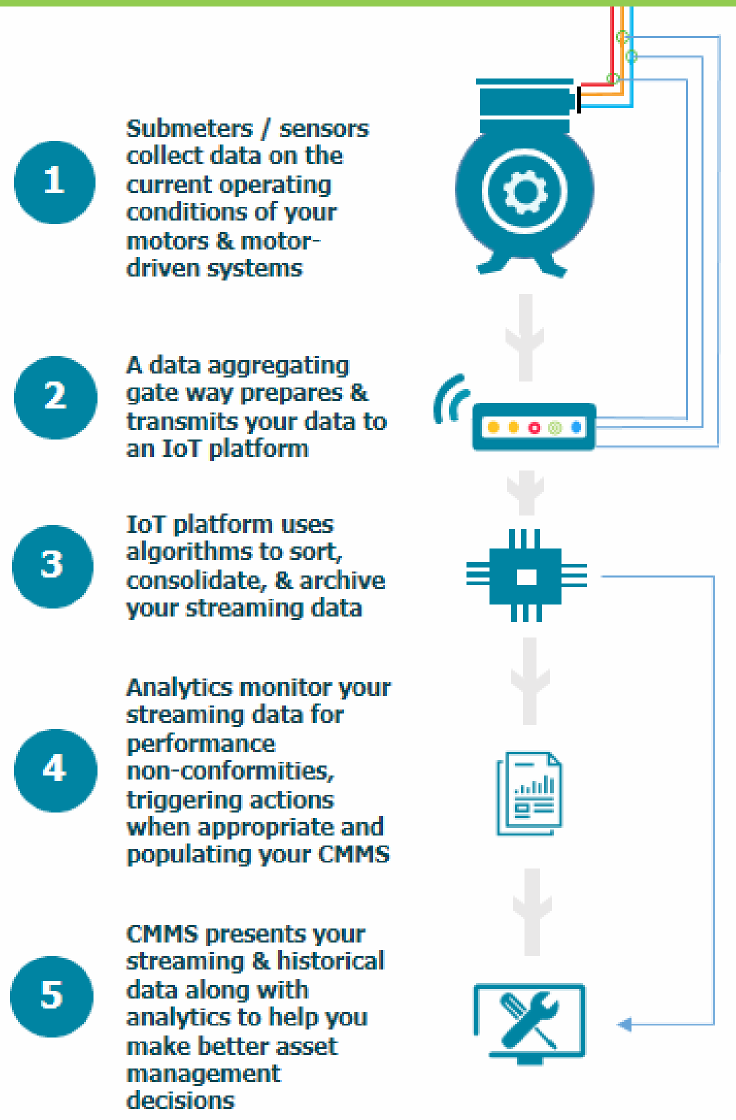

FIGURE 7 Condition monitoring collects and analyzes your operating data to provide timely, information-rich intelligence that supports better decision-making.

HOW CONDITION MONITORING SAVES YOU MONEY

By continuously tracking the health of your motors, condition monitoring enables you to maximize your capital investments in your motor-driven systems. Here are six ways that monitoring the condition of your motor assets empowers you to minimize your motor-related expenses:

1. Preserve the health and extend the life of your assets. By detecting and notifying you when situations stress your motors, condition monitoring alerts enable you to proactively correct issues before they irreparably damage your rotating equipment.

2. Reduce your energy expenses. Since motor efficiency declines with motor health, using condition monitoring to preserve the health of your motors also lowers your energy costs.

3. Extend your maintenance staff's reach. Having your motors alert you when they need maintenance reduces your maintenance expenses and extends your maintenance staff's reach — focusing on motors when they need maintenance and other tasks when they don't.

4. Optimize your maintenance processes. By intervening only when your asset needs maintenance, condition monitoring enables you to eliminate unnecessary and ineffective preventive maintenance practices while still achieving high availability and reliability performance.

5. Make smarter asset management decisions. By combining sensor data, historical trends, and maintenance records to assess the current health of your motors, condition monitoring helps you to identify which motors need replacing — and which don't. Avoiding the premature replacement of a heathy motor extends your capital investment while maintaining high availability and reliability metrics. Additionally, providing operations, maintenance, and engineering with visibility on how your equipment is performing helps these teams make collaborative, well-informed asset management decisions.

6. Avoid unplanned outages, minimize downtime, work safer, & reduce defects. Condition monitoring's asset health information enables you to make proactive, risk- and economic-based asset management decisions about the type and timing of maintenance to perform on your motor or motor-driven equipment. By making these decisions proactively — instead of in the heat of the moment after the asset fails — you can order supplies, stage equipment, and schedule the outage at a time that works best for you. Eliminating catastrophic failures and prepping people and supplies in advance reduces the time it takes you to complete maintenance tasks — by half, according to T.A. Cook[34] — getting you back up and running sooner. Studies also show that planned, condition-based maintenance is safer (i.e., results in fewer injuries) and results in up to 70% fewer defects.[35]

With all these benefits, why would you pay 2x to 5x more for reactive maintenance[36] than condition-based maintenance?

IMPROVING RELIABILITY WITH MOTORS@WORK

In 2011, Des Moines Water Works (DMWW) — a municipal water utility serving more than 500,000 people in Iowa's capital — implemented a new enterprise asset management (EAM) system to turn raw data collected utility-wide into more usable formats. While the new EAM tracked 250+ key performance indicators and produced more than 180 reports, Des Moines soon realized that it needed near-real-time equipment information to improve reliability and decrease emergency equipment failures.

"Maintenance, repair, and operations personnel would get alarms like 'high winding temperature' or 'pump failed.' Technicians then had to spend time researching trends to see what was happening when the alarm was received," reported Doug Oscarson, EAM project manager (retired).

So, in 2013, DMWW installed 37 electrical submeters on its critical motors and hired Motors@Work to provide analysis and ongoing monitoring of these motors. In addition to identifying more than $220,000 in annual energy expense savings, Motors@Work helps Des Moines' maintenance staff monitor asset health and improve overall reliability.

For example, last year Motors@Work alerted maintenance to an abnormally low power factor on a 1,250-horsepower, 20-million-gallon-per-day, finished-water pump. "Data like this would not be observed by the operators," said Oscarson.

Had this low power factor continued uncorrected, the motor would have overheated and tripped off, creating a large water hammer in the distribution system that may have broken water mains around the city. Instead, upon receiving Motors@Work's alert, maintenance successfully identified the faulty controller, ordered the part needed to fix the controller, and worked with operators to schedule the repair.

By enabling maintenance staff to identify and correct motor-stressing early, DMWW's mean time between failure (MTBF) for monitored pumps has increased 37% since implementing Motors@Work. Because Motors@Work's alerts provide historical data and troubleshooting tips, diagnosis and repair times have decreased. Maintenance overtime is down; reliability and availability of critical equipment is up.

"Protecting public health is our number one concern," Oscarson said, "and Motors@Work plays an important role in completing our overall mission."

MOVING FROM CONDITION-BASED TO PREDICTIVE MAINTENANCE

As we've discussed previously, condition monitoring is an effective and increasingly affordable way to improve reliability while decreasing maintenance and operations expenses. But what is the relationship between condition monitoring, condition-based maintenance, and the long-heralded predictive maintenance?

Condition monitoring is the process of collecting measurable, quantifiable performance indicators from assets. Once analyzed, condition monitoring data trigger condition-based maintenance practices, where performance thresholds drive maintenance activities instead of traditional interval-based preventive maintenance schedules. While proactive and not time-based, condition-based maintenance is still a preventive maintenance paradigm [Figure 8, next page].

	REACTIVE			PREVENTIVE		PREDICTIVE	
	Run-to-failure	**Repair-focused**	**Planned**	**Performance-based**	**Condition-based**	**Prescriptive**	**Reliability-centered**
	$	$$$$$$$	$$$$$$$	$$$$$	$$$	$$	$$
TAGLINE	Don't fix it	Fight the fires	Follow interval-based schedules	Meet the KPIs	Track our assets' health	Follow best practices based on forecast	Balance performance, safety, & risk while minimizing costs
WHO'S THE BOSS	The budget	The equipment	The schedule	The KPIs	The maintenance staff, armed with asset health data	The maintenance staff, armed with asset health data & best practices	The maintenance staff, armed with analyses on performance, safety, cost, & risk
STRATEGY	Reactive maintenance performing the minimum needed to return assets to service	Reactive maintenance prioritized by asset criticality, near-term operational needs, and personal preferences	Proactive maintenance aims to discover problems with critical assets thru regular PMs & to initiate repairs before failure	Proactive maintenance aims to avoid failures by fixing assets before they fail	Proactive maintenance uses near-real time condition monitoring data to adjust timing & type of PM service; staff spends majority of time improving equipment & operations	Proactive maintenance relies on near-real-time condition monitoring models to generate PM actions; staff spends majority of time reducing defects	Proactive maintenance uses all available data to balance performance, cost, safety & risk, inlcuding opting to let assets run to failure if if is the most economical / advantageous option
PROCESSES	No formal work management processes exist; assets allowed to decay; performance & operations sacrificed for short-term budget savings	Work tasks recorded manually, if at all; actions vary by user / event; no time to perform failure analysis or identify root cause	Formal work management processes exist; PMs performed on critical assets per OEM recommendations; still plenty of unplanned failures	Work management adapts PM schedules to operating conditions (e.g., run-hours, load); nested levels of PM service; assets replaced prematurely to avoid failures	Unneeded PMs eliminated, freeing staff to focus on improving equipment / operations; few, if any, unplanned breakdowns; staging of materials reduces downtime when it occurs	Condition monitoring data used to train & validate asset models & cognitive computing algorithms; models predict service type & timing, and with sufficient data, begin predicting P-to-F time	All processes are fully integrated & optimized; cognitive computing algorithms learn from each event; predictive analytics provide near-real-time decision support
DATA	Little, if any, and mostly manual data collection	Occasional manual data collection	Structured but still predominantly manual data collection	Structured & automated collection of limited data points	Structured & automated collection of data required to model equipment health	Structured & automated collection of all data points needed to model asset and/or process	Structured & automated collection of all data points needed to model asset and process
TECHNOLOGY	None used; little, if any, documentation	None used; ad hoc or disaggregated spreadsheets or databases; little ability to query historical data	Basic work management application used; may or may not be integrated with ERP and/or SCADA	Work management program integrates planning, scheduling, & procurement functions	Work management program integrates data collection to automate condition-based PM notifications	Fully integrated, real-time work management system continuously receives & sends data on asset health	Fully integrated, real-time work management system continuously receives & sends data on asset health
INSIGHT	Ad hoc, anecdotal reporting after action, if any	Spreadsheets & manually prepared reports provide intelligence after actions	Few high-level KPIs tracked, but not used to improve performance	Robust set of KPIs tracked; failure analyses conducted to identify root cause	Broad use of KPIs and dashboards increases productivity and control	Broad use of KPIs and dashboards increases productivity and control	Fully integrated & robust KPIs actively managed for continuous improvement

FIGURE 8 Maintenance maturity is a fluid scale that ranges from reactive to long-heralded predictive maintenance. Condition-based maintenance, while proactive and not time-based, qualifies as preventive maintenance on this scale. By collecting and analyzing massive amounts of asset operating data, Industrial Internet of Things (IIoT) tools like Motors@Work advance the industry towards predictive, reliability-centered maintenance.

Certainly, there are times where condition monitoring delivers predictive maintenance solutions; see, for example, the case study where Motors@Work's condition monitoring alerts helped Des Moines identify and correct issues with a 1,250-horsepower finished water pump before its possibly catastrophic failure. However, the full potential of condition-based maintenance will only be realized as we begin to analyze the reams of condition-monitoring data we're now collecting. Today, we do not have sufficient mechanical and operational data yet to predict P-to-F time; yet, this duration affects the cost-effectiveness of preventive versus reactive (run-to-failure) maintenance.

Because industry is just beginning to monitor operating data on a variety of assets, we trigger condition-based maintenance when an asset reaches a predetermined unacceptable operating level. While these thresholds originate from experts' experiences and manufacturers recommendations, we don't really know how these operating conditions affect P-to-F time, particularly when multiple complicating factors exist.

For example, in the late 1990s, after work by Dr. P. Pillay demonstrated the ubiquity of voltage unbalance and the effects of voltage variations (sags, swells) on motors in petro-chemical applications,[37] Austin Bonnett and Rob Boteler of Emerson Motors (now US Motors) decided to run motors to failure at varying voltage unbalances.[38, 39] From this work, we know that a motor operating with a 1% unbalance has half the life expectancy of the same motor operating at nominal, balanced voltages; a 2% unbalance yields one-quarter the life expectancy; 3%, one-eighth; and so on. Subsequent work shows that life expectancy changes based on whether the voltage unbalance occurs on the leading or lagging phase.[40] But what about a motor that operates with varying levels and phases voltage unbalances? With sagged or swelled voltage and a voltage unbalance?

As we collect and analyze condition monitoring data from different assets in various applications, such as through Motors@Work's partnership with IBM Watson, new insights about what's normal vs. abnormal will emerge. We'll unlock knowledge about what affects the P-to-F time of assorted assets in distinct application classes. And with that knowledge, we will unlock previously unthinkable levels of optimization.

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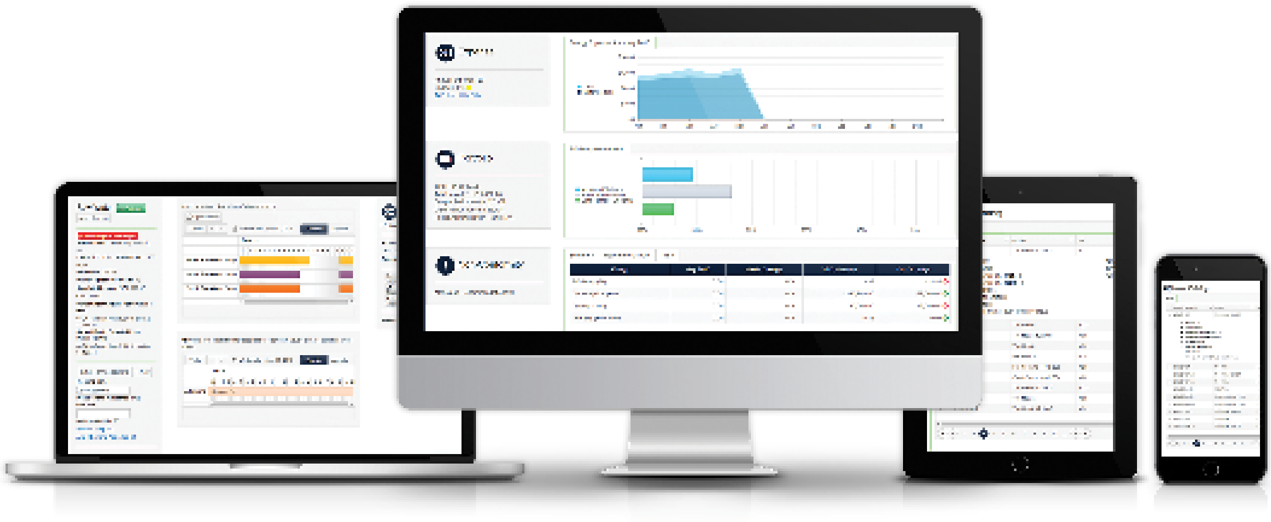
Nicole (Kaufman) Dyess has 20 years' experience optimizing the performance of motor-driven systems. She began her career at Advanced Energy testing thousands of motors, consulting with motor & appliance manufacturers on their designs, and documenting motor management best practices for the US Department of Energy. Subsequently, she managed statewide energy efficiency programs at the NC Department of Commerce and then facilitated sustainability projects for the City of Raleigh. Nicole holds master's degrees in mechanical engineering and public administration.

Although the industrial energy efficiency space is crowded, Motors@Work's goal is simple: to provide an intelligent, intuitive, systematic, and secure performance management service that enables our clients to optimize the performance of their motor-driven systems.

Motors@Work is a scalable, cloud-based, software-as-a-service solution that provides continuous monitoring of your motor-driven equipment's energy performance. Our analytics augment your asset management processes with energy management best practices. Our solution leverages your existing technology investment whether you collect motor inventory data with handheld devices, capture data in your ERP or CMMS, or gather data from your SCADA, sensors, and sub-meters. Motors@Work presents full life-cycle cost analyses, combining your motor readings with external data including weather forecasts, utility rates, and our extensive motor catalog.

Email info@motorsatwork.com to learn more.



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