Investigation into Condition-Based Monitoring Techniques for Valves, Pumps, and Storage Tanks

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Executive Summary

Maintenance makes up a large portion of every plant's budget. It is necessary to keep equipment running at maximum efficiency to produce quality product. It is cheaper and easier for a plant to plan repairs on equipment before they fail. To accomplish that many plants use a preventative maintenance (PM) program where they repair equipment on a set timeline. These plants can then schedule the work and production around those repairs to avoid unplanned process downtime. Not all repairs are found to be necessary per a PM schedule which adds unnecessary maintenance costs, and equipment still fails even while using a PM program. A new form of maintenance program that tries to identify the shortcomings of PM is condition-based monitoring (CBM). CBM uses sensors and monitors to identify the current operating condition of equipment to identify if it is running as intended, if it is showing signs of wear and needs to be repaired, or it is close to failure. This research identifies CBM techniques for three common asset classes: valves, pumps, and storage tanks. Tables were produced for each asset class to show which failure modes each monitoring technique could identify. Future work is needed to expand this list to additional asset classes. Data are necessary to determine when action should be taken based on the measurements from each equipment sensor or monitor.

Maintenance is required on nearly every piece of equipment in a chemical plant throughout its operating life. The goal of an effective maintenance program is to only perform maintenance when necessary while also keeping the equipment running at a high efficiency. The oldest type of maintenance program can be categorized as run to failure or reactive maintenance. In this program maintenance is not performed on a piece of equipment until it fails. This technique does eliminate all forms of unnecessary maintenance. However, it is often very detrimental to operations and production. In this program failures are not predicted and can lead to significant losses of production which can hurt the profitability of a plant. Figure 1 below shows how costs increase exponentially (red line) as the equipment condition worsens. The time between functional failure point F and the point of total failure is the reactive maintenance zone. The time between the point of initial equipment degradation (point P) and F is when proactive maintenance can be done. Finally, from time 0 to P is when predictive maintenance is done.

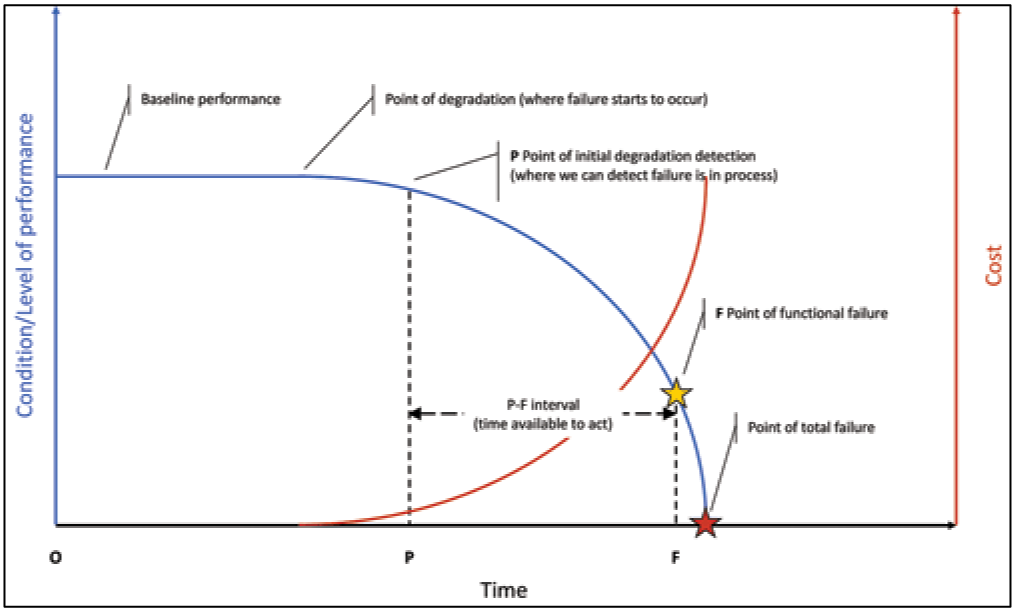

Figure 1: Performance-Failure Curve [1]

To try to avoid the major losses due to unpredicted failures a PM program can be implemented. In this program equipment is repaired based on a set time period or certain number of operating hours. As an example, the impeller on a pump could be replaced after 6 months, or, 4,000 operaing hours. By using a PM program, the maintenance can be scheduled ahead of time and the proper actions taken to minimize downtime or production loss, which can be a significant benefit to a plant. However, not all pieces of equipment need to be repaired within a fixed time frame, this means unnecessary maintenance can be done, which adds significant unnecessary maintenance costs to a plant’s budget. Many plants use PM programs within their maintenance groups, but there is room for improvement.

Many companies have begun to move towards condition-based monitoring (CBM). CBM is a technique where sensors and monitors are used to determine the current condition for a piece of equipment. Different operating conditions that can be monitored may include but are not limited to temperature, vibration, leaks, mechanical wear, corrosion, and decreased efficiency. Historical data can then be used to determine if a piece of equipment is operating normally, has suffered some form of wear and needs maintenance, or is likely to fail, which means CBM is a form of proactive maintenance on Figure 1. By using CBM, necessary maintenance can be completed before repair costs escalate and before functional failure occurs.

The goal of this research was to investigate three asset classes, valves, pumps, and storage tanks, and then determine how CBM could be used on each of those classes. Common failure modes were found for each asset class, and then monitoring techniques were found to identify conditions that would lead to each failure mode. The results of the research can be seen in the following pages.

Valves

Four common valve models were investigated to determine their compatibility with condition-based monitoring. They are as follows.

- Gate Valves: [2] A very common valve used primarily as a shut-off valve, meaning the valve is either fully opened or fully closed. A metal gate can be raised and lowered within the valve body to control flow. The gate sits within a seat inside the body of the valve, and the gate is raised or lowered by turning a threaded stem multiple times. This can be done with a hand wheel or pneumatic actuator. The seats of these valves can often become filled with solids, either from rust and corrosion or particulates in the fluid. This keeps the valve from completely closing, causing it to leak.
- Ball Valves: [2] Another common shutoff valve. A metal ball sits within the body of the valve and has a hole drilled through it that is the same diameter as the pipe. When the hole is parallel to the pipe the fluid flows through the valve, when the handle is rotated the hole becomes perpendicular and blocks flow. There are quarter turn valves, meaning the handle only must be turned 90 degrees to open or shut the valve. The seat is not as exposed as it is in a gate valve, so they are less likely to leak in the same manner.
- Globe Valves:[2] Globe valves are used to control and regulate flow. In a globe valve the fluid enters the valve body and flows through a circular seat, which sits horizontally, perpendicular to the normal flow path inside of the pipe. A circular disk or plug travels up and down to close and open the valve, which changes the flowrate. The characteristics of the valve seat and disk allow for throttling capabilities that are easier to regulate than standard ball or gate valves.
- Butterfly Valves:[2] Butterfly valves are another type of quarter-turn valve, like ball valves. Smaller valves use a quarter turn handle, however larger valves often use a handwheel with a gear box due to the high torque it takes to turn the larger disk. A butterfly valve operates with a thin disk of metal within the body of the valve. The disk can be rotated to completely close off flow. When the valve is opened the disk is parallel to the flow and not restricting flow. They can be used in a shutoff capacity or as flow control.

Valves can fail in many ways; one of the most common is leakage. Valves can leak around the seat on a closed valve, through the packing around the stem of the valve, or through the flanges where the valve and pipes meet. The seat, stem, and disk/gate/ball could be damaged. And finally, the actuator could fail, causing the valve to no longer operate. Figure 2 below shows the labeled cross section of a ball valve for the identification of the possible leak points.

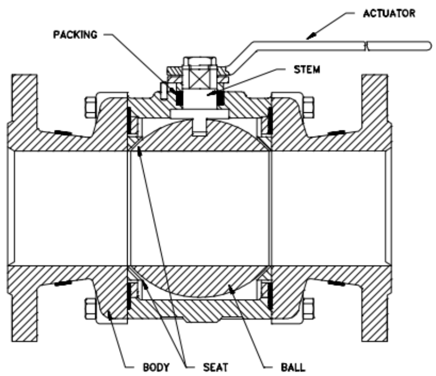

Figure 2: Cross Section of a Ball Valve [2]

Inspection techniques are done when the equipment is out of service. There are three inspection techniques that can be used for valves. Pressure testing is done by closing the valve fully and pumping fluid against it. If the pressure remains constant then there are no leaks, if the pressure drops then the fluid is leaking somewhere. Inferred testing can also be done on a closed valve, the monitor can detect leaking fluids as they are commonly at a temperature that is different from ambient conditions. Finally, visual inspection can be done to see if fluid is leaking externally from the valve.

Valves are not widely studied when it comes to CBM. However because there are so many within plants improving the maintenance of them can amount to significant cost savings over time. The following are techniques used for CBM on valves.

- Valve Torque: Sensors are attached to the stem of the valve near where it attaches to the actuator. This sensor monitors and records the torque necessary to move the gate, ball, etc of the valve. An unusually high torque may indicate a damaged seat, plugged valve body, or faulty actuator. Very low torque could indicate that the stem is broken since the actuator is not turning anything within the valve body. After unusual torque readings more investigation is necessary to determine the root cause. Sensors can be installed on new and existing equipment.
- Travel Time: A secondary calculation from the operation of the actuator that determines how long it takes the valve to open or close. If the valve takes too long to actuate then it can indicate damage to the seat.
- Position Monitoring: Most common position monitoring involves two limit switches to indicate when the valve is fully open or fully closed. More complex sensors can be implemented to show how far the valve is open, from 0-100%. This is often used to show if the valve has not fully seated when it is closed. Or if an actuator has failed and will not rotate.
- Acoustic Monitoring: Sensors used to detect the high frequency sounds that are associated with leaking seats. Software can then be used to estimate the amount of leakage based on

the frequency. Other sensors can measure the sound in decibels, that can then be compared to experimental data to determine how much leakage is occurring. The amount of leakage over time can be tracked so the valve is replaced or repaired before the leakage gets to an unacceptable level. [3]

- Electricity Consumption: Used on motorized actuators. The electricity consumption over time can be tracked to determine if an actuator is beginning to show signs of wear.
- Valve Flow Coefficients: Valve flow coefficients are experimental values determined by control valve manufacturers that correlates the flow of the valve to the differential pressure across the valve seat. When then actual flow across the valve is significantly different from the expected flow at a given differential pressure, it can indicate damage or a blockage within the valve.

The following table summarizes the valve CBM techniques that were discussed above and which failure modes they apply to. Multiple monitoring techniques can identify the same failure modes, and a single technique can identify many different failure modes. It is often necessary to use many of the monitoring techniques together to cover all the possible failure modes.

Table 1. Application of Condition-Based Monitoring Techniques to Valve Failure Modes

	Inspection		**Condition Monitoring**			**Predictive**		
Valve Failure Mode	Pressure Testing	IR-Leak Detection	Valve Torque	Travel Time/ Hysteresis Curve	Position Monitoring	Acoustic Testing	Valve Flow Coefficients	Electricity Consumption
Seat Leakage	x					x		
Seat Damage			x	x	x		x	
Packing Leaks	x	x						
Flange Leaks	x	x						
Actuator Failure								x
Stem Failure			x	x				
Control Failure					x			

Pumps

Three types of pumps were investigated to determine how CBM could be used to improve their operation and reliability. The three types are as follows.

- Centrifugal: Centrifugal pumps are one of the most common types of pumps in industry. An impeller sits within the pump housing. The impeller is fitted with numerous vanes. Liquid enters the inlet of the pump and the vanes on the spinning impeller impart energy to the fluid. This energy initially increases the velocity of the fluid; however, it is flung into the wall of the pump where the energy is converted into pressure. As the liquid flows out of the pump its pressure has been significantly increased.

- Reciprocating:[4] A reciprocating pump has a chamber with two valves, the inlet or suction valve opens as the piston moves backwards. As the piston moves back the volume of the chamber increases and fills with liquid. Once the piston begins to move forward the inlet valve closes, and the discharge valve opens. The piston forces the fluid out through the discharge at a higher pressure than in the inlet. An electric motor is attached to the crankshaft which can move 1 or more pistons. It is common to have 3 pistons that are all slightly out of phase with each other to help make the flow more constant.
- Rotary: Rotary pumps can come in many forms; common types are vane and lobe. Rotary pumps are positive displacement pumps. Liquid flows through the inlet and into the body of the pump. The two lobes rotate in opposite directions, one clockwise and the other counterclockwise. As they rotate liquid is trapped between the lobes and the wall of the pump. As the lobes continue to rotate it pulls the trapped liquid along with it. The liquid is then released on the other side of the pump body. The liquid from the next lobe forces the rest of the liquid out.

Pumps can fail in many ways, which will be categorized in three forms, hydraulic, mechanical, and corrosion & erosion. Hydraulic failures occur because of pressure changes in the pump or piping system. These are often due to changes in the fluid flowrate, velocity, or temperature. These commonly lead to issues like cavitation, pressure pulsations in the fluid discharge, or excessive thrust on the impeller and shaft.

Mechanical failures are very common. There are many bearings in the pumps which can fail. The seal around the shaft can fail which causes the fluid to leak into the external environment. Lubricants and oils can lead to performance decreases due to high temperature. Excessive vibration in the equipment can damage it. The equipment can have fatigue which causes it to crack and fail. Finally, the motor can fail for a variety of reasons.

The last form of failure is corrosion and erosion. Corrosion is the chemical deterioration and alteration of a material. This often occurs due to the environment and the chemical capability between the equipment and the fluid. Erosion is the physical wear on the equipment, often due to solid particles in the fluid. [5]

Pumps are a widely studied asset class when it comes to condition-based monitoring. There are many ways that pumps can fail which means there are numerous ways to perform CBM. The following list shows some of the most common techniques that are used for pumps. [6]

- Vibration Monitoring and Analysis:[6] This detects imbalance, misalignment, and looseness for different pieces of the pump. It is one of the most common techniques used for all rotating equipment. Accelerometers are often used as sensors and can easily be placed on new and existing equipment. There are numerous studies that discuss the amount of vibration that is acceptable for different size equipment.

- Lubricant Sampling:[6] It is common to get metallic particles in the lubricant, especially during the initial wearing in phase of the pump. The total amount of particles in the lubricant will increase over time, however, if the rate increases that can be a sign that something may be wrong. A common sign of excessive wear is very large particles. There are many testing methods, some can be done in the field and often measure iron concentration. More in-depth testing is often done at a third-party lab.
- Head-Flow Measurement:[6] A measurement of how much head a pump produces. A decrease in the amount of head produced indicates the total wear on the pump. This requires a repeatable flow measurement or other indication of flow. Variable speed pumps need to have the head produced corrected to the standard speed using pump affinity laws.
- Shut-Off Head Method:[6] A measurement of the shut-off head produced by the pump. The head produced can then be compared to the initial shut-off head to determine the amount of wear. This requires the discharge of the pump to be closed with a valve which can upset process operations or cause the pump to cavitate.
- Temperature Difference over the Pump:[6] Measures the temperature rise that a fluid sees as it goes through a pump. The temperature rises due to inefficiencies within the pump. More wear leads to a less efficient pump.
- Thermography:[6] The use of an infrared scanner to identify hot spots on the equipment. It can identify poor insulation, hot bearings, bad wiring, and even thin or wear spots on the pump casing.
- Ultrasonic Thickness Testing:[6] Used to measure the thickness of the pump casing point by point. Measurements can show how the pump wears over time. Specialized mechanics can use the monitor to detect and follow cracks.
- Motor Current Analysis:[7] Used to find broken rotor bars within the electric motor. This is done with vibration analysis tools with tong type probes.

The following table summarizes the pump CBM techniques discussed above and which failure modes they apply to. This table is specifically for centrifugal pumps as they are the most common pump used in industry. Multiple monitoring techniques can identify the same failure modes, and a single technique can identify many different failure modes. It is often necessary to use many of the monitoring techniques together to cover all the possible failure modes.

Table 2. Application of Condition-Based Monitoring Techniques to Pump Failure Modes

Centrifugal Pump	**Inspection**				**Condition Monitoring**				**Predictive**		
Failure Mode	Shut-Off Head	Lubricant Sampling	Ultra-Sonic Thickness Testing	Thermography	Head Flow Measurement	Temperature Difference Over Pump	Motor Current Analysis	Temperature Monitoring	Electricity Consumption	Acoustic Testing	Vibration Monitoring
Cavitation										x	
Pressure Pulsations											X
Radial Thrust				x				x			
Axial Thrust											X
Bearing Failure		x		x				x			X
Seal Failure				x				x			
Lubrication Failure		x									
Excessive Vibrations											x
Fatigue	x		x		x	x					
Erosion	x		x		x	x					
Corrosion	x		x		x	x					
Excessive Power Consumptio n							x		x		

Tanks

For the purpose of this research tanks are specified as only atmospheric storage tanks with fluids that are at or near ambient conditions. Other vessels like reactors, pressurized tanks, distillation columns, and others are not covered through this current research.

The failure modes for tanks will be broken up into 3 forms: roof failures, wall failures, and floor failures. Roof failures are most commonly caused by internal beam failure, usually due to corrosion, or vent failures.

Wall failures most commonly occur along the welds. This can be due to poor weld quality, further corrosion, or the density of the fluid in the tank can be greater than the density the tank was designed for.

Finally, floor failures are caused by corrosion. Internal corrosion is often due to solids built up in the tank, where external corrosion is due to moisture being trapped under the tank bottom.

Tank failures can be differentiated between catastrophic and non-catastrophic. Catastrophic failures occur suddenly without much warning. Explosions, roof and wall failures are common catastrophic tank failures. Non-catastrophic failures are often seen as general corrosion and pinhole leaks. They will get worse over time, but they can be corrected if acted upon in a timely manner.

Corrosion itself can be broken up into many forms as it is the most prevalent failure mode for tanks. [8]

- External Corrosion: This is largely due to the environment that the equipment is installed in. Tanks are often painted, or a coating is used to protect the tank against the conditions it will be exposed to.
- Internal Corrosion: Internal corrosion is due to the product within the tank and potential oxygen containing atmosphere. The conditions, like temperature and pressure, inside of the tank can also be factors. Materials of construction for the tank must be compatible with the product that will be stored within it. There are many chemicals that will attack nearly all metals so liners can be used to protect the walls. Tanks that hold solutions with high solids need to be drained and cleaned regularly. The build up of solids can lead to additional corrosion along the tank bottom.
- Stress Corrosion Cracking: Due to being exposed to a corrosive environment, often in conjunction with oxygen and high temperatures. In tanks that are susceptible to this corrosion liners may be necessary.
- Hydrogen Embrittlement: Common when metals are exposed to hydrogen, often below 150 C. It is most common at higher temperatures. This is not a common issue in storage tanks since they are at low pressures and molecular hydrogen is not found in liquids at those conditions.
- Corrosion Under Insulation: Very common in many asset classes especially tanks and pipelines. It is always necessary to choose the correct insulation for the expected environment. Additional precautions should be taken if necessary, that could include

painting the tank under the insulation, or adding additional weather barriers and flashing on the insulation.

Tanks are not a common area of study for condition-based monitoring. Most of the failure modes for tanks are non-catastrophic, meaning the plant often notices them before they get out of hand and has time to repair the equipment before complete failure. However, CBM can still help the plant predict failures and save money on maintenance over time. The following list summarizes various CBM techniques used for tanks focused on detecting corrosion as well as poor welds.

- Ultrasonic Testing:[9] A safe, simple, and accurate way to test tanks. It can be used to detect weld quality as well as corrosion. It detects the most common flaws in low alloy steel and is a portable testing system.
- Dye Penetrate Testing:[9] Used to find surface defects in welds. A dye is placed over welds and will seep into any cracks in the surface. This dye can then be seen with a developer to identify any poor welds.
- Radiographic Testing:[9] Often X-ray and gamma ray testing. X-ray is the most common, but gamma ray is portable. It can be used to detect internal defects within the welds as well as corrosion.
- Magnetic Particle:[9] Used to supplement radiographic testing. Films from radiographic testing are looked at with the naked eye which may cause the operator to miss small defects. A magnetic flux is introduced using a two-pronged yoke, cracks and corrosion between the prongs will introduce discontinuities in the flux which can be analyzed by an experienced operator.
- Eddy Current:[9] The best use is on equipment that is subject to cyclical loading. AC current passes through the probe and creates an electromagnetic field within the metal. Current flows through the metal and changes based on the material's condition, like corrosion or cracks. This is reflected on the signal that the probe receives. Experienced operators can determine where the defects are based on the resulting voltages and phase angles.
- Ultrasonic Guided Waves:[10][11] Commonly used in tanks and pipelines. Transducers are attached around the outer base of a tank. They send ultrasonic waves through the tank floor. The waves are reflected when they contact any corrosion or deformities in the metal. The reflected waves are then picked up and can be used to map the tank bottom, showing where the corrosion is occurring. This is one of the only techniques that can be used on an in-service tank.

The following table summarizes the tank CBM techniques discussed above and which failure modes they apply to. The failure modes were specifically corrosion and weld quality as they are the most common. Multiple monitoring techniques can identify the same failure modes, and a single technique can identify many different failure modes. It is often necessary to use many of the monitoring techniques together to cover all the possible failure modes.

Table 3. Application of Condition-Based Monitoring Techniques to Tank Failure Modes

	Inspection						**Condition Monitoring**
Failure Modes	Visual Inspection	Dye Penetrate Testing	Magnetic Particle	Radiographic testing	Eddy Current	Ultrasonic	Ultrasonic Guided Waves
Internal Corrosion	x		x	x		x	x
External Corrosion	x		x	x		x	x
Stress Corrosion Cracking			x	x		x	x
Poor Weld Quality	x	x	x	x	x	x	

Conclusions and Recommendations

Through this research condition-based monitoring techniques were identified for three common asset classes: valves, pumps, and storage tanks. Failure modes for each of the asset classes were also identified. Three tables were then produced to show which failure modes the condition-based monitoring techniques could identify. These tables are valuable to easily identify the application of the various techniques.

This work only identified and consolidated the CBM techniques for the three chosen asset classes. Future work will be necessary to identify similar information on other asset classes. Additional research and testing will also be needed for the application of CBM in a plant. While the various monitoring methods were found, many did not specify when further actions would be needed. As an example, the travel time of a valve can be used to identify if the valve seat is worn. However, it is not specified what travel time or increase in travel time from some standard is a cause for concern. Without that information the use of travel time as a CBM technique is not effective.

A probability of failure curve for each monitoring method will be useful for determining what actions must be taken. The curves would be created using experimental data. The measurement from the CBM technique is on the X-axis, in the travel time example that would be travel time in seconds, or a percentage increase of travel time. Along the Y-axis would be the probability of failure for that given measurement. From that figure each plant or maintenance group could decide when to use alarms or indicators so they could schedule maintenance or shut the equipment down to prevent major failures.

For some techniques, like vibration analysis, these levels have already been determined by several sources. For many other methods significant research has not yet been completed and will be necessary prior to extensive use in a plant environment.

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