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Operations and Maintenance of Unspared Compressor Trains and Their Auxiliary Systems

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ABSTRACT

This tutorial provides general guidance on the topic of operations and maintenance of unspared compressor trains and their auxiliary systems. It is targeted towards entry level engineers working in the operations and maintenance field. The tutorial will be divided into two major sections.

The first section covers 'online' checks and inspections including vibration monitoring, auxiliary system monitoring, regular visual inspections, online preventative maintenance, documentation maintenance, and performance monitoring.

The second section covers the efforts associated with turn-around and maintenance (planned or un-planned). This includes details on maintenance intervals, preparation and planning for outages and peripheral system checks during an outage.

INTRODUCTION

Supporting the operation and maintenance of unspared compressor trains and their auxiliary systems by a new machinery engineer is a complex undertaking. It requires knowledge of the equipment design and what to monitor during operation and careful preparation for planned maintenance.

Online checks and inspections are the first area requiring attention. Vibration monitoring equipment and the interpretation of the vibration signature is a critical area. Important performance parameters from the compressor train and its support systems need to be collected and periodically reviewed. This includes computer recorded data as well as the machinery engineer's field observations. The daily operation and maintenance requirements must be fully understood to maintain equipment reliability.

In addition the detailed planning required to conduct a scheduled maintenance outage is an important part of the machinery engineer's duties.

The machinery engineer must also ensure that all of these activities are performed in accordance with local safety regulations and site requirements. Safety is an integral part of the job; this includes safety of self and others in a broad array of situations such as proper caution around rotating shafts, use of proper lifting tools and techniques for heavy components, protection from thermal extremes, and careful maintenance of critical safety trip mechanisms. There is no aspect of the job that is more important than safety. Taking the time to properly evaluate the potential hazards of the task at hand cannot be overstated.

SECTION 1: ONLINE CHECKS AND INSPECTIONS

1-1 Vibration Monitoring Systems

Vibration monitoring is likely the most fundamental condition monitoring system for turbomachinery. Thus,

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ensuring that this system is properly designed, installed, and that the data is regularly reviewed are crucial to satisfactorily monitoring the equipment. Vibration monitoring of turbomachinery trains is typically accomplished using proximity probe systems. Gearboxes with their inherent high frequency vibration typically require the addition of accelerometers. *API 670 Machinery Protection Systems* provides a thorough overview of system design information for vibration monitoring as well as temperature and speed detection systems. Highlights from API 670 include the following:

- The proximity probe transducer system needs to be calibrated using a target that has the same electrical characteristics as the shaft material; for example 316SS is not the same as AISI 4140.
- Shutdowns require a time delay of one to three seconds. This means the vibration must be sustained for that period of time before the shutdown will actuate. One second is shown as the default however three seconds is more typical.
- Signal wire needs to be segregated and shielded to avoid noise in the signal.
- Proper grounding and shielding is extremely important to prevent trips from spurious electrical signals, such as electrical system faults, lightening or higher voltage control signals. (Consult the vibration system supplier for specific requirements.)
- Proper probe orientation is required to gain full diagnostic capability. For example, looking from the driver toward the driven equipment, the Y probe is on the left, and the X probe is on the right regardless of the direction of rotation. The probes are typically 90 degrees apart. On some older machines both probes are to the left or right of a vertical plane; in that case, rotate the axis but maintain orientation. Likewise the physical location of the once-per-rev reference timing mark sensor should be carefully recorded if it is not visible externally.
- Zeroing the rotor axially at the center of its float is specified as standard in API 670, but there are many facilities that zero on the active pad. Zeroing on the active pad may result in misunderstandings, mismatches or incorrect alarm/shutdown points. It is most important to choose a standard to follow throughout the facility to avoid confusion during troubleshooting.
- Field testing (discussed more below) should be an integral part of any overhaul.
- When automatic trips are in place, consider installing spare probes as back-up for those that cannot be replaced while the machine is in service. This should be considered for radial probes and is more important for thrust probes where two out of two (2oo2) voting for shutdown is more common.
- Power supplies for the system – specify redundant power supplies.
- Selecting a full scale setting of 10 mils (250 µm) is typically more applicable than the default of 5 mils (125 µm) (depending on the alarm and trip set points). This however is a function of machine size; a 2” (51 mm) journal will have a different default than, for example a 12” (305 mm) journal.

All proximity probe systems consist of a probe, an extension cable, and an oscillator-demodulator. Proper installation and configuration of these components is, like most turbomachinery work, an exercise in attention to detail. This attention to detail extends beyond the initial installation as most disassembly work for maintenance will require that the final portion of the proximity probe system be removed and reinstalled. Components must be properly matched to the target material and properly assembled in order for their calibration curve to fall within the specified range. Damaged probes can produce nonlinear calibration curves, and pairing the incorrect extension cable with a proximity probe will provide a linear signal, albeit with the incorrect slope. “Running curves” (calibration curves) on the probe systems should be a standard practice for all major outages along with a thorough review of the resulting data. (API 670 provides testing acceptance criteria of 80 mils (2 mm) linear range, deviation from straight line of +/- 1 mil (25.4 µm) and incremental scale factor of +/- 5% of 200 mV/mil (7.87 mV/µm); this criteria is applicable to AISI 4140 material). Documenting the proper part number for each component in a measurement system and validation of the readings from the probe tip to the oscillator-demodulator to the data management system to the plant data historian are critical. This allows signal interpretation for a properly physically located probe and validated tag number to be a much less frustrating event – especially under duress.

Incorrectly or insufficiently grounded systems can provide faulty signals even on channels that are properly installed. Basic troubleshooting of grounding issues should include the following:

- Ensure that all of the probes and extension cable connectors are isolated from ground. All connectors need protectors or self-fusing silicone tape to ensure that they remain isolated. Teflon tape can be used but should not be viewed as the optimum means of isolation.
- Ensure that all of the oscillator-demodulators are isolated from ground. Check that the oscillator-demodulator is truly isolated by removing the field wiring and the extension cable and then checking the resistance between the common on the terminal strip and the oscillator-demodulator housing. The resistance should be infinite.
- Ensure that there is not an electrical short between the probe shield and the probe case. Do this by testing the resistance between the probe case (or the machine case if the probe is installed) and the probe or extension cable connector shield. The resistance should be infinite.
- Ensure that the shields of all field wiring are cut off and taped back at the oscillator-demodulator and that they are connected to earth or common at the monitor rack only.

During maintenance activities, probes that cannot be accessed while the machine is in service are typically replaced

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as the cost of a replacement probe is typically negligible compared to the cost of an unscheduled outage.

The probe target is typically a burnished area, sometimes at a slightly reduced diameter near or within the bearing journal. Maintaining and protecting this surface is of utmost importance to get accurate and representative vibration data. Various industry standards such as *API RP 687 Rotor Repair* provide a limit of 0.25 mils (6.35 µm) electrical and mechanical runout (EMRO) for this target area, and while this is achievable it is not uncommon to accept values slightly greater (typical industry repair criteria is to complete three attempts to achieve this value after which the vendor and the client shall mutually agree on an alternate acceptance criteria). Once this activity is complete, electrical tape is placed over the target to protect it from handling and component assembly damage (it is to be removed upon completion of rotor installation). In the instance when damage does occur to the burnished area, there are few (no?) in situ mechanical methods that provide a fool-proof solution. The most viable path forward is to document the location of the damage relative to the time mark sensor and to use slow roll data to electronically compensate for the damage. The speed at which slow roll data should be obtained can generate quite a bit of discussion. The key takeaway is that the data should be taken at the lowest speed possible where the data is stable in amplitude and phase. Typical values of 500 rpm for a 3600 rpm machine have provided acceptable results.

With the system installed and equipment running, vibration monitoring can range from simply triggering alarm and danger switches (stand-alone field rack) to continuous data logging of waveforms and other associated probe data (machinery health management system). An intermediate installation might have overall vibration values trended on a plant data historian. Regardless of the installation, all systems have hardware alarms and danger settings to alert the user to abnormal conditions. There are several sources that provide guidance in determining radial set points. In general they agree, but ultimately a site should select one philosophy for consistency (there will be exceptions to the rule and machine specific design should dictate the final criteria). Figure 1 shows a comparison of several of the sources including Eisenmann and Eisenmann (1997). One can see that for machines operating at 3,600 rpm a typical radial alarm value would be 3.5 mils p-p (90 µm p-p) and a typical danger value would be 5.5 mils p-p (140 µm p-p).

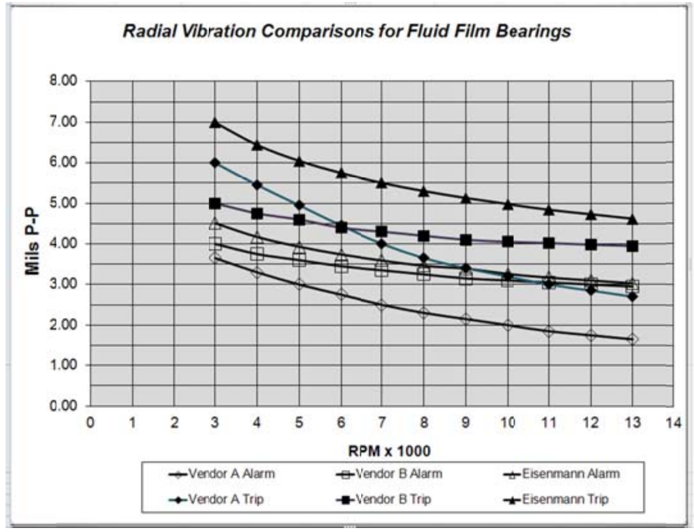

Figure 1. Radial Vibration Comparisons for Fluid Film Bearings.

Eshleman (1999) provides an alternate means of setting these values using bearing clearance. Alarm values for a speed of 3,600 rpm using his method would be 0.5 of the bearing clearance, and shutdown would be 0.7 of the bearing clearance. A speed of 10,000 rpm would alarm at 0.4 of the bearing clearance, and shutdown would be 0.6 of the bearing clearance.

Determining of thrust bearing alarms and shutdowns are a function of the thrust bearing clearance, the thrust loading and the machine internal clearances. A typical thrust alarm would be set 10 mils (254 µm) beyond one half of the total float and the shutdown would be set at least 5 mils (127 µm) beyond the alarm. Once the thrust probes are set, it is a good practice to record the DC voltage that corresponds to at least one physical position as a calibration reference. Thrust probe adjustment or calibration changes should not be attempted online.

Beyond hardware alarms, machinery health management systems offer significant flexibility for enhanced monitoring. Software alarms can and should be configured as these alarms provide recognition of changes in machine performance ahead of the hardware alarm operations personnel will receive. These values are typically set slightly above the "normal" values (experience and nuisance alarms will dictate the final margin above normal but a good starting point is 0.5 mils (12.5 µm) for overall values and 0.3 mils (8.5 µm) for 1x). Typical software alarms include:

- Overall vibration
- Synchronous vibration
- Non synchronous vibration
- Gap voltage
- Phase angle
- Spectral band alarms (less common)

Even with these alarms in place there should still be a system that provides a periodic review of machine performance. Quarterly review intervals of the trends ensure

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that issues beyond the capability of the health management system do not get out of hand.

With these systems in place, one can expect that problems will be identified. Anticipate that you will be asked to interpret the data and make decisions based upon your knowledge of the machine, the machine's history and its operating conditions. The best data interpretation is a compilation of multiple sources – colleagues, industry analysts, vendor representatives, site mechanics, and operations specialists to name a few – and knowing in advance who you might contact will be to your advantage. Each of these people brings a different knowledge set and perspective to the table that will ultimately provide a comprehensive response to address the problem. One should also expect that there will come a time when the machine goes into alarm. Sometimes this alarm quickly progresses to a trip value, and the system makes a decision for you. There are other times, however, when the values float or spike in and out of alarm and the path forward is not as clearly defined. The collaboration mentioned above will be necessary to develop a plan for a controlled shutdown or altered set of operating conditions that minimizes or eliminates the risks associated with the problem.

1-2 System Performance Monitoring of Auxiliary Systems

Auxiliary systems are necessary to support the rotating equipment. As such, their performance and readiness are critical to ensure trouble-free operation. Critical systems included in this discussion are the seal systems, auxiliary steam systems, and lube oil systems. Following are recommendations on how to monitor the performance of these systems.

Seal Systems (Dry Gas Seals and Liquid Seals)

Dry Gas Seal Systems

The primary purpose of a dry gas seal system is to provide clean dry seal gas to the compressors within an acceptable range of pressure, temperature, and flow. Monitoring the following will facilitate this effort.

- Filters – Monitoring differential pressure across the filter in operation provides indicates the cleanliness of the element. A log should be kept of this parameter, and the filter element should be changed when recommended differential pressure is reached. The seal gas supply system must be kept free of liquids with an appropriate monitoring strategy to check for oil (from previous seal oil systems) or gas condensate. If liquid is noted on regular basis, verification of the seal gas heater operation (if equipped) should be checked.
- Log Pressures/Temperatures/Flows – Following commissioning of the system, regular/expected values (seal supply, intermediate seal supply, barrier seal supply, vent flows, etc.) will be identified for the various pressures/temperatures/flows in the system. Trending this information will allow the operator to identify any changes over time.
- Low Point Drains on Primary/Secondary Vents – Regular checks (timing dictated by findings) for presence of condensate or other liquids. If liquids are found on a regular basis, you need to verify what type of liquid it is (condensate, water, lube oil,) and source. This could be an indication of a future seal failure.
- Heater Elements – If supplied, seal gas heater performance should be monitored and trended. The intent is to determine if fouling of the heating element is occurring, which is indicated by increasing/excessive electrical demand by the heater.
- Booster Performance – If supplied, any seal gas supply pressure boosters should be verified to be functional on a regular basis. While not in use the majority of the time, when called upon, they are vital to providing adequate seal gas supply flow. Assemblies should be regularly tested (weekly) and verified functional either via manual testing or through the control panel. Note that many of these types of assemblies depend upon shop air as a motive force. As such, maintenance of the shop air system cleanliness/dryness should be done a regular basis as well.
- Heat Tracing Performance – Many systems include heat tracing of the seal supply lines between the gas seal panel and the compressor to prevent liquid drop out. Recommendation is to monitor the electrical demand (as compared to baseline information post commissioning) for this system to ensure it is functional.

Liquid Seal Systems

As with dry gas seal systems, the intent is to provide a clean sealing medium (oil in most cases) to the compressor. Please note that in a sweet gas compression process, seal oil systems are often incorporated directly into the lube oil system. As such, many of the performance monitoring requirements are the same. The key difference is the presence of degassing tanks, and the necessary checks on these components.

- Sweet Oil Condition – Regular analysis of the sweet oil returning to the main reservoir should be performed. Intent is to verify that all the process gas has been removed from the oil.
- Log Pressures/Temperatures – Following commissioning of the system, regular/expected values (sour seal oil traps, degassing tank,) will be identified for the various pressures/temperatures in the system. Trending of this information will allow the operator to identify any changes over time.
- The sour seal oil leakage flow rate can be measured by "bucket-and-stopwatch" approach, e.g. block in the seal drainer outlet, and time the level increase in the sight glass. Large changes in sour oil flow rate can indicate a damaged or distressed seal. Trending of this data over time will indicate seal degradation.
- On some systems that have sight glasses where the leakage can be seen, it provides a qualitative amount of leakage which indicates when the seals are not performing as designed.

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Auxiliary Steam Systems

- Vacuum system – Monitoring of the vacuum is typically done continuously using pressure taps or transmitters. Inability to maintain vacuum in the desired range can be caused by a poorly operating vacuum system or excessive air leakage into the system. (Vacuum system leaks can sometimes be found using the "helium leak testing" method.)
- Gland system –Monitoring valve position (of both vent and make-up valves) to ensure they are stable and their position indicates acceptable performance along with visually inspecting gland areas for leakage due to excessive sealing steam or insufficient vacuum on the gland condenser.

Lube Oil Systems

The key purpose of the lube oil system is to provide clean oil at an appropriate pressure/temperature/flow rate, to the bearings, as dictated by the OEM. Monitoring the following will facilitate this effort.

- Filters – Monitoring differential pressure across the filter during operation indicates cleanliness of the filter element. A log should be kept of this parameter, and the filter element should be changed when recommended differential pressure is reached. They should also be replaced on a time limit because they may deteriorate due to contact with the oil or process gas.
- Oil Cleanliness/Quality – Regular oil analysis should be performed to ensure that there is no buildup of contaminants or water content.
- Log Pressures/Temperatures/Flows – Following commissioning of the system, regular/expected values (pump output pressure, reservoir temperatures, and oil flow) will be identified for the various pressures/temperatures/flows in the system. Trending of this information will allow operator to verify any changes over time.
- Coolers – Monitor/record pertinent cooling water flows/temperatures. Trend cooling water flow required in order to maintain required oil temperature levels. An upward trend could be a sign of fouling on either the oil or the water side.
- Oil Level – While there are generally alarms associated with low level, it is prudent to regularly check the oil level in operation. Small changes trended over a long period may indicate loss of oil either via piping leakage, excessive misting or worst case into either the dry gas seal system (if equipped) or the process (if oil seals installed). If identified, the source of loss needs to be determined.
- Valve Positions - It is a good practice to record the approximate valve position for reference immediately after startup, and just before a planned shutdown. This key information can be used to confirm operation is normal, or for troubleshooting of a system problem. Newer installations with current control valve designs provide electronic feedback for valve position, which is a rich source of information.
- Auxiliary or Secondary Oil Pumps - It is good practice to test the secondary pump at an outage to verify pump startup maintains oil pressure without initiating a trip of the unit.
- Accumulators - check on accumulator pressures on any systems that have them.
- Overhead Rundown Tank – Daily visual inspection while online of sight glass for signs of water in the oil.

1-3 Importance of Engineering Rounds

Most turbomachinery tends to be the heart of large scale production facilities, and it is important to recognize the benefits beyond instrumentation that field inspection can offer. While field inspection by operators can identify many issues, a set of trained eyes that haven't been narrowed by daily walk-arounds provides yet another means of ensuring production by predicting problems and improving work scope development. Suggested areas for field inspection are shown in Table 1.

Operator Rounds	**Engineering (and/or Specialist) Rounds**
Record local instrumentation readings	Record local instrument readings
Confirm local instrumentation matches "house" values	Determine exact location of oil/steam/water/process leaks for reference during repairs
Identify oil/steam/water/process leaks	Validate the acceptability/consequence of leaks
Identify unusual noise	Unusual valve rack position vs. load
	Evaluation of seal leakage rates
	Temperature and condition of seal drain lines
	Identify unusual noise
	Unusual component position or motion
	Auxiliary system performance (See Section 1-2)

Table 1. Suggested Field Inspections for Turbomachinery.

These walk arounds also tend to strongly encourage the engineer to learn the systems and interact regularly with the operators.

Occasionally including plant management during the engineer walk around can also be used to: (1) teach the manager a little about the machinery systems so that they have a basic knowledge level and (2) demonstrates to the operators that the plant management recognizes the importance of the attention to detail that is required of the operators on a daily basis. (It is not about the engineer looking good to the manager; it is about the teamwork on different levels- operator, engineer, and manager, to provide the knowledge, resources and detailed attention to properly maintain the equipment).

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A specific example of the benefit of the above rounds is illustrated in the following actual event. A compressor deck walkthrough by engineering identified an abnormally high frequency/low amplitude oscillation of a steam turbine valve rack. Machine throughput was not affected, and operators did not recognize the motion as abnormal. Additionally, the computer trend data was collected at one minute intervals and therefore did not accurately represent the field motion. Engineering personnel worked to understand the reason for the motion and provided a report to operations that the issue would need to be addressed or otherwise risk taking an unscheduled outage. A plan was developed to work the rack in service, and during the work, several components of the valve rack were identified as significantly worn. The rack was repaired and returned to service. Had this situation been allowed to continue unabated, the rack would have likely locked up forcing an unscheduled outage.

1-4 Preventative Maintenance

The first place to start with preventative maintenance is to look at the OEM manual. This document will form the foundation of the list of items to consider in the Preventative Maintenance (PM) program.

Some items can and should be performed while the machine is running. These are the items considered in this discussion. Those items that require a shutdown are the subject of sections 2-1 and 2-2 (Discussion of maintenance intervals and Prep-Planning for outages). Suggested PM items are listed below. The time interval to check them is dependent upon site experience and conditions. For a new installation, shorter intervals are recommended. Gradually lengthen the intervals with experience; perhaps some items can be lengthened to match the basic machine shutdown interval (discussed in section 2-2), but should rarely be completely eliminated.

- Keeping the equipment clean and the collection and disposal of any oil leakage will allow the observation of small changes. For example, leaks at oil/air/gas fittings will leave a telltale dirt track on the adjacent surface. This allows leaks to be caught and corrected before they can become a critical driver for a planned (or unplanned) shutdown.
- Compiling a list of “to do” items if the unit trips is wise, separated into categories of timing “hours”, “days”, “major”. For example, greasing a steam turbine linkage may take only an hour of down time, while replacing a leaking compressor seal may take a few days. Always keep this list evergreen and well-publicized for yourself and the maintenance and operating departments.
- Change oil filters on a regular basis. The interval should be based on unit experience, either time or filter differential pressure, but it should not be put off too long because some filter materials degrade with time.
- Oil coolers should be cleaned during the colder months of the year based on site experience. They can become fouled on the water side (or air if a fin-fan cooler type) AND on the oil side as oil contaminates (varnish) typically accumulate on the coolest surfaces in the system (the tubes in the oil coolers).
- The oil pumps and their drivers should be a part of the PM system. Address seal leaks promptly, check couplings (particularly if they are a wearing type) and maintain their drivers. Test and repair steam turbine traps, governor linkages, and over speed trip, as recommended. Motor drivers should be kept clean (fans and air passages) of debris.
- As stated in the previous section, it is good practice to periodically test the aux pump auto startup system. (If you don’t have confidence that it will start during a controlled test, how can you have confidence that it will start when you are not there?) Work out the bugs for the test during the next downtime opportunity. Develop a detailed procedure and checklist.
- Some locations have government requirements to test relief valves periodically.
- For large motor drivers, change the air filters at a regular interval. Sweep bugs and trash off the inlet grill periodically.
- Check large motors for internal oil leaks. If the motor is TEWAC (Totally Enclosed Water-Air Cooled) type check for water leaks. Keep oil sight glasses clean externally (clean them internally during a shutdown)
- Set up a regular interval to check the steam turbine Trip and Throttle Valve (TTV) partial stroke to prove it will close when demanded (partial stroke testing is NOT a preventative measure to keep the shaft clean of scale or deposits; it does show the stem to bushing clearance is acceptable.).
- Block in and stroke-check the compressor recycle and anti-surge valves periodically to confirm proper operation and record the opening times.
- Keep steam turbine insulation in good shape to protect adjacent sensitive controls and instrumentation. Oil soaked insulation should be promptly replaced as it represents a potential fire hazard. Check that insulation is not close to moving linkages or valve stems where it could impede motion.
- Change the oil at a planned turnaround or by bleed/feed in accordance with the oil supplier’s recommendations, and periodic oil test results. Most major oil suppliers have a test service available. To obtain the best information have the oil samples caught in a consistent location/method and test for particulates, water, acidity, viscosity, etc. Basic tests should be performed multiple times per year. An annual comprehensive test will point to which parameters to check more often.
- Check steam turbine linkages for wear on the linkage pins and shaft bearings visually on a regular basis. Some components can be lubricated or replaced online.
- Check oil centrifuges or vacuum dehydrators for proper function.
- Check/clean the rundown tank vacuum breaker.

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1-5 Documentation

The purpose of this section is to highlight both the documentation that should be available when you arrive at the site, as well as what documentation needs to be generated in the course of operation and maintenance efforts.

Importance of up-to-date OEM Installation and Operations Manuals

Existing materials that should be on hand at any facility consists of up-to-date Installation and Operation Manuals (IOM's) for all critical pieces of equipment. It is important to verify that the latest revision of the documents are available, as often times revisions (alarm/shut-down set points, part numbers, etc.) are generated during the original installation and commissioning period. It is also recommended to verify with OEMs if any applicable post shipment updates pertaining to your equipment are available.

Another potential pitfall is if a third party Engineering and Procurement Contractor (EPC) was involved with the original installation. In those circumstances, the OEM may still have them on record for any documentation updates. As such, it is recommended to confirm that the OEM has your organization registered to receive any IOM updates and/or post-shipment updates

Lastly, it is recommended that if in the course of operation and maintenance of equipment, you, as the end-user make any changes, and these should be relayed back to the OEM. This would include both the primary OEM, as well as whomever the end-user purchased the equipment through.

> Example – During the course of operation and maintenance of a gearbox, an end-user identified a vibration issue. The end-user consulted directly with the gearbox OEM. An alternate bearing design was recommended, which resolved the vibration issue. The problem was that the gearbox was purchased as part of a complete compression package, with the compressor OEM as the prime supplier. In this case if the end-user approached the compressor OEM for spare parts in the future, they would be supplied with the original design, as the compressor OEM are unaware of the design change. For this reason notification of both the OEM as well as the prime supplier (not the EPC) is recommended.

Additional documentation that should be on hand consists of applicable industry specifications, standards and recommended practices. This would consist of previously noted API 670 relating to Machinery Protection Systems (see Section 1-1) as well as any API Recommended Practices documents associated with equipment that you have at your facility.

Importance of Full and Accurate Documentation of Maintenance Efforts / History

During the course of operation of equipment, regular maintenance is necessary to ensure availability and long life. Section 2-2 of this tutorial covers the appropriate intervals for this maintenance:

Documentation and records of each maintenance effort should be retained to build a historical file on each key piece of equipment. Information that should be retained consists of the following.

- Full details of why the equipment was down for maintenance – Was it a planned outage? Or due to unforeseen circumstances?
- Full reports from key individuals associated with the maintenance effort. This should include details on what specific activities were undertaken, any general observations of the equipment, any recommendations for future maintenance that is not being performed at this time, and any difficulties with specific tasks. Anything out of the ordinary should be photo-documented for future reference.
- Full details (part numbers and quantities) on what consumable materials were used during the outage.
- Comment on whether any capital spares (such as rotor assemblies, dry gas seal assemblies, bull gear/pinion sets, etc.) are used. If so, details such as serial numbers (from OEM) or stock/inventory number (from end-user) should be recorded.

Retaining this information will be useful for future reference to document how often the same issue is recurring, as well as for guidance on setting maintenance intervals in the future.

1-6 Performance Monitoring

The benefits of performance monitoring differs from machine to machine based on service and machine type. Services that have high tendency for fouling tend to have more dramatic performance changes compared to clean services such as refrigeration. Steam turbines should be treated as a fouling type service regardless of how "clean" a system claims to be due to the potential for boiler chemistry upsets. Table 2 lists the key parameters that should be recorded for critical turbomachinery along with the suggested scan intervals.

Fouling Compressor (includes air machines)	
Stage efficiency (trend not actual)	Daily/real-time
Balance piston seal leakage rate	Monthly
Wheel to wheel pressure survey	Quarterly
Throughput vs design	Yearly
Clean Service Compressor	
Stage efficiency (actual)	Yearly
Balance piston seal leakage rate	Monthly
Wheel to wheel pressure survey	Commissioning
Throughput vs design	Yearly

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Steam Turbines	
Stage efficiency (trend not actual)	Daily/real-time
First stage wheel pressure	Daily
Thrust bearing temperature	Monthly
Hot well conductivity	Daily/real-time
Steam impurity	Daily/real-time
Throughput vs. design	Yearly

Table 2. Monitoring Parameters and Intervals for Turbomachinery.

SECTION 2: OUTAGE AND MAINTENANCE

2-1 Maintenance Intervals

There are two basic categories to consider when setting the maintenance strategy for the unit planned outages: operating constraints and maintenance/mechanical constraints.

- Operating constraints can include: fouling/corrosion/erosion of non-machinery operating equipment (drums, towers, reactors, etc.). There can also be government regulatory inspection interval requirements. Sometimes these intervals are shorter than the machinery requirements.
- Maintenance/mechanical constraints should initially be based on OEM recommendations when the unit is first commissioned. As unit experience is accumulated, the interval on certain items can be adjusted with careful review of the operational history.

Where the operating constraints interval is shorter than some (or all) of the maintenance mechanical constraints, the strategy for certain planned activities may be a mixture. For example the machinery must be shut down for a reactor catalyst change every three years. The OEM recommends seal overhaul/replacement every five years. The strategy may be to replace the seals at the first outage after three years of operation. If the seals are found to be in excellent condition, and the risk is believed to be low enough, then the seals will be replaced again in six years (skipping a planned outage).

In other words, based on actual experience, some base intervals can be lengthened by considering conditions found during the previous outage, or one/two turnaround intervals. Keep in mind that extending the interval without making fact based decisions is simply run to failure. Take prudent, well considered risks, using good judgment coupled with industry experience. Follow the OEM recommendation until there is clear justification and experience to suggest otherwise.

Items that can set turnaround intervals are:

- Large motor cleaning
- Steam turbine internal erosion (or fouling) of rotating or stationary components
- Compressor internal fouling, erosion, corrosion
- Compressor seal leakage rate increase (sour oil loss) due to fouling or coking of the seal
- Bearing temperature –long term trends
- Coupling wear (for the older gear type couplings)

2-2 Preparation and Planning for Outages (both planned and unplanned)

This section focuses on planning for both regular maintenance outages as well as being prepared for unplanned outages.

Identify different levels of outage

Based on the specific goals of an outage, there are several levels to be considered.

- Basic Inspection: This will generally be a short duration outage and is limited to minor visual/physical/dimensional inspections. Intent is to fine tune the maintenance intervals noted in Section 2-1.
- Routine Minor Maintenance: This will generally be for replacement of common consumable/wear items such as journal or thrust bearing pads as well as maintenance of various auxiliary systems that cannot be accessed during operation.
- Routine Major Maintenance: This will generally consist of maintenance or replacement of major capital spares such as rotor assemblies, dry gas seals, or bull gear/pinion sets.
- Full Overhaul / Revamp Outage: This consists of full rework of the equipment in question. This type of outage will generally require significant planning and longer outage duration.

Ensure availability of necessary spares for level of outage

As noted previously in this section, there are several different levels of outage. Each will have its own list of consumable materials required. It is recommended to generate a list of common outages, and what consumables are historically required for each type. Review of maintenance records should provide guidance on this. Prior to any planned outage it is recommended to verify that all appropriate spares/consumables are physically confirmed to be on hand and in good condition.

Note – The recommendation is to procure a full set of consumables before each outage, even if there is a set on the shelf. This gives you the advantage of having an additional spare if something is lost and/or damaged in storage or during maintenance efforts.

Ensure availability of necessary standard and special tools

As with spares, each type of outage will generally require a specific set of standard and special tools. As you go further into the equipment, the list will get longer. Definition of tools required for each specific task can be found by reviewing the maintenance section of the OEM service manuals.

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Recommendation is to review the list of special tools noted for the planned outage, and then physically gather and inspect these items. If any items are missing or damaged, they should be replaced/repaired prior to the shutdown. In addition, if any heavy lifting is required, all eye bolts/slings/chain falls/etc. should be physically inspected to ensure all are in good condition.

If there is potential that the alignment of the equipment could be affected, be sure to have necessary special tools on hand. In many cases this calls for laser alignment equipment, which may not have been supplied by the OEM. In that circumstance you will need to either procure or arrange for availability of this specialized tool. In addition, due to the nature of laser alignment equipment, it may be recommended to secure the services of a specialist technician to perform the alignment process. The key benefit here is that the specialist will generally be much more familiar with the equipment and process through regular use (as opposed to using once every couple years).

Identify key engineering and technical resources for level of outage

Depending on the level of outage, varying levels of Engineering and Technical resources may be required. As with spares and tooling, the recommendation is to generate a list of required resources for common outages, and ensure their availability. This can include but is not limited to the following.

- Mechanics
- Millwrights
- Welder
- Electrical/Instrument Technicians
- Maintenance Supervisor
- Safety Supervisor
- Process Piping Isolation Specialist
- OEM Field Service Representative

Note – If your outage is due to difficulty with a specific piece of rotating equipment (motor, gear, compressor), it may be prudent to confirm the contact information for the OEM Technical Support department. They can then be consulted either prior to or during the outage to provide assistance as necessary.

Contingency Planning

With respect to planning for unplanned outages, the key is to identify (ahead of time) potential issues with the equipment. Review of site specific process and historical service records can provide guidance.

- It is always a good idea to have a complete set of basic consumable materials (gaskets, O-rings, specialized sealant, etc.) to be ready to open and inspect all major components of the equipment train.
- Is site specific process noted for process upsets leading to vibration spikes? If so, be prepared with a complete set of bearings, consumables and internal seals.
- If equipped with dry gas seals, is source of high-pressure seal gas subject to interruption? If so, be prepared with spare set of dry gas seals.
- Are there any known issues with quality/reliability of plant utilities? If so, review what could happen if any systems were compromised.
    - Quality of cooling water can affect process coolers and lube oil coolers.
    - Quality/reliability of instrument air can affect control of process valves and bearing seals.
    - Quality/reliability of steam system can affect reliability and power of steam turbine drives. This would be true for everything from lube oil pump drivers up to prime mover turbines.
- Is the site specific process known to have an issue with wet or dirty process gas? If so, plan ahead for potential ingestion of large quantity of liquid and or solid material. This can encompass complete spare compressor internal bundles, spare bull gear/pinion sets, or full sets of drive couplings. While cost of these spares may be high, it is generally dwarfed by the cost of extended downtime to remove and repair/replace materials that may have failed in an incident.

2-3 Additional Peripheral Systems

In preparation for an outage, there are many pieces of equipment that are associated with the machinery trains that must also receive attention, and should be included in the planning process. Although outside the scope of this tutorial they are listed below so they are not overlooked. Experience has shown that many unplanned outages are initiated by items that are out of the machinery specialist normal scope, but are equally important. The machinery specialist should consider these items when discussing maintenance intervals, and finalizing outage plans:

- Large motor starters
- High voltage electrical switchgear
- Turning gear motors and their engagement mechanisms
- Check valves (compressors and steam turbine extraction)
- Motor operated valves
- Vacuum breaker valves on steam turbine condensers
- Condensers (tubes, internal deflectors, expansion joints)
- Suction drum demister pads or internal gratings
- Equipment foundation condition (oil issues, cracks, missing pieces, anchor hardware, etc.)
- Any other un-spared support equipment.

Many sites have specialists (other than machinery) that are more knowledgeable about these areas, and these specialists should be consulted. They can help formulate the specific plans and maintenance strategies for these peripheral pieces of equipment, complementing the machinery plans.

CONCLUSIONS

As noted in the various sections of this tutorial, there are quite a few aspects to consider relating to the operations and

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maintenance of un-spared compressor trains and their auxiliary systems. Neglecting any one of these aspects can lead to decreased performance of the equipment, decreased reliability, and an increase in maintenance costs.

Through careful consideration and planning, these risks can be mitigated by understanding the equipment requirements and diligent adherence to the recommendations noted in this tutorial. With regular review of operational trends and physical inspections one will become more intimately familiar with the equipment in question. With this, and review of historical maintenance records, one will be able to confidently predict when maintenance is required and what materials and documentation should be on hand to support these efforts. This will ultimately support the overall goals of safe operation, increased reliability and decreased maintenance costs associated with the equipment.

NOMENCLATURE

API	American Petroleum Institute
EMRO	Electrical and Mechanical Runout
EPC	Engineering and Procurement Contractor
IOM	Installation and Operation Manual
OEM	Original Equipment Manufacturer
PM	Preventive Maintenance
TEWAC	Totally Enclosed Water-Air Cooled
TTV	Trip and Throttle Valve

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