Introduction

- Maintenance has been fundamental to the survival of humankind and the development of our species.
- Our early ancestors learned heuristically that being effective hunter-gatherers required a basic set of tools such as stone blades, spears, hammers, flints, ropes, nets, etc.
- These tools and the maintenance thereof were essential to their food supply and personal protection.
- If your cave neighbor tried to take your tools you would beat him up to discourage this future behavior.
- If your tools deteriorated from use or the elements you had to fix or replace these tools – this is the essence of maintenance.
- As we progressed into the Bronze Age, advances in metallurgy allowed us to make harder, more durable tools for specialized applications.
- Industry at this time was still craft-based with individual specialists such as blacksmiths, masons, carpenters, leather makers, etc.
Introduction

• In 1913 Henry Ford implemented his idea of assembly line production to manufacture automobiles which brought the crafts together working simultaneously in series.

• Production line equipment such as conveyors, stamping presses, riveters, bending jigs, grinders, spray booths, etc. were serviced by mechanics when they broke down.

• Little to no maintenance was performed to prevent equipment failure except simple lubrication.

• In 1951 Toyota implemented the concept of Total Productive Maintenance (TPM) where the Operator of the equipment becomes an integral part of the preventive maintenance process.

• Toyota recognized that the Operator spends the majority of their workday with the equipment.

• Thus, they are uniquely qualified to identify any changes in performance, appearance, vibration, temperature, leaks, odors, etc. of the equipment.
Operational Excellence

Reliability Centered Maintenance

Introduction

• The equipment is like a comfortable pair of shoes to the Operators – they know when a pebble is in a shoe.

• Toyota empowered production line workers to perform cleaning with inspection (later to evolve into 5S).

• If an Operator discovered a problem with an equipment system they fixed it immediately (instantaneous maintenance) provided that they had been trained on how to perform the repair.

• If the repair was beyond the scope of the Operator a specialist from the maintenance department was dispatched to perform the repair.

• Instantaneous maintenance prevented a small problem from turning into a big problem with the potential of shutting down the production line.

• In 1978 Stan Nowlan and Howard Heap of United Airlines introduced the concept of evaluating components on the basis of Consequence of Failure Analysis (COFA).

• Components identified as critical to system performance were required to have a preventive maintenance strategy associated with them.
Introduction

• Moreover, Nowlan and Heap identified that only eleven percent of all components exhibited a time-based wear out pattern making scheduled equipment overhauls counterproductive.

• Instead of the traditional overhaul of “take apart and replace” they advocated “inspect and replace if necessary”.

• This approach to maintenance focused on the reliability of components which led to the terminology Reliability Centered Maintenance.

• Today, world-class organizations utilize a TPM/RCM approach to maintenance.

• Routine inspections are performed by the Operator and instantaneous maintenance performed if an undesirable condition is encountered.

• Inspections requiring specialized equipment and training are performed by maintenance technicians or outside contractors.

• On-line instrumentation is utilized for vibration, acoustic, thermography, particle size, oil analysis, etc. The emphasis is on component evaluation and system validation. The timeline of maintenance reliability practices may be visualized as in Figure 11.1.
Figure 11.1  Timeline of Maintenance Reliability Practices

**Time Line**

- **1.5M B.C.**
  Cavemen manufacture and maintain their own tools and supplies.

- **2000 B.C.**
  Bronze Tool Makers manufacture and sell tools to Craftsmen.

- **1913**
  Ford implements assembly line production. Equipment maintained by Mechanics.

- **1951**
  Toyota implements Total Productive Maintenance (TPM). Equipment maintained by Operators.

- **1978**
  United Airlines implements Reliability Centered Maintenance (RCM). Identifying Equipment which must be prevented from failure.

- **Today**
  TPM/RCM with an emphasis on Predictive Reliability Centered Maintenance and Condition-Based Maintenance.
Reliability Centered Maintenance Scope

• The reliability of a product, service or process is dependent upon many factors.

• Raw material availability, utility supply, worker availability, disaster preparedness, transportation systems, information and technology systems, effective equipment operation and effective equipment maintenance have a direct impact on reliability.

• In Operational Excellence, we employ the techniques of Lean Manufacturing to reduce waste and the techniques of Six Sigma to reduce variation.

• If we do not have reliable equipment we cannot hope to reduce waste or variation because the process never achieves steady state due to frequent downtime.

• Thus, it is natural that we focus our efforts on effective equipment operation and effective equipment maintenance.
Responsibilities

• Safety is the responsibility of every employee.

• Protecting the environment is the responsibility of every employee.

• Quality is the responsibility of every employee.

• By the same token, Reliability Centered Maintenance is the responsibility of every employee.

• If a company associate notices a leaking component, an unusual equipment sound, a temperature increase in a component, an unusual odor in a process area, an increase in equipment vibration or an unusual power draw of a system, the issue must be raised to the attention of the area supervisor.

• It is management’s responsibility to provide the necessary training, software systems, instrumentation, test equipment and resources to support a Reliability Centered Maintenance program.

• Management must empower employees to make decisions which protect the safety of personnel, prevent an environmental release of a hazardous material, protect equipment from damage, prevent the manufacture of discrepant product, and reduce total process downtime.
Definitions

• Maintenance and reliability professionals have developed a list of terms and acronyms which facilitate communication.

• The length of this list is rather extensive.

• Indeed, if you were to listen to a conversation between two maintenance professionals at a trade show you might be wondering if they were speaking a foreign language.

• Within any language, words can have more than one meaning, and depend upon the context in which they are used.

• The best way to avoid ambiguity is to define your terms.

• Commonly used terms in Reliability Centered Maintenance are defined below.

• **Asset Reliability Criteria** – Governing document for facility that defines the consequences of failure that must be prevented. The Asset Reliability Criteria is used in conjunction with the Reliability Component Decision Tree to classify a component as either critical, potentially critical, commitment, economic or run-to-failure.
Definitions

- **Consequence of Failure Analysis (COFA)** – The methodology used to determine the result of component failure which leads to the component classification as either critical, potentially critical, commitment, economic or run-to-failure.

- **Emergency Work** - a maintenance task that must be completed within 24 hrs to avert an immediate safety hazard, an environmental hazard, or to correct a failure with significant economic impact.

- **Mean Time Between Failures (MTBF)** - a measure of equipment reliability, calculated by dividing the time period an asset has been in service by the number of failures that have occurred during this time period or by taking the arithmetic average of the individual times between failures.

- **Mean Time To Repair (MTTR)** - a measure of maintainability. MTTR is the average time to repair an asset. It is pure repair time and is also known as *wrench time*.

- **Overall Equipment Effectiveness (OEE)** – a measure used to rate the effectiveness of an asset, calculated by multiplying availability by performance rate by quality rate.

- **Periodicity** – the time interval or number of cycles between repeated maintenance tasks.
Reliability Centered Maintenance

Definitions

• **Predictive Maintenance (PdM)** - a maintenance strategy based on measuring equipment condition in order to predict whether failure will occur during some future period, thus permitting the appropriate preventive actions to be implemented to avoid the consequences of that failure.

• **Preventive Maintenance (PM)** – a maintenance strategy designed to prevent an unwanted consequence of failure including condition-directed, time-directed, interval-directed, and failure finding tasks.

• **RAV in MRO Stores** – the value of maintenance, repair and operating materials (MRO) held in storage divided by the Replacement Asset Value (RAV) of the plant expressed as a percentage.

• **Reliability** - the probability that a system or product will perform its intended function for a specific period of time under stated operating conditions.

• **Replacement Asset Value (RAV)** - the valuation of a plant’s assets in today’s dollars (i.e., if you were to build a duplicate plant across the street today at equivalent capacity, the cost would total the RAV).
Keeping Score – RCM Metrics

• Today’s Computerized Maintenance Management Systems (CMMS) and Enterprise Resource Planning (ERP) systems are capable of tracking a number of Reliability Centered Maintenance metrics.

• But which metrics are most important to your organization?

• The answer to this question is dependent upon the type of industry, level of regulation, safety risk, environmental risk, performance rate, proximity of suppliers, etc.

• Ultimately, the management team has to decide what metrics to track and what targets to seek to ensure the sustainment of a healthy RCM program within the organization.

• Typically, this management team will consist of the Plant Manager, Operations Manager, Maintenance Manager and Supply Chain Manager.

• Metrics must be selected and defined such that the factory floor operator can understand the impact their performance can have on the metric. This is consistent with TPM principles and a Visual Factory. An example set of RCM metrics with associated world class performance targets is included in Figure 11.2.
Figure 11.2 Reliability Centered Maintenance Metrics and Benchmarks

<table>
<thead>
<tr>
<th>RCM Metric</th>
<th>World Class Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Equipment Effectiveness (OEE)</td>
<td>&gt; 80%</td>
</tr>
<tr>
<td>Annual Maintenance Cost as a % of RAV</td>
<td>&lt; 2.5%</td>
</tr>
<tr>
<td>Schedule Compliance</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>Emergency Work as a % of Total Work</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>Preventive and Predictive Hours as a % of Total Hours</td>
<td>&gt; 60%</td>
</tr>
<tr>
<td>Parts Stockout Rate</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

• If the above RCM metrics do not sufficiently capture the objectives of your RCM program an alternative list is provided in Figure 11.3.

• It is common to track metrics on a monthly basis so that trends and performance versus targets are immediately apparent.

• Example RCM Metrics charts are shown in Figure 11.4.

• Metrics charts, definitions, planned downtime schedules, upcoming training opportunities, vendor visits, maintenance and reliability newsletters, etc. must be kept current and posted in a central area of the plant with high personnel traffic.

• This is the way management demonstrates to the plant that they are serious about RCM performance.
## Figure 11.3 Alternative Reliability Centered Maintenance Metrics and Benchmarks

<table>
<thead>
<tr>
<th>RCM Metric</th>
<th>World Class Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance Cost per Unit Output</td>
<td>(1)</td>
</tr>
<tr>
<td>Return on Net Assets</td>
<td>(1)</td>
</tr>
<tr>
<td>Overtime Hours as a % of Total Hours</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Training Hours/Employee/Year</td>
<td>&gt; 80 hr</td>
</tr>
<tr>
<td>Total Recordable Incident Rate (TRIR)</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Lost Time Incident Rate (LTIR)</td>
<td>&lt; 0.15</td>
</tr>
<tr>
<td>Availability</td>
<td>&gt; 97%</td>
</tr>
<tr>
<td>Downtime as a % of Total Scheduled Operating Hours</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Planned Work Hours as a % of Total Work Hours</td>
<td>&gt; 85%</td>
</tr>
<tr>
<td>Planning Accuracy (estimated hours to actual hours)</td>
<td>± 10%</td>
</tr>
<tr>
<td>Wrench Time as a % of Total Time</td>
<td>&gt; 60%</td>
</tr>
<tr>
<td>Maintenance Rework Hours as a % of Total Hours</td>
<td>&lt; 2%</td>
</tr>
<tr>
<td>Work Orders Closed which include Comments</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td>Inventory Turns in MRO Store per year</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Inventory Accuracy by Cycle Count</td>
<td>&gt; 98%</td>
</tr>
<tr>
<td>%RAV held in MRO Stores</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Preventive and Predictive Maintenance Schedule Compliance</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td>Work Created by PM and PdM as a % of Total Hours</td>
<td>&gt; 25%</td>
</tr>
<tr>
<td>Root Cause Failure Analysis (RCFA) Performed on Failures</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td>Mean Time Between Failures (MTBF)</td>
<td>(1)</td>
</tr>
<tr>
<td>Mean Time To Repair (MTTR)</td>
<td>(1)</td>
</tr>
<tr>
<td>Faults Detected Prior to Failure</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td>Failures Due to Lubrication as a % of Total</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>% of Total Assets Rationalized by Consequence of Failure Analysis (COFA)</td>
<td>&gt; 60%</td>
</tr>
</tbody>
</table>

(1) Depends on industry type
Figure 11.4 Reliability Centered Maintenance Metrics Charts

- Overall Equipment Effectiveness (OEE)
- 12 Month Maint Cost as a % of RAV
- Schedule Compliance
- % Emergency Work
- Preventive and Predictive Work
- MRO Parts Stockout Rate

Metrics and charts are shown for each category, with data points indicating performance against targets over time.
Asset Reliability Criteria

• The primary goal of Reliability Centered Maintenance is the preservation of company assets.

• But a company can have thousands of assets.

• How can we identify the assets which require the protection of a preventive maintenance strategy?

• The Asset Reliability Criteria assists us with this decision.

• If the failure of a component can affect the safety of personnel or the public it is by definition a critical component.

• If the failure of a component can result in an environmental impact it is by definition a critical component.

• Operational considerations such as downtime, throttled production rate, control room alarm conditions, off-spec product, etc. are captured in the Asset Reliability Criteria.

• This is a document which the Plant Manager, Operations Manager and Maintenance Manager collaborate on to define the undesirable conditions which must be avoided.
Asset Reliability Criteria

- If the organization includes multiple plants and the RCM program is driven from the corporate level the Asset Reliability Criteria may be defined by company directors.

- The Asset Reliability Criteria is evergreen and subject to revision as an organization’s RCM program grows.

- For example, a company that is new to RCM may elect to confine their Asset Reliability Criteria to the mandatory criteria of personnel, public and environmental safety.

- As the organization becomes more comfortable with RCM implementation, the authorizing agents may elect to expand the Asset Reliability Criteria to operational considerations which will capture economic consequences.

- This allows the RCM program to grow at a rate which will not overwhelm resources but yet provide increased levels of risk management.

- The Asset Reliability Criteria Template is included in Figure 11.5.
## Figure 11.5 Asset Reliability Criteria Template

<table>
<thead>
<tr>
<th>Plant Location:</th>
<th>Revision Number:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Document Number:</th>
<th>Revision Date:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reason for Revision:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

- No personnel or public safety concerns (mandatory)
- No environmental impact concerns (mandatory)
- No process downtime exceeding ________ hours
- No critical control room alarm conditions exceeding ________ minutes
- No out-of-specification production exceeding ________ hours (excluding startup and change over)
- Other Criteria (specify below)

---

### Approvals

<table>
<thead>
<tr>
<th>Position</th>
<th>Printed Name</th>
<th>Signature and Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance Manager</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Component Classification

• The classification of components allows us to understand the impact of failure and thereby take preventive actions to avoid failure which increases reliability.

• Components are categorized as either critical, potentially critical, commitment, economic, or run to failure.

• Descriptions of these categories are summarized in Figure 11.6.

• Component classification is facilitated by The Consequence of Failure Analysis (COFA) Decision Tree as shown in Figure 11.7.

• You will note that some components are easy to identify as critical whereas other components require more detailed analysis for classification.

• For this purpose we use the Consequence of Failure Analysis (COFA) worksheet, an example of which is captured in Figure 11.8.
### Figure 11.6 RCM Component Classifications

<table>
<thead>
<tr>
<th>Component Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>A component for which the occurrence of failure is evident and the failure immediately results in an unwanted plant consequence.</td>
</tr>
<tr>
<td>Potentially Critical</td>
<td>A component whose immediate failure is not evident and is not immediately critical but has the potential to become critical either with a duration of time, with an additional component failure, or with an additional initiating event.</td>
</tr>
<tr>
<td>Commitment</td>
<td>A component that has certain regulatory, environmental, OSHA, insurance, or other commitments that must be maintained thereby requiring a preventive maintenance strategy to prevent component failure.</td>
</tr>
<tr>
<td>Economic</td>
<td>A component whose failure results in only an economic consequence (i.e., labor and/or material costs to repair).</td>
</tr>
<tr>
<td>Run to Failure</td>
<td>A component for which there is no preventive maintenance strategy. The failed component is repaired/replaced in a timely fashion upon failure.</td>
</tr>
</tbody>
</table>
Figure 11.7 Consequence of Failure Analysis (COFA) Decision Tree

- Is the occurrence of failure evident to operating personnel during their normal duties?  
  - Yes → Does the failure pose a threat to personnel safety or the environment?  
    - Yes → Component is Critical  
    - No → Can an additional component failure violate the Plant's Asset Reliability Criteria?  
      - Yes → Component is Potentially Critical  
      - No → Does the failure violate the Plant's Asset Reliability Criteria?  
        - Yes → Component is either Commitment, Economic or Run to Failure  
        - No → Component is Critical
## Figure 11.8 Consequence of Failure Analysis (COFA) Worksheet

<table>
<thead>
<tr>
<th>Component ID #</th>
<th>Description</th>
<th>Location</th>
<th>Functions of Component</th>
<th>Failure Modes</th>
<th>Failure Mode Detectable?</th>
<th>How Detectable?</th>
<th>Consequence of Failure Mode</th>
<th>Failure Mode Implications to Asset Reliability Criteria</th>
<th>Comments</th>
<th>Component Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP4826</td>
<td>Centrifugal Pump - 25 Hp</td>
<td>WWTP Pump House</td>
<td>Recirculates contents of primary digestion tank T3759</td>
<td>Power loss</td>
<td>Yes</td>
<td>DCS</td>
<td>Temporary loss of agitation</td>
<td>No plant consequences.</td>
<td>Power losses are typically short in duration.</td>
<td>Run to Failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flow restriction</td>
<td>No</td>
<td>N/A</td>
<td>Potential accumulation of solids at bottom of T3759. Potential loss of aerobic bacteria due to oxygen depletion.</td>
<td>Cost of replacing depleted bacteria.</td>
<td>No flowmeter present on recirculation loop.</td>
<td>Economic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cavitation</td>
<td>No</td>
<td>N/A</td>
<td>Potential accumulation of solids at bottom of T3759. Potential loss of aerobic bacteria due to oxygen depletion.</td>
<td>Cost of replacing depleted bacteria. Potential damage to impeller and pump housing.</td>
<td>If cavitation is severe, Operator may be able to detect during hourly rounds check.</td>
<td>Economic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flow loss</td>
<td>Yes</td>
<td>Operator hourly rounds check of T3759</td>
<td>Solids settling in T3759. Aerobic bacteria kill. Unable to process plant waste.</td>
<td>Imminent plant shutdown</td>
<td>Plant shutdown window is 24 hr</td>
<td>Critical</td>
</tr>
</tbody>
</table>
Component Classification

• You will notice that the COFA worksheet bears a striking resemblance to the FMEA worksheet, minus the numerical ratings for severity, occurrence and detection.

• This is not surprising, considering that both tools utilize a worksheet approach to capture potential failure modes identified through “what-if” scenarios and brainstorming techniques.

• Process Hazard Analysis (PHA) utilizes a similar technique in the chemical industry to ensure that the necessary control systems and safeguards are in place to prevent a safety or environmental incident.

• The first step in the COFA worksheet is to enter the unique identification number of the component you wish to classify.

• You may be using the exact same component in multiple locations throughout your plant, but each component must have a unique ID code and be rationalized for component classification separately.

• The same component could be classified as run to failure in one application but classified as critical in another application.
Component Classification

- The next steps are to enter a brief description of the component and the physical location within the plant.

- Step four in the COFA worksheet is to list all the intended functions of the component including those required under start-up, shut-down, normal and emergency operating conditions.

- Step five is to document all the potential failure modes which will prevent the component from fulfilling its intended functions.

- These failure modes come from a combination of plant experience, service records, technical bulletins, manufacturer warranty claims and other sources.

- In step six we indicate whether the failure mode can be detected by existing controls and procedures.

- Step seven describes how the failure mode would be detected by operating personnel.

- This includes control room alarms triggered by the Distributed Control System or by physical observation during Operator round checks as long as the round checks are a routine requirement of Standard Operating Procedures.
Component Classification

• Step eight describes the effects that each failure mode will have on the intended functions of the component and step nine rolls these effects up to the impact on the plant’s Asset Reliability Criteria.

• Comments which are helpful to the rationalization process of component classification are included in step ten.

• These comments come in handy during Root Cause Analysis investigations or when a component classification is revised due to a process or equipment design change.

• The impact on the Asset Reliability Criteria leads directly to the classification of the component by failure mode in step eleven.

• Failure modes which lead to loss of redundancy will receive the classification of potentially critical.

• This classification is also applied where there is a time limit for the component failure countermeasure to be implemented to prevent the failure from going critical.
Component Classification

- The final RCM classification of the component is the most severe of the classifications present in step eleven, that is, critical, potentially critical, commitment, economic or run to failure.

- RCM component classification may seem like a daunting task, especially when considering the great number of components which exist in a typical manufacturing plant.

- Nevertheless, it is the essential first phase of RCM implementation – identifying the vulnerabilities of your plant.

- The next phase is to select applicable and effective preventive maintenance tasks for the components whose failure violates the Asset Reliability Criteria, thus protecting your plant from these vulnerabilities.
Categories of Preventive Maintenance

- The term Preventive Maintenance (PM) is self-descriptive.
- You are taking some action now to prevent a future failure.
- The common vernacular of maintenance departments will include reference to PM’s.
- In this context, PM is not a strategy but a task.
- But is it the right task for the failure mode which has caused the component to be classified as critical?
- We will explore this concept in more detail and learn that PM tasks, unless carefully constructed, can actually increase the vulnerability of your plant rather than decrease it.
- Preventive Maintenance tasks may be categorized as time directed, interval directed, condition directed or failure finding.
- Automobile maintenance provides us with common examples of different PM categories.
Categories of Preventive Maintenance

- The service manual recommends that the crankcase oil and filter be replaced every 6 months (time directed) or 5,000 miles (interval directed), whichever comes first.
- In this case the time period is clock time, independent of the operating hours of the vehicle.
- Some equipment, like that boat sitting on a trailer in your back yard, spends most of its life idle.
- Recognizing this duty cycle, boat manufactures refer to the time period for maintenance in engine hours, the cumulative time that the engine has been run.
- Time directed PM tasks are beneficial when component degradation, wear, corrosion, fouling, etc. are independent of the component duty cycle.
- For example, if you have lubricating oil in a compressor which is exposed to a corrosive process gas at a fixed pressure, the diffusion rate of the process gas into the oil will be directly proportional to the pressure, temperature and time of exposure.
- If the compressor is idle but the lubricating oil is still exposed to a fixed pressure and temperature, the oil will continue to become fouled by the process gas.
Categories of Preventive Maintenance

• PM tasks in this case would be best initiated by reaching a specific time period between oil changes.

• On the other hand, the piston rings in the compressor do not wear unless the compressor is operating.

• If the compressor can be operated at different speeds, the PM would be best initiated by an operating interval, for example, when one million cycles have been achieved.

• The term condition directed maintenance is used interchangeably with predictive maintenance (PdM).

• It includes tasks which inspect, measure, monitor or analyze the condition of the component to determine if the quality characteristics are within operating specifications.

• If not, a work order is issued to address the deficiency before the component loses functionality.
Categories of Preventive Maintenance

- Inspections may be performed by process Operators on an hourly round basis, at extended periods by maintenance technicians, or continuously by on-line instrumentation.

- Your dentist performs conditioned directed maintenance on your teeth when you go for a check-up.

- You wouldn’t want your dentist to pull a tooth, hold it in front of you with forceps and conclude “this was a good tooth”.

- Instead, your dentist uses diagnostic tools such as x-ray imaging and the feel of a dental explorer to assess the condition of your teeth.

- Failure finding tasks are designed to detect the hidden failures in your plant.

- They are directly applicable to components which are potentially critical.

- Let’s say you have installed redundant pumps in parallel to protect a process from loss of flow.

- If pump A is operating and pump B is on standby how do you know that pump B can supply the required flow rate and head pressure when called upon?
Categories of Preventive Maintenance

• The simple answer is you don’t know unless you periodically check the redundant pump performance.

• Failure finding tasks are used extensively in the preventive maintenance of safety systems.

• A quarterly test of a diesel engine emergency electrical system would be an example of a failure finding PM task.
Types of Preventive Maintenance Tasks

- Preventive Maintenance (PM) tasks are a natural progression of Consequence of Failure Analysis.

- Now that you have identified the dominant failure modes that cause a critical component to lose functionality, how can you prevent these failure modes from occurring, or at the bare minimum, how can you mitigate the effects of the failure by taking preemptive action?

- Multiple departments are stakeholders in the success of your reliability program.

- The Operations Group lives with the equipment, thus, they are the first line of defense in preventive maintenance.

- Operators can detect changes in sound, appearance, odor, vibration, temperature, etc.

- They can respond to changes in equipment performance or environmental conditions to avoid component failure and extended downtime.

- Operators can perform basic cleaning and inspection tasks integrated into the 5S + Safety program and hourly round checks.
Types of Preventive Maintenance Tasks

• PM tasks can be built into these inspections to include functional tests, sample analyses and performance monitoring.

• Of course, Operators must be provided with the necessary tools, instrumentation and training to effectively perform these PM tasks.

• It is common for Operators to develop levels of craft expertise in the preventive maintenance of equipment which allow them to gravitate to roles of increasing responsibility within the Maintenance Department.

• This is a healthy sign of process ownership, internal promotion and infrastructure development within an organization.

• The Maintenance Group will perform PM tasks which are more involved, require specialized training, equipment and/or instrumentation outside the scope of routine operations.

• These PM tasks typically include inspections, calibrations, bench tests, overhauls, replacements, defouling operations, lubrication and oil changes.

• A process shutdown may be required to perform these tasks which frequently involve the deployment of outside contractor services.
Types of Preventive Maintenance Tasks

• Consequently, the shutdown (often termed plant turnaround) is a carefully choreographed schedule of events including Gantt Chart and Critical Path Management to minimize downtime.

• The Engineering Group performs PM tasks which are also specialized and require careful analysis to determine the implications on plant reliability.

• Process stress tests, vibration analysis, thermography, eddy current testing, acoustic monitoring and motor current signature analysis are examples of PM tasks typically performed by the Engineering Group.

• Process stress tests are designed to measure the performance capability of systems.

• For example, if a particular process is rated for a product throughput of 20 metric tons per day but the current customer demand only warrants an operating rate of 10 metric tons per day, the Engineering Group may schedule a stress test to operate the process at the design rate for a short duration to confirm process capability.

• This will bring any problems to light and provide time to address deficiencies through corrective maintenance prior to an increase in customer demand.
Types of Preventive Maintenance Tasks

• Stress tests are common in the utility industries as a measure of readiness to supply power during peak demand periods.

• Stress tests must be carefully designed to avoid catastrophes such as the Chernobyl nuclear plant disaster.

• This incident was triggered by a capability test to measure the performance of reactor number four to ride through a one minute loss of grid power to the reactor coolant water pumps.

• The Laboratory Group also plays an important role in your preventive maintenance strategy.

• Chemical analyses, oil evaluation, pH control, particulate analysis, contaminant identification are common PM tasks performed by the Laboratory Group.

• If on-site laboratories do not have the instrumentation or equipment required to perform a specific analysis, there are a number of contract laboratories available to perform sample analyses on demand with twenty-four hour response time. In addition, these laboratories often have divisions devoted to failure analysis which can assist you in your Root Cause Analysis investigations.
Component Life Cycles

- The typical life cycle of a population of similar components may be represented by the bathtub curve of Figure 11.9. This curve is based upon the hazard function developed by Dr. Waloddi Weibull in 1951 shown in Equation 11.1.

**Figure 11.9 Bathtub Curve of Component Reliability**

![Bathtub Curve of Component Reliability](image)
Equation 11.1  Weibull Distribution Hazard Function

\[ f(t) = \left( \frac{\beta}{\eta} \right) \left( \frac{t}{\eta} \right)^{(\beta-1)} e^{-\left( \frac{t}{\eta} \right)^\beta} \]

where \( f(t) = \) Failure Rate (time\(^{-1}\))
\( t = \) time
\( \beta = \) Shape Parameter (\( \beta > 0 \))
\( \eta = \) Scale Parameter (\( \eta > 0 \))

- To understand the implications of the bathtub curve let us consider a population of 1000 brand new motors of the same model from the same manufacturer.
- At time zero we turn all motors on simultaneously.
- Within a few hours some motors stop working.
- We call this infant mortality.
- The motors have failed early due to some material defect, manufacturing error or installation error.
- As time progresses, the number of motors failing per unit time decreases.
Component Life Cycles

- We call this region I in our chart – the region of decreasing failure rate, where small β values dominate the hazard function ($0 < \beta < 0.5$).

- In region II the failure rate becomes nearly constant at some low level due to random failures.

- We call this the useful life region characterized by midrange values of β ($1 < \beta < 3$).

- After some extended period of time the number of failures per unit time dramatically increases.

- At this point, time has become our enemy and the forces of friction, corrosion, material fatigue, thermal decomposition, embrittlement, etc. begin to take their toll.

- We call this region III in our chart, the wear-out region where large β values dominate the hazard function ($\beta > 5$).

- Stan Nowlan and Howard Heap studied the effect of time on failure rate extensively at United Airlines during their pioneering work in Reliability Centered Maintenance.
Component Life Cycles

- They discovered that only about eleven percent of all components exhibited a time-based wear-out point, the beginning of region III in our chart.

- Another way of stating this finding is that eighty-nine percent of all components fail randomly, thus making time-based component replacements counterproductive.

- If a component is replaced because it has exceeded its “recommended life” the timeline of the component is reset to zero making the component susceptible to failures in the infant mortality region.

- This increases the probability of failure.

- A better preventive maintenance approach is to develop condition-directed maintenance inspections which flag a component for overhaul or replacement when it reaches a specified threshold operating quality characteristic.

- For example, replace motor within 500 operating hours of detecting motor current signature analysis with low frequency demodulated current exceeding 50 amps.
Benefits of Condition Directed Maintenance

- Condition Directed Maintenance tasks emphasize inspection and analysis as opposed to remove and replace.

- You may be thinking “I wish my automobile mechanic would read this presentation”.

- How many times have you taken your automobile in for service to address a problem and had to return multiple times until the problem was finally corrected?

- This is the “poke and hope” approach to maintenance which is costly and inefficient.

- Today, automobile manufacturers include diagnostic modules within the engine control module circuitry of the vehicle.

- Trouble codes can be retrieved on a code reader by your local automobile mechanic which will direct him to the offending component.

- Condition directed maintenance tasks are less invasive than overhauls, result in less downtime, avoid equipment burn-in periods, and prevent human errors associated with reassembly and installation.
Benefits of Condition Directed Maintenance

- They are designed to extend the useful life region of the component by checking quality characteristics and taking corrective action if quality characteristics are outside specifications.

- For example, replace seal fluid when its color exceeds a visual standard or replace compressor oil when measured viscosity is outside of specifications.

- In this manner, overall plant reliability is increased while maintenance costs are decreased since components are replaced less frequently.
Types of Condition Directed Maintenance

• There are many types of condition directed maintenance.
• Instrumentation, sensor technology and methods development drive the availability of diagnostic tools.
• Vibration monitoring and analysis typically applies to rotating equipment and is used to detect bearing wear, unbalanced conditions or alignment problems.
• Sensors can detect loose bolts, cracked support mounts, bent shafts and coupling issues.
• Sensor output can be tied into your plant’s Distributed Control System (DCS) to permit real-time trending analysis and to trigger alarm conditions which will prevent incipient failures from causing downtime.
• Alternatively, hand-held vibration monitors may be utilized during periodic mechanical integrity inspections.
• Acoustic monitoring is used to detect internal and external leaks in valves or to detect leaks through cracked or corroded heat exchangers.
Types of Condition Directed Maintenance

• Eddy current testing uses magnetic eddy currents to detect surface flaws or cracks in materials.

• Magnetic particle inspection detects surface cracks in metallic parts by setting up a magnetic field around the component being tested.

• Dye penetrant testing can be used to detect surface cracks or voids in pipes, welds and other metallic parts.

• Ultraviolet light is used to make the absorbed dye fluoresce.

• Ultrasonic testing can detect subsurface flaws in metallic parts using sound waves.

• Radiography inspection detects subsurface flaws in weld and metallic parts using X-rays.

• The equipment is typically rather bulky, expensive and requires safety shrouding. Consequently, this service is normally performed by an outside contractor.

• Oil sampling and analysis is a common technique used to detect incipient bearing or gear failures.
Types of Condition Directed Maintenance

• A small sample of oil is drained from the component and inspected for wear particles, contaminants, water intrusion, viscosity breakdown, burning smell, etc.

• Basic analyses can be performed on-site.

• More complicated analyses such as contaminant identification and heavy metal analysis can be performed by contract laboratories.

• Borescope inspections are useful to view the interior of components through an access port.

• This inspection technique is commonly used for turbines, cylinder and large valves.

• Thermography or infrared monitoring is a common technique for finding “hot spots” within equipment caused by loose electrical connections, faulty relay coils or defective motor windings.

• Instrumentation can be as simple as a hand held infrared thermometer or as complex as a high-resolution infrared camera/thermal imaging system. These instruments may also be used for field validation of installed thermocouples, thermistors or Resistance Temperature Detectors (RTD’s).
Types of Condition Directed Maintenance

- Motor Operated Valve Diagnostics (MOVATS) utilize a system of sensors to diagnose problems with motor operated valves.

- These systems measure stem torque, stem thrust, torque switch trip, spring pack displacement, limit switch settings, motor voltage, motor current and motor power.

- Air Operated Valve Diagnostic Systems detect problems with air operated valves such as diaphragm leakage, solenoid switch failures, valve positioner failure, relay degradation and regulator failure.

- Motor Current Signature Analysis (MCSA) is used to detect problems with electric motors such as cracked rotor bars, winding shorts and bearing deterioration.
Preventive Maintenance Task Selection

- We must now select the preventive maintenance tasks and periodicities for each component in the Consequence of Failure Analysis (COFA) worksheet whose failure mode violates the Asset Reliability Criteria.

- The PM Task Selection Flow Chart presented in Figure 11.10 will assist us in this process.

- Our first choice for PM tasks is condition directed for the reasons we have highlighted previously.

- If this is not viable, the second choice is time or interval directed.

- These tasks are normally more intrusive than condition directed and typically require process downtime.

- If this is not viable we have to ask if the component has been classified as either critical, commitment or economic.

- If the answer is yes a design change to the component and/or process is required.

- If the design change is not implemented the plant is not protected from this failure mode.
Figure 11.10 Preventive Maintenance Task Selection Flow Chart

1. Can an effective condition directed PM activity be specified to prevent component failure?
   - Yes: Specify the PM task and periodicity
   - No
2. Can an effective time or interval directed PM activity be specified to prevent component failure?
   - Yes: Specify the PM task and periodicity
   - No
3. Is the component classified as critical, commitment or economic?
   - Yes: Initiate a design change or accept the risk
     - No - component is potentially critical
4. Can an effective failure finding PM activity be specified to identify the failure?
   - Yes: Specify the PM task and periodicity
   - No: Initiate a design change or accept the risk
Preventive Maintenance Task Selection

• If the answer is no, then the component is potentially critical and its hidden failure must be identified through failure finding PM tasks.

• If this cannot be done, then a design change to the component and/or process must be initiated to protect the plant from the hidden failure.

• The selected PM tasks and periodicity are added to the column in step twelve of the COFA worksheet which is appended in Figure 11.11.

• The COFA worksheet has thus evolved into a comprehensive document describing the potential failure modes of a component, the effect these failure modes have on the plant’s Asset Reliability Criteria, and the preventive maintenance countermeasures that have been implemented to protect the plant from these failures.
Figure 11.11  Appended Consequence of Failure Analysis (COFA) Worksheet

<table>
<thead>
<tr>
<th>Component ID #</th>
<th>Description</th>
<th>Location</th>
<th>Functions of Component</th>
<th>Failure Mode Detectable?</th>
<th>How Detectable?</th>
<th>Consequence of Failure Mode</th>
<th>Failure Mode Implications to Asset Reliability Criteria</th>
<th>Comments</th>
<th>Component Classification</th>
<th>PM Task &amp; Periodicity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prevents solids settling in T3759</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td>No flowmeter present on recirculation loop.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Provides oxygen supply to aerobic bacteria in T3759</td>
<td></td>
<td></td>
<td>流 loss</td>
<td>No</td>
<td>N/A</td>
<td>Cost of replacing depleted bacteria.</td>
<td></td>
<td>Economic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cavitation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td>Cost of replacing depleted bacteria. Potential damage to impeller and pump housing.</td>
<td>If cavitation is severe, Operator may be able to detect during hourly rounds check.</td>
<td>Economic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td>Cost of replacing depleted bacteria.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PM Task Periodicity Considerations

- Periodicity refers to the time period or number of cycles between repeated maintenance tasks.

- Components work in harmony to add value to the supply chain of manufacturing, service and distribution.

- Any preventive maintenance activity that interrupts the momentum of the supply chain has an associated cost which is typically many times greater than the cost of the component and labor to install it.

- Thus, PM tasks must be judiciously selected and timed to minimize intrusion to the supply chain.

- Periodicity is influenced by many factors such as component accessibility, Mean Time Between Failures (MTBF), corrective maintenance history, existing monitoring equipment, vendor recommendations, industry benchmarks, regulatory requirements, safety hazards, environmental hazards, planned outages, schedule conflicts, customer demand, shut-down losses, start-up losses, availability of outside contractors, weather, etc.
PM Task Periodicity Considerations

- The RCM Implementation Team decides on the periodicity for the PM Task in question by balancing these factors with the associated risks of losing functionality of the component.

- Once the decision is made – stick to it.

- Remember that schedule compliance is a Key Performance Indicator of the health of your RCM program.
Root Cause Analysis

- Root Cause Analysis (RCA) is a powerful technique for identifying the causal factors leading to an event-based failure.

- The National Transportation Safety Board (NTSB) demonstrates root cause analysis when investigating civil aviation accidents.

- The Chemical Safety Board (CSB) utilizes root cause analysis when investigating chemical accidents.

- The key to these investigations is the meticulous collection of data including communications, interviews, sensor measurements versus time records, distributed control system output, weather data, maintenance history, etc.

- In addition, the forensic evidence derived from autopsy (failure analysis) of the component and ancillary components in question is critical.

- Root cause analysis is like a crime scene investigation.

- Law enforcement officers have been trained to cordon-off the location of a crime and preserve the integrity of evidence.
Root Cause Analysis

- The lead detective assigned to the investigation rushes to the crime scene to begin collecting evidence needed to unravel the unknowns of the crime including motives.

- He is keenly aware that as each minute ticks by, the probability that a key piece of evidence will go missing or become contaminated increases, making his job more difficult.

- In addition, eye-witnesses begin to leave the area and/or their memories become fuzzy as they rationalize the potential repercussions their statements may have on their personal safety.

- It is similarly important to freeze the crime scene of equipment failures.

- If a pump has failed, and the underlying root cause is solids contamination in the process fluid, the RCA will be complicated if the pump is flushed out removing all the solids evidence.

- If electrical switchgear has failed, loose connections will be missed if the switchgear is disassembled before RCA investigation.
Root Cause Analysis

- If structural members have failed, it is important to preserve the failure area of the structure to facilitate corrosion and stress analysis.

- If rotating equipment has failed, witness marks where component surfaces were abrading against each other will be important to the investigation.

- Failures often occur due to a chain of events which have transpired in parallel to existing conditions.

- This leads to multiple root causes for an event-based failure.

- Once the root causes have been identified it is a relatively straightforward process to implement countermeasures which will prevent future failures.

- These countermeasures may include modification of component operating parameters, installation of monitoring sensors and alarms, revision of equipment operation check sheets, installation of component shielding, installation of overload protection, change in component materials, change in process design, change in assembly, installation and/or start-up procedures, relocation of component to another area of the plant, installation of contamination protection, modification of PM strategy to include periodic fluid analysis, vibration analysis, thermal imaging, etc.
Root Cause Analysis

• Root cause analysis should be conducted on any component failure which violates your established Asset Reliability Criteria.

• The size of the RCA investigation team depends on the scope of the failure incident. If it is a simple component failure with limited scope the RCA team could consist of just one person.

• If personnel safety or the environment were compromised, or there was a significant economic impact from the failure incident the RCA team would consist of representatives from key departments.

• In certain circumstances, it may be beneficial to involve the Original Equipment Manufacturer (OEM) and/or an outside failure analysis laboratory.

• RCA consists of asking the right questions and performing the right analyses to drill down to the root causes of failure.

• As in a crime scene investigation, it is important to gather as much process data leading up to the component failure as possible. The Root Cause Analysis Template shown in Figure 11.12 includes a collection of typical questions to ask with implications to root cause and ultimately, your preventive maintenance strategy.
### Root Cause Analysis Template

**Figure 11.12 Root Cause Analysis Template**

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
<th>Don’t Know</th>
<th>#</th>
<th><strong>Root Cause Analysis Question</strong></th>
<th><strong>Root Cause Implication</strong></th>
<th><strong>PM Strategy Implication</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Was the failure preceded by a process interruption?</td>
<td>Investigate details of process interruption</td>
<td>Modify startup procedure &amp; checklist</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Was the failure preceded by a process spike (eg temperature, pressure, flow rate, concentration, etc)?</td>
<td>Investigate details of process spike</td>
<td>Consider additional process controls and/or alarms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>Did the component fail during the time frame of another component failure?</td>
<td>Investigate which failure has occurred first</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>Was the component operated outside of process specifications?</td>
<td>Investigate reason for non-standard operation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>Was there a change in utilities (air, steam, water, electricity, etc) prior to component failure?</td>
<td>Investigate details of utility change</td>
<td>Consider additional utility controls and/or alarms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>Was there a dramatic change in the ambient environment (eg temp fell below freezing, thunderstorm, high humidity, high temp) prior to component failure?</td>
<td>Investigate details of ambient environment change</td>
<td>Consider insulating component from ambient environment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>Is the component brand new?</td>
<td>Infant mortality, warranty claim</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>Has this same component failed in the last 6 months?</td>
<td>Component under-specified, start-up, shut-down and/or operation procedure inappropriate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9</td>
<td>Was the component recently rebuilt?</td>
<td>Rebuild procedure, install procedure</td>
<td>Depends on autopsy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>Did the component fail suddenly?</td>
<td>Fatigue failure, contamination, thermal overload</td>
<td>Depends on autopsy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>Did the component performance degrade over time?</td>
<td>Dirt accumulation, component deterioration, lubrication failure</td>
<td>Depends on autopsy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>Is the component performance requirement at or above its design limit?</td>
<td>Component under-specified</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13</td>
<td>Did the component exhibit any external signs prior to failure (eg vibration, temperature build-up, leaking, noise, odor, etc)?</td>
<td>Use external sign to focus root cause detection during autopsy</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>Is there evidence of external damage to component?</td>
<td>Component may have been accidentally damaged</td>
<td>Consider installing protective shielding</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>Does autopsy indicate component corrosion as failure mode?</td>
<td>Material selection inappropriate for process fluid</td>
<td>Increase frequency of wall thickness &amp; corrosion check</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>Does autopsy indicate incorrect assembly or missing parts?</td>
<td>Warranty claim or inadequate rebuild/install procedure</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>Does autopsy indicate excessive wear for the service time of the component?</td>
<td>Material selection inappropriate, lubrication insufficient</td>
<td>Consider adding periodic lubricant analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>Does autopsy indicate external particulate contamination?</td>
<td>Component requires particulate contamination protection</td>
<td>Consider installing protective shielding and/or filtration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19</td>
<td>Does autopsy indicate presence of foreign liquid?</td>
<td>Identify source of foreign liquid and eliminate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>Does autopsy indicate seal failure?</td>
<td>Seal material/design, seal fluid system</td>
<td>Add seal fluid check to Operator Round Sheets</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>21</td>
<td>Does autopsy indicate electrical system failure?</td>
<td>Identify failed component and potential sources of failure</td>
<td>Consider adding electric power supply controls/conditioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>Does autopsy indicate loose electrical connections or shielding failure?</td>
<td>Connector and/or shielding design and thickness</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>23</td>
<td>Does autopsy indicate wear parts have fallen below their acceptable tolerance?</td>
<td>Material selection inappropriate or component under specified</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td>Does autopsy indicate damaged internal parts?</td>
<td>Identify source of internal damage</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>Does autopsy indicate jammed or slow-moving internal parts?</td>
<td>Identify source of internal friction or jam</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26</td>
<td>Does autopsy indicate nothing wrong?</td>
<td>Intermittent failure - conduct bench top stress tests</td>
<td></td>
</tr>
</tbody>
</table>

Compile as much process information leading up to the component failure as possible. Assemble a small team of operating and maintenance personnel who are intimately familiar with the operation of the component in question. Include personnel that were on shift at the time of the failure. Ask the following questions in order to direct the failure analysis to the root cause.
Root Cause Analysis

• The relevant questions depend on the type of component which has failed and the failure mode, thus, blanks have been added for your team to add more specific RCA questions.

• Dean Gano has developed an effective technique for drilling down to the root cause of event-based failures which he has called the Apollo method.

• It consists of defining the problem including the significance or consequence to stakeholders.

• Identifying the condition causes and action causes that combined to create the defined problem.

• Including a graphical representation and evidence to support each cause.

• Describing how the solutions will prevent recurrence of the defined problem.

• Linking solutions to your corrective action tracking system to ensure that countermeasures are validated for effectiveness.

• Providing a final report that summarizes the root cause analysis.
Root Cause Analysis

- The basis of the Apollo method is that any primary effect will be caused by a set of condition causes and action causes.

- Each condition cause will in turn have its own set of condition and action causes and each action cause will in turn have its own set of condition and action causes.

- Consequently, cause becomes effect, they differ only in the time frame for which we perceive them.

- In practice, we only need to drill down to the level of condition and action causes where we can implement a sustained, cost-effective countermeasure.

- Let us apply this technique to the root cause analysis of the centrifugal pump failure presented in Case Study XVIII.
Case Study XVIII: Root Cause Analysis of Centrifugal Pump Failure

Background
Pump CP4826 is a 25 Hp centrifugal pump used in the Waste Water Treatment Plant (WWTP) to recirculate the contents of the primary digestion tank T3759. CP4826 recirculates the process fluid through eductor nozzles at the bottom of tank T3759 to promote aeration of the tank and to prevent solids settling. It is considered a critical component since extended periods of time without tank recirculation will cause not only tank fouling with solids but more importantly, oxygen-deficient stratification layers within the tank causing depletion of the aerobic bacteria necessary for the digestion process.

The mechanical seal on pump CP4826 has been a constant headache for the maintenance department. The seal has failed three times in the last 12 months and had just been replaced 30 days ago. This chronic seal failure has prompted the Maintenance Manager, Jim Phillips to proclaim “those darn Jack Crane seals are no good ... I’ve always had better luck with Chesterfield seals!” The seal fluid, as recommended by the manufacturer, is a 50/50 mixture of propylene glycol and water.

Incident Description
On Tuesday morning, at 5:15 am, Kevin Walters, the WWTP Operator, was just completing his hourly rounds and had returned to the WWTP control room. Kevin noticed a critical alarm on the alarm management screen of his DCS monitor. A high pressure indication was being registered by pump CP4826 within the tandem seal buffer cavity. Kevin went out to physically inspect the pump and when he arrived at the pump location he described the scene as such “there was seal fluid everywhere, and the pump was making a high pitch squeal like metal grinding on metal!” Kevin immediately shut down the pump and alerted his supervisor.

Incident Investigation
Since this was the fourth seal failure for this pump, Dave Sutherland, the Operations Manager formed a Root Cause Analysis Team to investigate this most recent failure. It was found that the damage was more severe than the last three failures. The main bearing of the pump had seized causing scoring to the drive shaft. This accounted for the “high pitch squeal” which Kevin reported. Kevin has not been with the company long (only three months) but he is recognized as a conscientious worker. Kevin was interviewed the same morning of the incident and he mentioned that the temperature in the pump house was unusually cold during his shift. A cold front had moved in during the night reducing temperatures below freezing. This is a rare occurrence for the plant’s geographical location. Kevin said there were no process upsets which occurred during his shift except an electrical power outage which happened at 2:00 am for less than 30 seconds. This is a common occurrence at the plant since it is supplied from a residential power grid.
Case Study XVIII: Root Cause Analysis of Centrifugal Pump Failure

Kevin mentioned that he thought the pump was making more noise and vibrating more than usual on his hourly rounds but it was difficult to tell because the pump room is so noisy. He also mentioned that he thought he noticed that the pump housing was warm to the touch but he did not have a thermometer to measure it.

The failed mechanical seal was sent to Jack Crane Industries who performed an autopsy. They responded in their failure analysis report that the seal had an unusual oval wear pattern indicative of eccentric loading on the seal. The report did not elaborate further on possible causes of eccentric loading.

The failed bearing was sent to SKG Bearings for failure analysis. They found debris within the bearing from the bearing material itself. The bearing material was sent to their metallurgical laboratory which concluded that the bearing material had failed due to fatigue. Fatigue failure could be caused by a combination of high temperature and high vibration brought on by misalignment of drive and pump shafts.

David Williams, the maintenance mechanic who typically works on pump CP4826 was interviewed. He reported that he had to replace the motor last year because it had burnt out. When asked how he aligned the motor drive and pump shaft he responded that he doesn’t have any tools to align shafts. He does the best he can to line up the shafts by eye and by feel.

Root Cause Analysis
The RCA team first compiled the incident time line as shown in Figure 11.13, and then proceeded to ask the questions prompted by the Root Cause Analysis Template, the answers for which are summarized in Figure 11.14.
Figure 11.13  Centrifugal Pump CP4826 Failure - Incident Time Line

- **Plant:** Baton Rouge
- **Component Code/Descr:** CP4826 Centrifugal Pump 25 Hp
- **Component Location:** WWTP Pump House
- **Failure Mode:** Seal Failure/Bearing Failure
- **Date of Failure:** January 12  5:15 AM

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 12 12:00 AM</td>
<td>Round Check OK</td>
</tr>
<tr>
<td>January 12 1:00 AM</td>
<td>Round Check OK</td>
</tr>
<tr>
<td>January 12 2:00 AM</td>
<td>Plant-wide power outage for approx. 30 seconds.</td>
</tr>
<tr>
<td>January 12 3:00 AM</td>
<td>Round Check OK, Recovery from power outage OK.</td>
</tr>
<tr>
<td>January 12 4:00 AM</td>
<td>Round Check OK, CP4826 running rough (noisy and warm to touch).</td>
</tr>
<tr>
<td>January 12 5:00 AM</td>
<td>Round Check OK</td>
</tr>
<tr>
<td>January 12 5:15 AM</td>
<td>Low pressure alarm for CP4826 seal on DCS panel.</td>
</tr>
<tr>
<td>January 12 5:17 AM</td>
<td>K. Walters inspected CP4826 condition.</td>
</tr>
<tr>
<td>January 12 5:18 AM</td>
<td>K. Walters observed high pitch squeal and seal fluid leak around CP4826.</td>
</tr>
<tr>
<td>January 12 5:20 AM</td>
<td>CP4826 manually shut down at local panel.</td>
</tr>
<tr>
<td>January 12 5:25 AM</td>
<td>CP4826 locked and tagged-out</td>
</tr>
<tr>
<td>January 12 5:35 AM</td>
<td>Seal fluid spill contained and cleaned-up</td>
</tr>
<tr>
<td>January 12 8:00 AM</td>
<td>Root Cause Investigation Team formed.</td>
</tr>
</tbody>
</table>
### Figure 11.14  Centrifugal Pump CP4826 Failure - RCA Template

**Plant:** Baton Rouge  
**Component Code/Descr:** CP4826 Centrifugal Pump 25 Hp  

**Instructions:**  
Compile as much process information leading up to the component failure as possible. Assemble a small team of operating and maintenance personnel who are intimately familiar with the operation of the component in question. Include personnel that were on shift at the time of the failure. Ask the following questions in order to direct the failure analysis to the root cause.

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
<th>Don’t Know</th>
<th>#</th>
<th>Root Cause Analysis Question</th>
<th>Comments</th>
<th>Root Cause Implication</th>
<th>PM Strategy Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>1</td>
<td>Was the failure preceded by a process interruption?</td>
<td>Not really - but there was an electrical outage at 2:00 am</td>
<td>Investigate details of process interruption</td>
<td>Modify startup procedure &amp; checklist</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>2</td>
<td>Was the failure preceded by a process spike (eg temperature, pressure, flow rate, concentration, etc)?</td>
<td>Investigate details of process spike</td>
<td>Consider additional process controls and/or alarms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>3</td>
<td>Did the component fail during the time frame of another component failure?</td>
<td>Investigate which failure has occurred first</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>4</td>
<td>Was the component operated outside of process specifications?</td>
<td>Investigate reason for non-standard operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>5</td>
<td>Was there a change in utilities (air, steam, water, electricity, etc) prior to component failure?</td>
<td>Investigate details of utility change</td>
<td>Consider additional utility controls and/or alarms</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>6</td>
<td>Was there a dramatic change in the ambient environment (eg temp fell below freezing, thunderstorm, high humidity, high temp) prior to component failure?</td>
<td>Yes - temperature in the pump house fell below freezing during the night.</td>
<td>Investigate details of ambient environment change</td>
<td>Consider insulating component from ambient environment</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>7</td>
<td>Is the component brand new?</td>
<td>Infant mortality, warranty claim</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>8</td>
<td>Has this same component failed in the last 6 months?</td>
<td>Yes - CP4826 pump seal has failed 3 times in the last 12 months.</td>
<td>Component under-specified, start-up, shut-down and/or operation procedure inappropriate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>9</td>
<td>Was the component recently rebuilt?</td>
<td>Seal was replaced last year on December 14.</td>
<td>Rebuild procedure, install procedure</td>
<td>Depends on autopsy</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>10</td>
<td>Did the component fail suddenly?</td>
<td>Seal should last longer than 30 days.</td>
<td>Fatigue failure, contamination, thermal overload</td>
<td>Depends on autopsy</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>11</td>
<td>Did the component performance degrade over time?</td>
<td>Dirt accumulation, component deterioration, lubrication failure</td>
<td>Depends on autopsy</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>12</td>
<td>Is the component performance requirement at or above its design limit?</td>
<td>Component under-specified</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>13</td>
<td>Did the component exhibit any external signs prior to failure (eg vibration, temperature build-up, leaking, noise, odor, etc)?</td>
<td>Pump seemed to be more noisy and vibrating more than usual during hourly rounds.</td>
<td>Use external sign to focus root cause detection during autopsy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>14</td>
<td>Is there evidence of external damage to component?</td>
<td>Component may have been accidentally damaged</td>
<td>Consider installing protective shielding</td>
<td></td>
</tr>
</tbody>
</table>
**Figure 11.14 Centrifugal Pump CP4826 Failure - RCA Template**

- **Plant:** Baton Rouge
- **Component Code/Descr:** CP4826 Centrifugal Pump 25 Hp

**Instructions:**
Compile as much process information leading up to the component failure as possible. Assemble a small team of operating and maintenance personnel who are intimately familiar with the operation of the component in question. Include personnel that were on shift at the time of the failure. Ask the following questions in order to direct the failure analysis to the root cause.

<table>
<thead>
<tr>
<th>Yes/No</th>
<th>Don’t Know</th>
<th>#</th>
<th>Root Cause Analysis Question</th>
<th>Comments</th>
<th>Root Cause Implication</th>
<th>PM Strategy Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>Does autopsy indicate component corrosion as failure mode?</td>
<td></td>
<td>Material selection inappropriate for process fluid</td>
<td>Increase frequency of wall thickness &amp; corrosion check</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>16</td>
<td>Does autopsy indicate incorrect assembly or missing parts?</td>
<td>Seal had oval wear pattern. Bearing was totally seized.</td>
<td>Material selection inappropriate, lubrication insufficient</td>
<td>Consider adding periodic lubricant analysis</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>17</td>
<td>Does autopsy indicate excessive wear for the service time of the component?</td>
<td></td>
<td>Component requires particulate contamination protection</td>
<td>Consider installing protective shielding and/or filtration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>Does autopsy indicate external particulate contamination?</td>
<td>Bearing has debris inside from the bearing material itself.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>Does autopsy indicate presence of foreign liquid?</td>
<td></td>
<td>Identify source of foreign liquid and eliminate</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>20</td>
<td>Does autopsy indicate seal failure?</td>
<td>Primary seal has failed.</td>
<td>Seal material/design, seal fluid system</td>
<td>Add seal fluid check to Operator Round Sheets</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>21</td>
<td>Does autopsy indicate electrical system failure?</td>
<td>Identify failed component and potential sources of failure</td>
<td>Connect and/or shielding design and thickness</td>
<td>Consider adding electric power supply controls/conditioning</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>22</td>
<td>Does autopsy indicate loose electrical connections or shielding failure?</td>
<td>Unable to tell because bearing and seal have been badly torn up.</td>
<td>Material selection inappropriate or component under-specified</td>
<td>Identify source of internal damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23</td>
<td>Does autopsy indicate wear parts have fallen below their acceptable tolerance?</td>
<td>Main pump bearing has seized causing scoring to the drive shaft. Metallurgical report from SKG indicates that bearing has fatigue failure which could be caused by high temperature and high vibration conditions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>24</td>
<td>Does autopsy indicate damaged internal parts?</td>
<td></td>
<td>Identify source of internal friction or jam</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>Does autopsy indicate jammed or slow-moving internal parts?</td>
<td>Bearing has debris inside which could have jammed balls.</td>
<td></td>
<td>Intermittent failure - conduct bench top stress tests</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>26</td>
<td>Does autopsy indicate nothing wrong?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>27</td>
<td>When was last time drive motor or pump were replaced on CP4826?</td>
<td>Drive motor was replaced last year in December because it had burnt out.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>28</td>
<td>Were any alignment tools used during motor installation to ensure that the drive shaft and pump shaft were in alignment?</td>
<td>There are no tools available. There is no procedure for drive/pump shaft alignment.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Component Location:** WWTP Pump House
- **Failure Mode:** Seal Failure/Bearing Failure
- **Date of Failure:** January 12 5:15 am

2/18/2017 Ronald Morgan Shewchuk 62
Operational Excellence

Reliability Centered Maintenance

Case Study XVIII: Root Cause Analysis of Centrifugal Pump Failure

The RCA team next prepared the Reality Chart, a horizontal tree diagram linking effects to action causes and condition causes as shown in Figure 11.15. The term reality chart is used to indicate that all action causes and condition causes are supported by evidence such as Operator observations, DCS alarm records, data historians, laboratory analyses, failure analysis autopsies, etc. Nothing on this chart can be conjecture; otherwise it does not reflect reality.

Figure 11.15 Centrifugal Pump CP4826 Failure - Reality Chart

Problem Statement:

Centrifugal Pump CP4826 had to be shut down due to loss of seal fluid
Case Study XVIII: Root Cause Analysis of Centrifugal Pump Failure

The team started from the right side of the Reality Chart working toward the left, proposing solutions to eliminate condition and action causes. These proposed solutions are captured in Figure 11.16. The RCA team utilized a PICK Chart to prioritize solution alternatives, shown in Figure 11.17. It was decided to purchase a laser alignment kit, write an alignment Standard Operating Procedure (SOP) and train the relevant maintenance personnel on the alignment SOP. The Operations Group did not want to be held waiting for an outside contractor to perform the work. This equipment purchase and training was viewed as a necessary skill set development for the plant to increase reliability.

Incident Report
The Incident Report should concisely communicate the conclusions and recommendations of the Root Cause Analysis team. Required elements of the incident report include date investigation started, problem definition, summary statement of causes, solutions, action items and associated causes, responsible person and completion date, incident timeline, laboratory/failure analysis reports, reality chart, cost information, contact name and investigation team members, and report date. Thus far, we have utilized the software tools of the Microsoft Office Suite to generate the graphics for root cause analysis. If we chose to use the wizard function of RealityCharting software as shown in the screen shot of Figure 11.18, an incident report would be automatically generated provided that we have properly completed each of the RealityCharting steps. The Apollo RCA Incident Report is captured in Figure 11.19.
Problem Statement:
Centrifugal Pump CP4826 had to be shut down due to loss of seal fluid

Proposed Solutions
Eliminate pump:
(8) Use compressed air sparge

Proposed Solutions
Eliminate mechanical seal:
(7) Use magnetic seal:

Primary Seal Failure in Mechanical Seal
Caused By

Loss of Mechanical Seal Fluid
Caused By

Press Indicating Transmitter
Operator Observation

Bearing Failure
Autopsy by Mechanical Seal Mfg
Caused By

Debris in Bearing
Autopsy

“Oval” Wear Pattern
Autopsy

Fatigue Failure of Materials
Caused By

High Vibration
Operator Observation

High Temp
Operator Observation

No Alignment Tools

No Alignment Procedure

No Alignment Training

Proposed Solutions
Drive/Pump Misalignment
Caused By

Maint. Mech. Interview

Proposed Solutions
Provide WWTP Operator with predictive maintenance tools:
(5) Infrared thermometer
(6) Vibration analyzer

Proposed Solutions
Align drive and pump shafts:
(1) Purchase laser alignment SOP
(2) Write alignment SOP
(3) Train maintenance personnel
(4) Subcontract alignment outside

Operational Excellence

Figure 11.16 Centrifugal Pump CP4826 Failure - Reality Chart with Proposed Solutions
Figure 11.17  Centrifugal Pump CP4826 Failure – Solution Prioritization via PICK Chart

Solutions 1, 2 & 3 or 4 are best alternatives.
Figure 11.18  Centrifugal Pump CP4826 Failure – RealityCharting Software
Figure 11.19  Centrifugal Pump CP4826 Failure – Apollo RCA Incident Report

I. Problem Definition
What: CP4826 Centrifugal Pump Failure
When: Jan. 12 5:15 am
Where: WWTP Pump House
Significance: Risk of solids settling in digestion tank T3759. Risk of aerobic bacteria depletion in tank.
    Safety: Slip hazard due to propylene glycol/water seal fluid spill on floor of WWTP
    Environmental: Risk of shutting down WWTP
    Revenue: Shutting down WWTP will result in production shut down.
    Cost: Replacement pump, mechanical seal, drive shaft and installation labor $13,750
    Frequency: 4 times in last 12 months

II. Realitychart Summary
Reality Chart has indicated that the action cause of improper alignment of CP4826 motor shaft and pump shaft led to the seal failure. We don't have the proper tools to perform the drive/pump alignment, the procedure or the training. We could have an outside company come in and do this on an as-needed basis but this would result in production delays. The RCA team decided that it is better to develop this knowledge and skill set in-house.

III. Solutions
<table>
<thead>
<tr>
<th>Causes</th>
<th>Solutions</th>
<th>Owner</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Alignment Procedure</td>
<td>Write alignment SOP</td>
<td>Jim Phillips</td>
<td>Feb. 5</td>
</tr>
<tr>
<td>No Alignment Training</td>
<td>Train maintenance personnel on alignment SOP</td>
<td>Jim Phillips</td>
<td>Feb. 10</td>
</tr>
<tr>
<td>No Alignment Tools</td>
<td>Purchase laser alignment kit</td>
<td>Jim Phillips</td>
<td>Jan. 29</td>
</tr>
</tbody>
</table>

IV. Team Members
<table>
<thead>
<tr>
<th>Name</th>
<th>Email</th>
<th>Member Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dave Sutherland</td>
<td></td>
<td>Operations Manager</td>
</tr>
<tr>
<td>Jim Phillips</td>
<td></td>
<td>Maintenance Manager</td>
</tr>
<tr>
<td>Kevin Walters</td>
<td></td>
<td>WWTP Operator</td>
</tr>
<tr>
<td>David Williams</td>
<td></td>
<td>Maintenance Mechanic</td>
</tr>
<tr>
<td>Bill Johnson</td>
<td></td>
<td>Jack Crane Representative</td>
</tr>
<tr>
<td>Fred Sylvester</td>
<td></td>
<td>SKG Bearings Representative</td>
</tr>
</tbody>
</table>
Reliability Analysis

• We have been introduced to the reliability metric of failure rate through the Weibull distribution hazard function of Equation 11.1.

• The practical application of this function in a plant environment is to calculate failure rate by Equation 11.2.

\[
\lambda = \left(\frac{r}{T}\right)
\]

Eqn 11.2

where

- \(\lambda\) = Failure Rate
- \(T\) = Total run time for both failed and non-failed components
- \(r\) = Total number of failures occurring during the investigation period

• Let’s say we have eight electric motors which have been in service for three years. During this period four of the motors have failed. The failure rate is calculated as follows.

\[
\lambda = \left(\frac{4 \text{ failures}}{8 \text{ motors x 3 years}}\right)
\]

\[
\lambda = 0.167 \text{ failures/yr}
\]
Reliability Analysis

- Another common reliability metric is mean time between failures (MTBF), the reciprocal of the failure rate as indicated in Equation 11.3.

\[ \theta = \left( \frac{T}{r} \right) = \left( \frac{1}{\lambda} \right) \]  
Eqn 11.3

where
- \( \theta \) = Mean Time Between Failures
- \( T \) = Total run time for both failed and non-failed components
- \( r \) = Total number of failures occurring during the investigation period
- \( \lambda \) = Failure Rate

- Continuing our example from above, the mean time between failures is calculated as follows.

\[ \theta = \left( \frac{8 \text{ motors x 3 years}}{4 \text{ failures}} \right) \]

\[ \theta = 6 \text{ years} \]

- It is common for reliability engineers to track failure metrics for a population of components and analyze the failure rate and MTBF to determine where the population stands with respect to component life cycles. This is demonstrated in Case Study XIX.
Ricky Parker is the facility manager of a food distribution warehouse in southern California. The complex is relatively new with over 2.5 million square feet of warehouse space serviced by 366 air handling units, considered critical to maintaining product quality. Ricky joined the company around three years ago. The previous facility manager left in a huff after a dispute with senior management regarding capital equipment expenditures.

The facility start-up was difficult with many premature failures, exacerbated by an accelerated time line to open the warehouse. After the first couple months, however, the number of air handling units failing in a given month has stabilized at the baseline level shown in Figure 11.20.

Lately, the number of failures per month has been increasing and Ricky is concerned that the air handling units are headed for a repeat performance of their start-up days. He decides to conduct a reliability analysis on the air handling unit population as shown in Figure 11.21.
Open the Excel worksheet with the air handling unit failure records. Add a column for cumulative number of failures, failure rate as calculated by Eqn 11.2 and mean time between failures as calculated by Eqn 11.3.
Figure 11.21 Steps for Reliability Analysis

Open a new worksheet in Minitab. Copy and paste the air handling unit failure data into the worksheet.

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4 (months⁻¹)</th>
<th>C5 (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>47</td>
<td>47</td>
<td>0.128415</td>
<td>7.7872</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>10</td>
<td>57</td>
<td>0.077859</td>
<td>12.8421</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>9</td>
<td>66</td>
<td>0.060105</td>
<td>16.6364</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>7</td>
<td>73</td>
<td>0.049863</td>
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</tr>
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<td>5</td>
<td>5</td>
<td>9</td>
<td>82</td>
<td>0.044809</td>
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<td>6</td>
<td>6</td>
<td>6</td>
<td>88</td>
<td>0.040073</td>
<td>24.9545</td>
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<tr>
<td>7</td>
<td>7</td>
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<td>96</td>
<td>0.037471</td>
<td>26.6875</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>4</td>
<td>100</td>
<td>0.034153</td>
<td>29.2800</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>6</td>
<td>106</td>
<td>0.032180</td>
<td>31.0755</td>
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<td>10</td>
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<td>11</td>
<td>11</td>
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<td>0.028813</td>
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<td>12</td>
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<tr>
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<td>43.8169</td>
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<td>18</td>
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<td>0.022617</td>
<td>44.2148</td>
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Insert a column at the left hand side of the spreadsheet and label it as Start_Month. Rename the column Time in Service to End_Month.

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Figure 11.21  Steps for Reliability Analysis
Figure 11.21 Steps for Reliability Analysis

Click on Graph → Scatterplot on the top menu.
Select the Scatterplot With Connect Line icon in the dialogue box. Click OK.
Select Failure Rate for the first Y variable and End_Month for the first X variable. Select MTBF for the second Y variable and End_Month for the second X variable in the dialogue box. Click Multiple Graphs.
Click the radio toggle button to show pairs of graph variables in separate panels of the same graph in the dialogue box. Check the box to select the same X scale for the graphs. Click OK. Then click OK one more time.
Scatterplots are generated for failure rate and mean time between failures versus time in service.
Next, we will determine which distribution best fits the data set. Return to the active worksheet. Click Stat → Reliability/Survival → Distribution Analysis (Arbitrary Censoring) → Distribution ID Plot on the top menu.
Select Start_Month for start variable, End_Month for end variable, and Number of Failures for frequency column in the dialogue box. Click the radio toggle button to use all distributions. Click OK.
Probability plots are generated for each distribution.
Figure 11.21  Steps for Reliability Analysis

Probability plots are generated for each distribution.
The 3-Parameter Weibull distribution and the Smallest Extreme Value distribution have the highest Pearson Correlation Coefficient implying the best fit to the data set. For the sake of example, we will focus on the Weibull distribution.
Figure 11.21 Steps for Reliability Analysis

Return to the active worksheet. Click Stat → Reliability/Survival → Distribution Analysis (Arbitrary Censoring) → Distribution Overview Plot on the top menu.
Select Start_Month for start variable, End_Month for end variable, and Number of Failures for frequency column in the dialogue box. Click the radio toggle button to perform parametric analysis using the Weibull distribution. Click OK.
Figure 11.21  Steps for Reliability Analysis

Distribution Overview Plot for Start_Month
LSXY Estimates-Arbitrary Censoring

A Distribution Overview Plot is Created
Output Interpretation

Failure data can be entered into Minitab in several forms. In this case study, the failure data is *interval censored*, that is, the failure has occurred sometime between the start month and the end month. Right censored data means that the failure has not yet occurred and left censored data means that the failure has occurred at some time prior to a stated value. The latter case would apply when a component is inspected at a time interval and discovered to be in a failed condition. The analysis routine we have utilized, Distribution Analysis (Arbitrary Censoring), is applicable to exact failure times, right censored data, left censored data and interval censored data.

The scatter plot of failure rate looks a little like the left had side of the bathtub curve we reviewed during component life cycles. The current failure rate is still in the useful life region where random failures dominate. The mean time between failures scatter plot provides more resolution to the right hand side of the failure rate curve. There is an indication that we have turned the corner of component reliability and now are in a decreasing MTBF mode. Ricky need not panic about the current situation but he must be vigilant about continued reductions in MTBF. This may cause him to adjust his preventive maintenance strategy for the air handler units to include more frequent inspections utilizing methods such as vibration analysis, motor current signature analysis, thermal imaging, drive belt inspection, etc. He may also choose to increase the frequency of bearing lubrication preventive maintenance tasks if root cause analysis of the failed air handling units justifies this countermeasure.

The Distribution Overview Plot provides us with a table of statistics on the failure data. Notice that the shape parameter, $\beta$ of the Weibull distribution has been calculated to be 0.828. This supports our conclusion that the air handler unit population is within the useful life region. The infant mortality failures, however, have taken their toll. The survival function plot predicts that less than 15% of the original air handling units will last to 4 years of service time. Perhaps the previous facility manager was right when he quoted from Benjamin Franklin “The bitterness of poor quality remains long after the sweetness of low price is forgotten.”
Operational Excellence

Reliability Centered Maintenance

Audit System

• A performance audit should be conducted at facilities which have implemented Reliability Centered Maintenance (RCM) on an annual basis to check the health of the system and to identify focus areas for improvement.

• The audit should be conducted by an outside party such as representatives from another plant, another business unit or an outside consultant.

• The size of the audit team will depend on the size of the facility.

• A small facility could be audited by a team of only two people while a large facility would be subdivided into audit sectors, each assigned to a minimum of two auditors.

• Audit duration is typically three days.

• The audit must be objective, unbiased and supported by evidence (visual observation and documentation).

• Auditing is conducted on the factory floor through interviews, inspections, observations, reviews of documentation, Computerized Maintenance Management Systems (CMMS) records, key performance indicators, etc.
Operational Excellence

Reliability Centered Maintenance

Audit System

• The purpose of the audit is to provide guidance to the RCM team as to where their program needs concentrated effort to get to the next level of reliability centered maintenance.

• A series of questions are posed in the areas of management support and commitment, asset management, risk management, key performance indicators, preventive maintenance, predictive maintenance, root cause analysis, maintenance materials management, contractor management, and training.

• The answers to these questions will come in the form of no evidence; there is no demonstration of the RCM aspect or documentation thereof, some evidence; there is sporadic evidence of the RCM aspect but it is not recorded, documented evidence; there are records to support that the RCM aspect has been implemented, and execution evidence; the RCM aspect has been properly designed, developed and deployed and there is visible evidence that the RCM practice is being utilized (i.e. it is not a paper tiger).

• Typical RCM audit questions are compiled in the audit template of Figure 11.22 which is then used to create the audit scorecard of Figure 11.23.
Reliability Centered Maintenance Audit

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<th>Facility:</th>
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<th>Date of Audit:</th>
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### 1. Management Support and Commitment

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<td>1.2 Management supports maintenance at the same level as Health, Environment &amp; Safety (HES) initiatives</td>
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<td>1.3 Annual reliability objectives are built into individual performance objectives for the Plant Leadership Team</td>
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<td>1.7 Management demonstrates empowerment of RCM team members to cause reliability improvements</td>
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### 2. Asset Management

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<td>2.2 Database established which includes all equipment identification</td>
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<td>2.3 Computerized Maintenance Management System (CMMS) effectively utilized</td>
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<td>2.4 Bill of materials established in CMMS for all components except those classified as Run to Failure</td>
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<td>2.6 Life cycle costing is effectively utilized in capital expansion decisions</td>
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Figure 11.22 Reliability Centered Maintenance Audit Template

Reliability Centered Maintenance Audit

Facility:
Audit Team:
Date of Audit:

3. Risk Management

3.1 All component functions evaluated by Consequence of Failure Analysis (COFA)
3.2 All components classified as either Critical, Potentially Critical, Commitment or Run to Failure
3.3 Preventive Maintenance (PM) tasks and periodicities defined for all components classified as either Critical, Potentially Critical, or Commitment
3.4 PM Standard Operating Procedures (SOP's) documented for all components classified as either Critical, Potentially Critical, or Commitment
3.5 Capital expansions consider equipment operability, inspection access, and ease of maintenance as key design requirements

4. Key Performance Indicators

4.1 RCM Key Performance Indicators (KPI's) have been selected
4.2 KPI's have been defined such that a factory floor operator can understand the impact their performance can have on each metric
4.3 Targets for KPI's established
4.4 KPI's are updated in a timely fashion
4.5 KPI's are communicated within the organization in a timely fashion
4.6 KPI analysis is used to identify reliability improvement projects
Figure 11.22 Reliability Centered Maintenance Audit Template

Reliability Centered Maintenance Audit

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5. Preventive Maintenance

5.1 Operators are routinely involved in conducting PM tasks
5.2 CMMS utilized for planning and scheduling all maintenance work
5.3 Work requests are documented appropriately in CMMS
5.4 Work requests are appropriately prioritized on the basis of safety, environment, productivity and asset protection
5.5 PM task deferral is rationalized by COFA
5.6 Overdue PM tasks are prioritized and appropriately expedited
5.7 Operations personnel are included in component inspection, repair/replacement and return to service
5.8 Work orders are closed with appropriate documentation in CMMS including reason for component failure, repair time, material costs and work performed
5.9 Craftsmen have the appropriate tools, instruments and training to conduct PM tasks
5.10 Lubrication requirements are built into PM task SOP’s
5.11 Mechanical Integrity inspections are built into PM task SOP’s
5.12 Mechanical Integrity inspection results lead to countermeasures which are implemented in a timely fashion
5.13 Instruments are calibrated on time as per calibration schedule
5.14 Pressure relief devices are inspected on time as per inspection schedule
5.15 Steam traps are inspected on time as per inspection schedule
5.16 Planned shutdowns are scheduled well in advance
5.17 Turn-around Manager keeps track of schedule progress using Gantt Chart and utilizes Critical Path Management
5.18 Daily shutdown coordination meetings are held with trade and contractor representatives
5.19 Turn-around objectives and timeline are realistic and routinely met
5.20 A shutdown closure meeting is held to review results, conclusions and recommendations for future shutdowns
Reliability Centered Maintenance Audit

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### 6. Predictive Maintenance

6.1 Vibration monitoring is effectively utilized

6.2 Lubrication oil analysis is effectively utilized

6.3 Thermography or infrared monitoring is effectively utilized

6.4 Borescope inspections are effectively utilized

6.5 Magnetic particle, eddy current and/or ultrasonic testing are effectively utilized to detect metallic part surface flaws

6.6 Motor current signature analysis is effectively utilized

6.7 Weld repair quality is validated by X-ray analysis

### 7. Root Cause Analysis

7.1 Root Cause Analysis (RCA) conducted for all component failures which violate facility's Asset Reliability Criteria

7.2 RCA team formally trained in RCA methodology

7.3 RCA improvement recommendations are implemented

7.4 RCA improvement actions are validated for effectiveness
Figure 11.22 Reliability Centered Maintenance Audit Template

Reliability Centered Maintenance Audit

Facility:
Audit Team:
Date of Audit:

8. Maintenance Materials Management

8.1 CMMS effectively used to manage maintenance materials
8.2 Spare parts are available for all components classified as either Critical, Potentially Critical, or Commitment
8.3 Spare parts are labeled and traceable to bill of materials
8.4 Spare parts are stored in a controlled area
8.5 All material additions or removal from maintenance stores are recorded in CMMS at the time of inventory movement
8.6 Bar coding system is used to track maintenance stores inventory
8.7 Cycle counts are performed on a routine basis to validate inventory accuracy
8.8 Spare parts received to maintenance stores are inspected for conformance to specifications
8.9 Maintenance stores performance including stock-out rate, inventory value, turnover rate, on-time delivery from suppliers, and quality rejection rate are included in KPI's

9. Contractor Management

9.1 A documented policy for contractor management/performance is established
9.2 Contractors understand that their behavior, work quality, productivity, performance level, safety and environmental conduct are held to the same standard as a company employee
9.3 A review process is in place to validate contractor deliverables
9.4 Contract work above the established bid threshold is competitively bid to a minimum of three (3) contractors
### Reliability Centered Maintenance Audit

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</tr>
<tr>
<td>10. Training</td>
<td></td>
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</tr>
<tr>
<td>10.1</td>
<td>Operations personnel have been trained to operate equipment in a safe manner which promotes equipment reliability</td>
<td></td>
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</tr>
<tr>
<td>10.2</td>
<td>Operations personnel have been trained to conduct routine preventive maintenance on the equipment in their functional area</td>
<td></td>
<td></td>
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<tr>
<td>10.3</td>
<td>Maintenance personnel have been trained in process design, unit operations and process throughput requirements</td>
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<tr>
<td>10.4</td>
<td>Maintenance personnel have been trained to perform the specialized tasks required in PM and PdM Standard Operating Procedures</td>
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<tr>
<td>10.5</td>
<td>RCM training program is in place including annual refresher training</td>
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</tr>
</tbody>
</table>
Figure 11.23 Reliability Centered Maintenance Audit Scorecard

- **Facility:** Philadelphia Works
- **Audit Team:** J. Hancock, J. Adams, R. Morris, E. Ross
- **Date of Audit:** July 4

<table>
<thead>
<tr>
<th>Category</th>
<th>Final Score</th>
<th>Possible Score</th>
<th>% of Possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management Support and Commitment</td>
<td>9</td>
<td>18</td>
<td>50.0%</td>
</tr>
<tr>
<td>Asset Management</td>
<td>6</td>
<td>15</td>
<td>40.0%</td>
</tr>
<tr>
<td>Risk Management</td>
<td>6</td>
<td>12</td>
<td>50.0%</td>
</tr>
<tr>
<td>Key Performance Indicators</td>
<td>7</td>
<td>15</td>
<td>46.7%</td>
</tr>
<tr>
<td>Preventive Maintenance</td>
<td>30</td>
<td>54</td>
<td>55.6%</td>
</tr>
<tr>
<td>Predictive Maintenance</td>
<td>9</td>
<td>18</td>
<td>50.0%</td>
</tr>
<tr>
<td>Root Cause Analysis</td>
<td>6</td>
<td>12</td>
<td>50.0%</td>
</tr>
<tr>
<td>Maintenance Materials Management</td>
<td>12</td>
<td>21</td>
<td>57.1%</td>
</tr>
<tr>
<td>Contractor Management</td>
<td>6</td>
<td>9</td>
<td>66.7%</td>
</tr>
<tr>
<td>Training</td>
<td>6</td>
<td>12</td>
<td>50.0%</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td><strong>97</strong></td>
<td><strong>186</strong></td>
<td><strong>52.2%</strong></td>
</tr>
</tbody>
</table>
Communication

- Communication is the lifeblood of your RCM program.
- Timely, fact-based and forthright dialogue allows your organization to identify the evolving needs of reliability within your organization.
- Honest discussion exposes problems which need to be built into the Consequence of Failure Analysis (COFA) worksheet for the component in question.
- This leads to preventive maintenance tasks and periodicities which protect your facility from downtime.
- There are numerous ways in which the progress of RCM can be communicated such as monthly reports, email, sharepoint websites, newsletters, bulletin boards, etc.
- The key points are that the information must be timely, relevant and credible. Avoid sanitizing the data to paint the RCM message in a positive light. The results are what they are, as indicated in the Key Performance Indicators. Countermeasures to address RCM areas for improvement are a healthy sign of a flexible organization which will respond to changing needs of the business. An example RCM bulletin board posting is included in Figure 11.24.
Operational Excellence

Reliability Centered Maintenance

Key Performance Indicators

- Overall Equipment Effectiveness
- 12 Month Maint Cost as a % of RAV
- Schedule Compliance
- % Emergency Work
- Preventive and Predictive Work
- MRO Parts Stockout Rate

KPI Definitions

- Overall Equipment Effectiveness (OEE) - a measure used to rate the effectiveness of an asset, calculated by multiplying availability by performance rate by quality rate.
- Replacement Asset Value (RAV) - the valuation of a plant’s assets in today’s dollars (i.e., if you were to build a duplicate plant across the street today at equivalent capacity, the cost would total the RAV).
- Preventive Maintenance (PM) - a maintenance strategy designed to prevent an unwanted consequence of failure including condition-directed, time-directed, interval-directed, and failure finding tasks.
- Predictive Maintenance (PdM) - a maintenance strategy based on measuring equipment condition in order to predict whether failure will occur during some future period, thus permitting the appropriate preventive actions to be implemented to avoid the consequences of that failure.
- Emergency Work - a maintenance task that must be completed within 24 hrs to avert an immediate safety hazard, an environmental hazard, or to correct a failure with significant economic impact.
- MRO Parts Stockout Rate - The number of occurrences where a stocked maintenance, repair and operating (MRO) material was unavailable divided by the total number of MRO stores withdrawals within a given time period.

Next Plant Turnaround

- Turnaround Team
  - Turnaround Manager
  - Operations Coordinator
  - Process Coordinator
  - HES Coordinator
  - Scheduler
  - Planner
  - Contractor Coordinator
  - Procurement Coordinator
  - Material Expeditor

- Work Schedule

- Primary Objectives

News Updates

RCM Newsletter

Training Opportunities

Vendor Visits
We have covered a lot of ground!

Thus, it is prudent for us to review the steps required to implement Reliability Centered Maintenance in your facility as summarized in Figure 11.25.

Even a small facility can have thousands of components requiring consequence of failure analysis (COFA).

Don’t become overwhelmed.

Start with your components which are obviously critical (failure results in a safety, environmental or plant shutdown consequence) and expand your RCM program outward from this core group of components.

You will notice that Reliability Centered Maintenance is autocatalytic.

As the reliability of your plant increases, emergency maintenance decreases, freeing up resources to allow you to expand the scope of your RCM initiative.
### Reliability Centered Maintenance Implementation Steps

1. Choose an RCM point of contact
2. Select team members from Maintenance, Operations, Engineering and Craftsmen
3. Define Asset Reliability Criteria
4. Establish database to include all plant equipment ID's (use your plant's CMMS)
5. Analyze each component function in the Consequence of Failure Analysis (COFA) Decision Tree
6. Analyze each component function classified as Potentially Critical
7. Analyze each component function classified as Economically Significant
8. Enter all data in the COFA Worksheet
9. Classify each component as Critical, Potentially Critical, Commitment or Run to Failure
10. Define PM tasks for all components except those classified as Run to Failure using the PM Task Selection Flow Chart
11. Enter all Preventive Maintenance SOP's and periodicities in the COFA Worksheet
12. Establish RCM program documentation requirements including record retention policy
13. Select Key Performance Indicators and Targets for RCM program
14. Communicate Monthly Key Performance Indicator Results
15. Establish and maintain RCM Training Program including refresher training
16. Maintain vigilance of RCM based Preventive Maintenance Program
17. Expand RCM Program to Ancillary Equipment and Suppliers to mitigate risk
References


Internet Resources

- Society of Maintenance and Reliability Professionals
  http://www.smrp.org/

- Plant Maintenance Resource Center
  http://plant-maintenance.com/

- Maintenance Technology Magazine
  http://www.mt-online.com/

- Apollo Root Cause Analysis
  http://www.apollorca.com/

- Reliability Engineering Resources
  http://www.weibull.com/

- GE Sensing & Inspection Technologies

- Laser Alignment Tool
  http://www.laser-alignment-tool.com/