MAINTENANCE

1. Introduction

Chemical plants are built to produce a particular product, in a particular quantity, and at a particular quality. Once the plant is built the following three items must converge for the manufacturing to take place.

1. Equipment Custody (control) in good working order and up to specifications.
2. Bill of Materials (all of the resources such as raw materials, specialized tooling and consumables).
3. Labor with the requisite competencies.

Whenever a product design changes (eg, color, size, specifications) one or more of the three elements have to change also. If the plant makes latex paint and a change in color is desired a new Bill of Material for the new batch must be issued. Everything that goes on in the plant with regard to production can be traced back to these three elements.

These elements are extensively dealt with by the plant's MRP (Material Requirements Plan) which is activated by the marketing forecast. All of the processes to make a product and deliver a product are intensively studied, discussed, and pondered by top management. Billions of dollars are spent developing systems and procedures to ensure that these three elements converge at the right time, in the right sequence, and at the right place.

For the plant to make a product, it must have machine capacity capable of delivering the product as per the marketing forecast defined by the MRP. Within the design limits of the equipment chosen, good maintenance delivers that capacity. Consistently without surprises for as long as the company needs the output.

Maintenance operates in a very similar way and also has a product. The product of maintenance is the capacity or uptime to make the ultimate product. Thus, production makes products and maintenance makes capacity to make production possible.

The same three elements must be present for maintenance to make its product. In this case

1. Equipment Custody (control) of the equipment to make repairs and for preventive activities.
2. Bill of Materials (all of the resources such as parts, tools, equipment and consumables necessary for all maintenance activity).
3. Labor with the requisite competencies either employees or contractors. In this case repair, troubleshooting, installation competencies.

All of the maintenance management effort is geared toward managing one or more of these elements. The maintenance management effort is detailed in Table 1 and some items of this articles are discussed in individual sectors. Unlike the process of production, top management in maintenance spends very little effort, time or funds to optimize, study or even understand the maintenance process.

Before the strategies for managing maintenance are discussed the nature of failure must be examined.

1.1. The Nature of Failure. It is essential to understand failure in order to effectively design tasks that will either detect failure or tasks that will extend life. In the P-F curve shown in Fig. 1, the nature of failure is dissected.

One key is that the engineers of RCH methods determined that for each failure mode there was a precipitating event that starts the train of events that ends in failure. This event is called the critical event (CE). Damage, contamination, heating, overloading, corrosion, and even operations abuse could cause this critical events.

The P-F (performance–failure curve) describes the performance characteristics from the CE point to the ultimate total loss of performance, which is called failure. Note that the slope of the curve in Fig. 1 (decay in performance) starts slowly and increases at a more rapid rate. This means that there may be little or no discernable decay in performance in the beginning (near the CE). As time goes on, once the process goes over the hump in the curve, the performance decays rapidly.

The curve shows two facts that are essential for the proper determination of the task frequency. The first fact is how long does it take from when an event happens to ultimate failure? This fact determines the frequency of the task to be effective. Any task must be done about twice as often as this interval. The second fact is what does inspection and PdM buy? In other words, what depth task is necessary to achieve the reliability goal?

1.2. PM Activity. There are several ways to measure the P-F interval

The PM inspection routines are designed to detect the failure modes unfolding and determine when failure will take place so an effective intervention can be made. Since the failure modes cannot yet be seen directly (point D), the goal is to find a measure that is easy to use and is more directly proportional to wear.

PM is a series of *tasks* performed at a frequency dictated by the passage of time, the amount of production (eg, cases of beer made), machine hours, mileage, or condition (eg, differential pressure across a filter) that either:

1. *Extend the life of an asset.*

   Example: Greasing a gearbox will extend its life. All the tasks with E in the box in Fig. 2 (see section 2) are life extension type tasks

   or

2. *Detect that an asset has had critical wear and is about to fail or break down.*

   Example: A quarterly inspection shows a small leak from a pump seal. Finding this leak allows it being repaired before a catastrophic breakdown. All the tasks with D in the box of Fig. 2 are impending breakdown detection type tasks

1.3. Task Direction. These tasks should be directed at how the asset will fail. The rule is the tasks should repair, delay or detect the unit's most dangerous, most expensive or most likely failure modes (in that order). The following warnings should be headed.

1. Even with the best PM systems there will still be failures and breakdown. The goal is to reduce the breakdowns to levels financially and operationally appropriate, and consistent with a safe and secure environment. In a hazardous chemical environment the threshold might be significantly higher (a much more intensive PM) then in a nonhazardous environment. Through early detection, the breakdowns that occur will be of a reduced size and scale. Ideally the breakdowns that are left into learning experiences could be converted to improve the delivery of maintenance service and improve the PM system.
2. A major consideration is that whatever PM is performed, iatrogenic failures are factored in. Iatrogenic means: a symptom or illness brought on unintentionally by something that a doctor does or says. In this case, it means any breakdown or service due to an action of the mechanic or service caused breakdown. In fact, every interaction with a machine or other asset has some probability of going badly. The more PM activity there is on any asset, the higher the probability of iatrogenic failure. Training, proper tools, adequate time, limiting distraction, and good working conditions reduce these kinds of failures.

2. PM and Pdm Defined Preventive and Predictive Maintenance

The flow of all information in a maintenance department can be organized around PM as shown in Figure 2(1) .

2.1. Details.

Description of the details in Fig. 2 are discussed below.

1. *Row 1*

   Task List: a list of all the tasks or actions to be performed at that time, there are four major types of task lists–unit, string, standing, and future benefit.

   Tasks (row 2 and 3) are organized into Task Lists

   Each task is marked off when it is complete. Some tasks require readings or measurements. There should always be room on the bottom or side of the task list to note comments and readings. Actionable items should be highlighted to make it easy for the reader

   Types of clocks and frequency: PM is periodic. The clocks determine how often or when to perform tasks on the task list. Measured in days, units, tonnage, cycles, miles, or even readings (such as temperature), changes to readings, findings (oil slick on floor under truck). Almost any trigger can be designed into a PM clock.
2. *Row 2 and 3*

   D-detect failure, E-extend life are rows that represent possible types of tasks

Inspect: Stop, look, and listen, by using human senses or instruments (PdM)

PdM (predictive maintenance): Any inspection carried out with high technology tools that use advanced technology to detect when failures will occur. Such tools can increase your returns and give you more time to intervene before failure.

TLC (tighten, lube, clean): Start with the basics. Caring for equipment is the core of the PM approach. This care does not require any fancy equipment or techniques and involves just basic care. Much of the benefit from PM flows from TLC.

Adjust: Making the equipment work optimally by tightening, changing, fine-tuning, or modifying the machine set-up or operation.

PCR (planned component replacement): Also called scheduled replacement. This technique has been made popular by the airlines. PCR can improve reliability in many circumstances.

Readings: Write down or enter data concerning measurements of pressure, temperature or other parameters. Spotting trends in these readings can frequently uncover problems before they impact production or safety.

Interview operator: Ask questions about machine operation and note answers. Many problems are apparent to the operator or driver before they are obvious to anyone else.

Notes about machine condition: These notes are related to readings and will tell the skilled observer of any subtle changes taking place in the asset.

Row 4

There are four results possible from a PM inspection:

1. Everything okay and no actions is needed.
2. Deferred maintenance item is problem that is usually ignored and it is hoped that the unit does not fail. The problem is that these deferred items have a way of coming back to haunt the process. They only rarely go away by themselves. Deferred maintenance items have been studied. When looked at economically they tend to deteriorate at a great rate compared to the interest rate that could be received on the money not spent by deferring them in the first place. It rarely pays to defer an action unless the machine or process is being closed down.
3. Corrective maintenance is any item found by inspection that you plan to schedule. This is called plannable maintenance (it can be planned). The goal of the inspection process is plannable maintenance. With this kind of work you have the lead-time to work efficiently. Plannable could be not planned because not every firm is committed to planning maintenance activity (for details see Ref. 2)
4. Short repairs are done by the PM person when they are doing the PM, including repairs of short duration with the tools and materials that the PM person carries. These actions are different from temporary repair. A

short repair is a complete repair that can be accomplished in a short time. Short repairs are an easy way to improve productivity.

Row 5

All data flows to the design and engineering review. One of the primary reasons for collecting data is to use it in the review (and redesign) of breakdowns and disruptive events. These events include data from breakdowns, data from manufacturers, readings, reports of machine condition, and all work orders. RCM or PCO style design and engineering review uses the structures of RCM to manage the process.

RCM (Reliability Centered Maintenance) is one of the most important approaches to PM, and was developed in the aviation industry. One result from a review of what happened is feedback to the task list in the form of details of increased (decreased) frequency, depth, or technology.

PMO (PM Optimization) is an offshoot of RCM and recognizes the difficulty (and sometimes futility) of RCM in a mature operational plant. PMO embodies techniques to optimize the PMs that are done to get the most reliability from the least resources.

2.2. Other Facts of the PM Systems. PM systems also include:

1. A record keeping system to track PM, failures and equipment utilization. Part of the job of the PM effort is creating baselines for other analysis activity.
2. All types of predictive activities. These include both human sense inspection and the use of instruments for taking measurements and readings. Included is inspecting of production for quality. PM includes the recording of all data for statistical and trend analysis.
3. Short or minor repairs. In this sense short repairs refer to repairs that can be done completely and properly in a short time. Short repairs are a great boost to productivity since there is little or no lost time. Short repairs are to be written up for equipment history because minor or small problems often signal larger underlying problems.
4. Documenting any conditions that require attention (conditions that will lead or potentially lead to a failure). Specifically this refers to write-up of corrective maintenance action items onto work orders or work requests. This also includes reports about machine condition. All PM systems have to manage the feedback cycle effectively from written up conditions and work order creation to successful work completion and possibly re-inspection.
5. Scheduling and actually doing these corrective repairs written up by PM inspectors within a reasonable timeframe (before they fail). A necessary step before scheduling is planning each job so that maintenance resources are used in an optimum way.
6. Keep the PM process going and refine the task lists and task frequencies. One way to accomplish this is using the frequency and severity of failures to refine PM task list. In other words when too many failures on equipment under the PM program are experienced, examine the task list and add items, add depth, increase frequency or add technology.

7. Management of and investigation into trends uncovered by inspections and an intelligent determination of who should do what analysis and when they should do it.
8. Continual training and upgrading of inspector's skills.

The goal is the results from PM, lower downtime, higher reliability. PM requires both equipment custody and money for parts and labor. Both can be scarce resources and are extremely expensive. The goal is the highest stable long-term output. In other words the day production can run 100% uptime with 100% safety without PM will be the last day for PM.

3. Introducing and Managing Predictive Maintenance (PdM)

The ideal situation in maintenance is to be able to peer inside components and replace them right before they fail. Technology has been improving significantly in this area. Tools are available that can predict corrosion failure on a transformer, can thread through, examine and videotape boiler tubes, or detect a bearing failure weeks before it happens.

Scientific application of proven predictive techniques increases equipment reliability and decreases the costs of unexpected failures. Predictive maintenance is an activity geared to indicating where a piece of equipment is on the P-F curve and predicting its useful life.

Any inspection activity on the PM task list is predictive; PdM is reserved where instruments are used for the readings.

3.1. Condition-Based Maintenance. Condition-based maintenance is related to predictive maintenance. In condition-based maintenance, the equipment is inspected and based on a condition further work or inspections are done. For example, in traditional PM a filter is changed monthly. In condition-based maintenance, the filter is changed when the difference in pressure between a gauge before the filter and a gauge after the filter reaches a particular value. The differential pressure notes the condition of the filter.

The most sophisticated application of condition-based maintenance is a computer processor monitoring the asset on an on-going basis. When the measured parameter exceeds the engineering limit, the computer issues an alarm. If it exceeds a higher second limit, the computer might issue an emergency shutdown sequence.

All of the predictive techniques discussed (except condition based methods) should be on a PM task list and controlled by the PM scheduling system. The PdM tasks should be coordinated with other PM activity. Most PdM tasks are handled in string based PMs (short activities on many assets).

3.2. PdM Checklist. The checklist is as follows (3):

1. What is our objective for a predictive maintenance program? Do we want to reduce downtime, maintenance costs or the stock level in storerooms? What is the most important objective?
2. Are we, as an organization, ready for predictive maintenance?

3. Is (are) the specific technique(s), the right technique(s)?
4. Is this the right vendor?
5. Is there any other way to handle this instead of purchase?

An excellent treatment of the whole field of predictive maintenance can be found in Ref. 4.

3.3. Deterioration Technologies. Technologies are grouped around detecting deterioration in sub effects: dynamic (vibration), particle (ferragraphy), chemical (water analysis), physical (crack detection), temperature (infrared), electrical (ampere monitoring) (see Table 2).

Chemical Analysis. One of the most popular families of techniques to predict current internal condition and impending failures is chemical analysis. There are seven basic types of chemical analysis. The first two are related to particle size and composition.

Type	Material
atomic Emission (AE) Spectrometry	all materials
atomic Absorption (AA) Spectrometry	all materials
gas chromatography	gases emitted by faults
liquid chromatography	lubricant degradation
infrared spectroscopy	similar to AE
fluorescence spectroscopy	assessment of oxidation products
thin- layer activation	uses radioactivity to measure wear

Oil analysis is a significant subset of all of the chemical analysis used for maintenance. The two spectrographic techniques are commonly used to look at the whole picture. These techniques are used to report all metals and contamination and are based on the fact that different materials give off different characteristic spectra when burned. The results are expressed in ppt or ppm (ppt, parts per thousand; ppm, parts per million; ppb, parts per billion).

Vibration Analysis. Vibration analysis is a widely used method in plant/machinery maintenance. Each element of a rotating asset vibrates at characteristic frequencies. A bent shaft will always peak at twice the frequency of the rotation speed. A ball bearing, on the other hand, might vibrate at 20 times the frequency of rotation.

There are over nine different types of vibration analysis. Each individual technique focuses on one aspect of the way assets deteriorate that can be detectable by vibration. Techniques include octave band analysis, narrow band frequency analysis, real time analysis, proximity analysis, shock pulse monitoring, kurtosis, acoustic emission, and others.

The most popular is broadband analysis. This analysis measures the changes in amplitude of the vibration by frequency over time. This amplitude by frequency is plotted on an XY axis chart and is called a signature (also for a given service load). Changes to the vibration signature of a unit means that one of the rotating elements has changed characteristics. These elements include all rotating parts such as shafts, bearings, motors, and power transmission components. Also included are anchors, resonating structures and indirectly connected equipment.

Temperature Measurement. Friction (or electrical resistance) creates heat. Temperature is the single greatest enemy for lubrication oils and for the power transmission components. Advanced technologies in detection, imaging, and chemistry allow the use of temperature as a diagnostic tool.

Today, there is technology to photograph by heat rather than reflected light. Hotter parts show up as redder (or darker). Changes in heat will graphically display problem areas where wear is taking place or where there is excessive resistance in an electrical circuit. Infrared is unique since it is almost entirely noninterruptive. Most inspections can be safely completed from 10 or more feet away and out of a danger zone.

Ultrasonic Inspection. There are four or five techniques that make up the one of the most exciting families of technologies based on ultrasonic. The technology is widely used in medicine and has moved to factory inspection and maintenance.

Ultrasonics can determine the thickness of paint, metal, piping, corrosion and almost any homogenous material. New thickness gauges (using continuous transmission techniques) will show both a digital thickness and a time based scope trace. The trace will identify corrosion or erosion with a broken trace showing the full thickness and an irregular back wall. A multiple echo trace shows any internal pits, voids and occlusions.

Advanced Visual Techniques. The first applications of advanced visual technology used fiber optics in bore scopes. In fiber optics, fibers of highly pure glass are bundled together. The focus on some of the advanced models is 1/3″ to infinity. The limitation of fiber optics is length. The advantages are cost (about 50% or less of equivalent video technology and level of technology (they do not require large amounts of training to support). Another visual technology gaining acceptance is ultra-small video cameras. These are used for inspection of the interior of large equipment, boiler tubes, and pipelines. They use a miniature television camera smaller then a pencil (about 1/4″ in diameter and 1″ long) with a built-in light source. They are extensively used to inspect pipes and boiler tubes.

Other instruments not discussed here, but should be considered part of a predictive maintenance tool box are meggers, pyrometers, VOM meters, strain gauges, temperature sensitive tapes, and chalk.

4. PCR (Planned Component Replacement)

PCR is strategy formerly widely recommended by the aircraft manufacturers and used by the airlines is scheduled component replacement (and return of the component to the depot for rebuild) (5).

PCR is an option on the PM task list. The novelty of this option is the elimination of failure because components are removed and replaced after so many hours or cycles, but before failure. Depending on the substrategy some of the components are then returned for inspection, rebuilding, or remanufacturing, and others are discarded. The result of this strategy is controlled maintenance costs and low downtime. The strategy does *not* work when the new component experiences high initial 'burn-in' type failures.

For example, fleets with time-sensitive loads realized that breakdown costs with downtime are sufficiently high to justify PCR. It is standard procedure in some fleets to replace hoses, tires, belts, filters, and some hard components, well before failure on a scheduled basis. These soft items (belts, hoses) are called planned discard since there is no intention of using them elsewhere.

PCR is an expensive option. Even in the aircraft industry, significant effort has gone into improving reliability so that fewer components would be in the periodic rebuild program. According to John Moubray (4), after an extensive RCM analysis the number of overhaul items (planned rebuild items) went from 339 on the Douglas DC 8 to just 7 items on the larger and more complex DC 10. Although the number has dropped dramatically, PCR is still an important tool to the maintenance professional.

5. Inventory Management

5.1. MRO (Maintenance Repair and Overhaul).

The second element of managing maintenance is the Bill of Material. Having the whole Bill of Material work smoothly is essential to the ability to deliver maintenance to customers. The storeroom or maintenance warehouse is considered the single largest barrier to productive maintenance delivery. In fact, studies by Dun and Bradstreet list the storeroom the single largest reason for delays in repairs and downtime.

The goal of storeroom is to have the right part available in time to support essential maintenance activity while using the least organizational resources. Included in the goals are

Give the parts needed quickly to maintenance customers.

Know where everything is.

Keep track of quantities.

Protect parts from spoilage.

Report facts to management.

Manage order points.

Place orders or issue requisitions.

Receive and put away parts.

5.2. Often Confused Concepts.

COO (cost of ownership): All of the costs associated with storage and retrieval of the inventory. Prominent are the cost of money, labor, and the facility. Common ratios range from 2.5 × prime rate (6) to 3 × prime rate (7) per year.

COA (cost of acquisition): This is the cost of purchasing, receiving and accounting for each purchase transaction. Direct links using the Internet and the use of purchase cards are driving down the cost of routine purchases. Multiple quotes, bidding, and engineered products have significantly higher COA.

COA for an extensively negotiated and engineered purchase could be a thousand times higher then a routine buy.

5.3. Importance of Storeroom Management. The biggest reason to manage the storeroom is the consequence of downtime. Downtime might be a hundred times more expensive then carrying the spare part list. A related but opposite reason is the high cost of wasted money represented by the wrong maintenance inventory. Ideally management balances downtime costs with the cost of the inventory.

Inventory management does not mean that the inventory is too high (it might be too low). Management should respond to real business conditions. Traditionally since the true function of the inventory is masked, management has meddled in the amount and rules of purchases. Management would cut the number of line items, deny the ability to add items, or delay purchases beyond the reorder point as part of an overall cost cutting strategy. The results will be felt weeks or months later, not in the maintenance department but rather in downtime or airfreight costs.

6. Planning

A typical maintenance worker's day with and without planning and scheduling is described in Table 3.

The 35% direct work in reactive mode versus the 65% direct work in proactive mode provides a simple but clear justification for establishment of a planning, coordination, and scheduling component.

Another way to appreciate the advantage of job planning is to depict what happens within an individual job without planning. Technicians jump into the work without forethought. Shortly they encountered a delay for lack of a spare part, tool, or authorization. This sequence may be repeated several times before the job is completed. In the planned mode, the needs are anticipated and provided for before a technician is assigned. The comparison is graphically presented in Fig. 3.

Each dollar invested in planning typically saves three to five dollars during work execution and the duration of a planned job is commonly only half as long as that of an unplanned job. See Ref. 2.

6.1. Steps in Planning. *Development of Work Programs.* Work programs are the vehicles whereby maintenance resources are perpetually balanced with maintenance workload. Without this balance, deferred maintenance increases progressively and the benefits of preventive/predictive maintenance (PPM) cannot be realized. Because maintenance is managed by controlling backlog within established limits, the current backlog upon maintenance crews (measured in weeks) must be calculated and analyzed. A work program should be developed at least monthly.

Work Program. Work programs consist of the following:

1. Gross labor hours authorized each week including budgeted overtime and contract support.

2. Quantify resources committed to various indirect activities including vacation, absenteeism, training, meetings, etc. This subtotal is subtracted from gross resources to calculate the resources available during a typical week for direct work.
3. Deduct average weekly consumption of direct work resources for response to urgent conditions such as equipment failures causing production downtime.
4. Deduct all projected PPM work for next week.
5. Finally the resources available for backlog relief are identified. This is the number that the planner goes into the coordination meeting with. The available hours are divided into current levels of "Ready" and "Total" backlog to quantify backlog weeks compared to established benchmarks.

Planning Package. A planning package for every job in the backlog may include (larger and high hazard jobs might have more of these items) is shown in Fig. 4.

7. Scheduling

The first step of scheduling is coordination. Coordination is the first task for scheduling after the bulk of the individual job plans are complete. The planner will first run the ready backlog. All jobs that have been identified that are ready to go. All materials, engineering, rental equipment, and authorization are in place. The ready backlog and the scheduled PMs for next schedule period are presented to operations. Also the accurate number of hours available for work is presented. Coordination is actually a meeting. The outcome of the meeting is a schedule for the next week. Before the actual coordination action items come up in the agenda, other things (such as what happened last week) must be dealt with.

7.1. Scope. The scope of scheduling includes:

1. Bringing together in precise timing the six elements of a successful maintenance job: labor; tools, materials, parts and supplies; information, engineering data and reference drawings; custody of the unit being serviced; and the authorizations, permits, and statutory permissions.
2. Matching next week's demand for service with resources available after accounting for all categories of leave, training, standing meetings, and indirect commitments, plus consideration of individual skills.
3. Preparation of a weekly schedule that represents the agreed upon expectation regarding planned work orders to be accomplished with available resources. The schedule also assures that all preventive and predictive routines will be accomplished within established time limits.
4. Consideration of alternative assignment strategies where the schedule assigns specific jobs to specific people (eg, whether people with less training into the process to gain experience is feasible).

Part of the planner/scheduler's challenge is ensuring that responsible supervisors receive and understand the planned job packages for scheduled jobs.

7.2. Activities For Scheduling.

1. Job loading, sets forth jobs to be completed during the schedule period. Scheduling of these jobs stems from coordination between maintenance and operations to assure that the near term operating needs and the long-term assurance of asset and capacity reliability are both served.
2. Job scheduling, sequences the loaded jobs through the schedule week based on meaningful estimates of the required duration and agreed upon equipment access.
3. Personnel commitment, ensures optimal utilization of resources.

8. Training

The skills needed to run today's factories and buildings are changing faster than people can assimilate. Jumps in technology disorient even the most dedicated worker. See also Ref. 2

In training terms there are three types of learning that apply to this situation; knowledge, skill, attitude (see Table 4). For higher-level jobs (such as chief service person) all three must shift to competence. Many types of training address one or other of these types of competences without regard for the other. Maximum effectiveness in this case must shift all three areas.

There are four steps in the design of tailored learning program:

Step 1: Determine what knowledge, skills, and attitudes are needed for the job. Before teaching anything, it is necessary to see what is needed. Look at the job as it is today and forecast where the job is going in the short term. The big picture of competencies is called the General Learning Objective (GLO). The concrete and specific skills, knowledge, and attitudes required to do the job are called specific learning objectives or SLOs. If the job were properly deconstructed, a person achieving these SLOs would be successful in this job.

Step 2: Evaluate the potential trainee's current skills, knowledge, and attitudes. A direct supervisor might be able to make an educated guess. If the trainee has good insight they might know where they are weak. Most situations require some kind of testing (either observation on the job or more formal written or bench tests). The testing should be designed to uncover the skills on your required list. It is important to note that success on the test should correspond to success on the job.

Step 3: Translate the voids in skills, knowledge and attitudes of the potential trainee from the required list to develop a training lesson plan. The training plan should list all of the types of learning that this person/group needs. The plan summarizes the skills, attitudes and knowledge that the specific candidate lacks and needs for the job. At this point, estimate the time requirement for the trainee and the requirement for any supporting staff.

Step 4: As a post test determine if the candidate learned all the skills and knowledge and adopt the attitudes needed from the training to be successful on the job. In simplified language, was the training successful? If it was not, then the candidate must be retrained.

This exercise might be necessary for all related jobs. The service technician might have related SLOs that can be economically incorporated into this training.

9. Reliability Centered Maintenance (RCM)

One of the best models for continuous improvement is the application of reliability-centered maintenance. RCM is one of the radical and powerful ways to improve maintenance because it addresses the core of the customer need, that is, an increasingly reliable system. The technology is an outgrowth of deep investigations into reliability on behalf of the aircraft manufacturers and the airlines (8).

9.1. Five-Step Process. The RCM process is usually team driven with members from operations, engineering and maintenance (where there is significant hazard then safety or environmental specialists would be included). A RCM specialist with good knowledge of the process and products usually facilitates it.

1. Identify all of the functions of the asset. At first this might seem trivial. On a second examination there are many secondary functions that are important. Functions are divided by primary, secondary and protective (also called hidden). Each function is defined by a specification or performance standards.

   For example, the primary function of a conveyor is to move stone from the primary crusher to the secondary crusher. The specification calls for 750 tons per hour capacity. Secondary functions include containment of the crushed stone pieces falling through the conveyor could hurt someone.
2. The second step is to look at all ways the asset can lose functionality. These are called functional failures. One function can have several functional failure modes. A complete functional failure would be that the unit could not move any stone to the secondary crusher. A second failure would be it could move some amount less then the specification of 750 tons per hour. A third functional failure is if the conveyor starts moving more then 750 tons per hour and starts to over fill the secondary crusher.
3. Review each loss of function and determine all of the failure modes that could cause the loss. Failure modes are not restricted to breakdowns. Operational problems, problems with materials, utilities are also considered. In the example, the list might be 20 or more failure modes to describe the first functional failure alone. Failure modes or our rock conveyor include motor failure, belt failure, pulley failure, inadvertently turning the unit

off, power failure, etc. Each functional failure is looked at and the failure modes are defined.

It is essential that the team identify the root cause of the failure and not the resultant cause. A motor might fail from a progressive loosening of the base bolts, that strains the bearing. This would be listed as motor failure due to base bolts loosening up.

It is important to include failure modes beyond the normal wear and tear. Operator abuse, sabotage, inadequate lubrication, improper maintenance procedure (re-assembly after service), would be considered.

4. What are the consequences of each failure mode? Consequences fall into four categories. These include safety, environmental damage, operational and nonoperational. A single failure mode might have consequences in several areas at the same time. John Moubray (3) says "Failure prevention has more to do with avoiding the consequences of failure then it has to do with preventing the failures themselves."

   The consequences of each failure determine the intensity with which the next step is pursued. If the consequences include loss of life, it is imperative that the failure mode be eliminated or reduced to improbability. A belt failure would have multiple consequences which would include safety and operational. A failed belt could dump stone through the conveyor superstructure hurting everyone underneath. The failed belt would also shut down the secondary crusher unless there is a back up feed route. Other failures might only have nonoperational consequences. Nonoperational consequences include only the costs to repair the breakdown.

5. The final step is to find a task, that is technically possible and makes sense to detect the condition before failure or otherwise avoid the consequences. Where no task can be found and there is safety or environmental consequences, then a redesign is demanded.

   For example, if it is found that the belts start to fail after they are worn to 50% of their diameter, an inspection might be indicated. If the belts fail rapidly after cuts or other damage, then a sensor might catch these problems. In all cases where safety or environmental damage is the main concern, the task must lower the probability of failure to a very low level.

9.2. Hidden Failures. Some failures of sensors or protective devices are hidden. A failure is hidden if it occurs and the operators would, under normal conditions, not notice the problem. For example, if a belt thickness gauge fails then (unless the design is failsafe) the operators would have no way of knowing that the sensor is out of service. After a hidden device has failed a rip (of the belt) could develop and cause complete belt separation without notice and cause an accident.

10. Total Productive Maintenance (TPM)

There is a revolution occurring, on the factory floor of selected organizations. The ideas of TPM are to make the operator an equal partner in the maintenance effort. This import from Japan has taken root in factories, refineries, mills, and power plants throughout North America. It succeeds because it forces one to realize that more and more of the capabilities of every employee have to be used to remain competitive. The group of operators is traditionally viewed as underutilized in most factories.

The machine operator is the key player in a TPM environment. Many of the losses are under the control of the operator, involve the operator, or happen while the operator is near the machine. There is less reliance on the maintenance department for basic maintenance (but more for coaching, training, and mentoring). Control and responsibility are passed to the operators.

There is complete focus on the losses from production. The losses can come from six areas. Rigorous data collection followed by analysis is necessary to identify loses in each of the six areas.

TPM can be summarized as attention to and elimination of the six losses of production: Points one and 2 are considered downtime, 3 and 4 are speed losses, and 5 and 6 are defects.

Equipment failure from breakdowns. This is the biggest element directly the responsibility of maintenance. With TPM, first line maintenance activity is transferred to operations. Proper design ensures reductions in breakdown related downtime.

Setup and adjustment. The stated goal is single digit minute set-up times. This allows up to 9 minutes for set-up. Adjustments are simplified or eliminated from the system. Overall re-engineering to reduce these exposures is expected.

Idling and minor stoppages due to abnormal operation of sensors, blockage of work on chutes, etc. These slow-downs are tracked and analyzed to see what is really happening. Analysis of root causes and of processes is on going until the system no longer has losses in these areas.

Reduced speed due to discrepancies between design and actual speeds. Design speeds are reviewed and actual speeds are observed. The comparison, if unfavorable, initiates a design and engineering review.

Process defects due to scraps and quality defects to be repaired. Quality problems are not tolerated. Deep analysis is undertaken until these losses approach zero.

Reduced yield from start-up to stable production. The production process is tracked and watched for start-up problems. Any startup problems uncovered are fixed permanently. Stable production should follow start-up very closely.

TPM is one of the most effective methods of improving the delivery of maintenance service while increasing the effectiveness of the equipment. While in its entirety it does not apply in many situations, aspects apply to all maintenance situations. TPM is the maintenance department's answer to the empowerment, job enrichment, and total quality programs on the production floor. The great advantage is that TPM can be incorporated into and can greatly enhance these programs. The dual goal for TPM is zero defects and zero breakdowns.

11. Outsourcing

One of the most powerful trends is the increased use of contractors for routine maintenance (as well as their traditional use for specialized work and during shutdowns). Companies are increasingly aware of the high costs of severance in both pure dollars and in lowered morale. They are crewing maintenance at a lower number of employed workers and making up the shortfall with contract workers.

This gives the department leadership flexibility to reduce costs when times are lean and bulk up when needed. Special projects can be accommodated far easier also.

The fundamental goal with contractors is to make a few of them into team members. They can help with all kinds of decisions relating to maintenance. To foster the partnership, allow these contractors to make some profit on the work. As team members, over time they will look out for the companies interests when no one is around. Even when the craft is in-house, continue to use other contractors. Occasionally this acts as a check and balance on the team member to see if the pricing, quality, or delivery has drifted out of line.

12. Quality

How important is quality in maintenance? Bad quality has killed people, has forced unscheduled shutdowns for rework, and has forced customers to look elsewhere for product. The stakes are high.

Quality has three parts that have to be woven into each job from initial planning to completion. In this respect quality is just like safety, security, or cost control. The job plan has to be built on the bedrock of quality (as well as safety, security, cost control etc). Quality must be written into the mission of the department so that it becomes the background for all decisions.

12.1. Quality Planning. Quality planning is essential for success. For example, having quality built in might mean requiring proof of proficiency from any contract employees before they are allowed on the job site. But it is much more than that. The keys to quality are simple: right skills, right mental state (not tired, not preoccupied), right supervision, right parts, right tools, proper physical environment (lighting, temperature, etc). These conditions are among the primary reasons for being, and of the maintenance planning function, whether for conventional maintenance work or for a shutdown.

W.E. Deming, 1900–1993, the foremost quality expert in the 20th Century, said that the greatest motivator for workers was pride in a job well done. The key to quality in maintenance is to plan and manage work so that the maintenance workers have the opportunity to feel that pride. The plan must ensure that they have the right tools, right parts, etc, and are not pulled off jobs, so that they get that feeling of satisfaction from having done a job well. Quality flows from having removed the barriers to quality.

12.2. Quality Measurement. Quality is measured by the craftspeople themselves (remember pride in a job well done), by their supervisor, and by operations (the customer) when the item is turned over.

12.3. Quality Control. The last aspect of quality is control. Quality control consists in making random inspections, performing NDT, and keeping supervisors on the job floor. The control aspects again are built into the shutdown plan with scheduled activities such as pressure testing, vibration checks, amp readings, etc.

13. Maintenance Technical Library (MTL)

Increasingly the maintenance technical library is becoming virtual (meaning it exists where ever there is a connected computer). Even with an Internet based technical library, it is ideal to have a place where maintenance technicians can have access to a computer and printer. They can then use the local network or the Internet to look up repair history jackets, equipment manuals, parts lists, assembly drawings.

One good idea for the MTL is a display cabinet for broken parts, bearing and other small items. A display where one can pick up and handle burned bearings, fatigued brackets and other worn items can be a powerful teacher for new workers, plant people outside maintenance and even maintenance old timers. Clean them up and label them. People will not be able to keep their hands off of them and this is a potent learning tool.

In addition the MTL should be the location of a copy of plant drawings, site drawings, vendor catalogs, handbooks, engineering text books, etc. If there is computerized maintenance, stores or purchasing, CADD, or CAM then access is located in the MTL.

13.1. Some Considerations that Should be Taken into Account are.

Explicitly check if backups are being made of the files of the CMMS and MTL data. Normally the IT department is already efficient at this but it does not hurt to ask.

Protect from paper files from fire, flood, theft (consider fire- proof file cabinets and off- site storage of copies).

Use some kind of sign-out system if material must be removed.

Make it someone's responsibility to keep it up to date.

Manage the revisions so that all copies are updated (coordinate with ISO 9000).

When the MTL is set-up, it will provide: A ready reference for make verses buy decisions, repair history, repair parts reference with history, repair methods referral, planning information source, time standard development, data bank for continuous improvement efforts, maintenance improvement team headquarters.

The Internet is now being used for maintenance information. The advantage, if there is access is that the capabilities are available around the clock, 365 days a year.

14. Acknowledgment

Many of the sections in this article have been adopted from other word by the author see the specific listing in the Cited Publications.

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Joel D. Levitt
Springfield Resources, Inc.

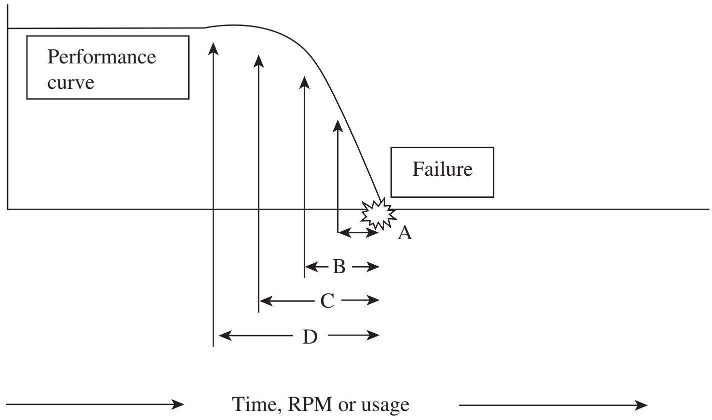

Fig. 1. P-F curve (performance-failure). **D** represents the amount of time or use between the CE and the ultimate failure. Generally this point cannot be detected with existing technology. It is a limit or a maximum theoretical time to failure. **C** is a point in the decay where very high tech PdM technology can detect either the decay in performance or the unfolding failure itself. The C point is the maximum practical time between inspection and failure. If PdM is used the PM inspection has to occur sometime between points A and C. Generally if a frequency 1/2 C-A to 3/4 C-A is chosen at least one inspection will fall between A and C. Using a PdM task gives the greatest amount of time between detection and failure. **B** is a point where skilled technicians without technology can detect impending failure. No technology is needed at this point. This is the greatest interval without using PdM. **A** is a point where, even unskilled workers, if told what to look for will be able to detect the failure. Although anyone can detect the failure, there is not much time to intervene.

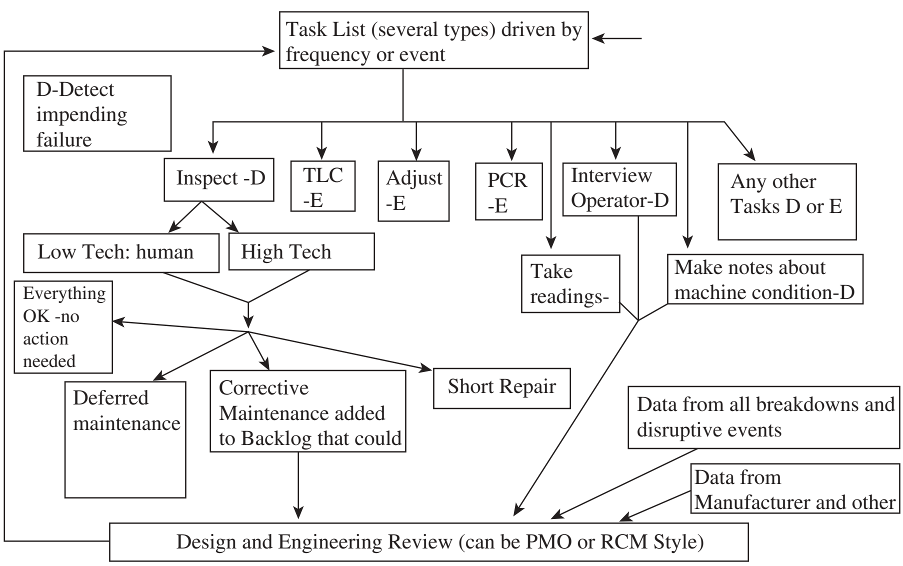

Fig. 2. PM and Pdm Defined Preventive and Predictive Maintenance.

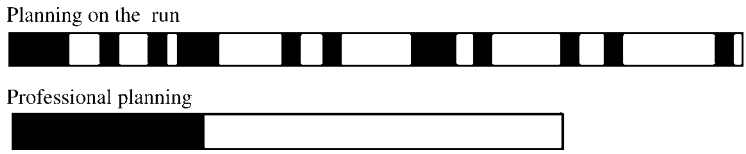

Fig. 3. Professional Planning Versus Planning on the Run.

Work order
Work planning sheet
Job plan with details by task with step-by-step procedures. Time for each step (task), summarized by resource group and for the total job For any large jobs: Labor deployment plan by craft and skill including labor-hour estimates. Consider contract as well as in-house resources. Use of the GANTT bar chart or PERT network chart to help plan task sequencing to assigned crews is important. Do everything possible to minimize the time the asset is out of service.
Job Hazard Safety Analysis looks at all hazards of the job and seeks to remove or mitigate the hazards.
Pre-shutdown work list (prefabricated parts)
Bill of Material. List all materials needed for the job, including an acquisition plan for major items. Determine if the material is authorized inventory or a direct purchase item. The planning package should include spares reservation and staged location.
Requisitions
Shutdown protocol and start-up protocol
Site set down plan (where to put everything used for major tear downs)
A copy of all required permits, clearances and tag outs
Prints, sketches, digital pictures, special procedures, specifications, sizes, tolerances and other references that the assigned crew is likely to need

Fig. 4. Planning Package.

Table 1. **Maintenance Management Effort**

Item	Relation to the three elements necessary for successful maintenance
PM (Preventive Maintenance) schedule	The PM schedule needs to be rolled out for an entire year (or other long period) and meshed with the production schedule. The MPR schedule for production must be synchronized with the PM schedule.
PM activity	Preventive maintenance activity assures capacity by detecting impending failure and by life extension. The activity itself requires equipment custody, bills of material fulfillment, and competence.
PdM (Predictive Maintenance)	Predictive maintenance predicts impending breakdowns and alerts maintenance managers. This gives the maintenance department time to plan the job, order materials, and schedule the job when it will impact the production the least.
PCR (Planned Component Replacement)	Technique to improve reliability of a system that has significant failure consequences. PCR minimizes future unscheduled custody changes.
Inventory management	The second item of the three is the Bill of Materials and inventory management assures that the material is available.
Planning	Planning identifies the resources for the maintenance job so that everything is ready and available to minimize the impact on the production schedule. The resources compromise both the Bill of Materials (parts, tools) and labor requirements (competence).
Scheduling	The schedule is designed to minimize the impact of maintenance activity to productive outputs. The product of maintenance is equipment availability, so the maintenance schedule should minimize disruption to production (eg, by scheduling work during product changeovers or color changes).
Training	The third element is competence. Training helps align the competence of the maintenance crew with the competency needed to take care of the equipment.
RCM (Reliability Centered Maintenance)	Technique to maximize equipment availability and increase safety. An overall approach to maximization of uptime.
TPM (Total Productive Maintenance)	Spreading of competence to perform basic maintenance to operations. Increases the amount of basic life extension maintenance to improve equipment capacity. In its best implementations TPM is a holistic focus on improvement of overall equipment effectiveness.
Outsourcing	Use of outsiders is indicated when there are not enough available hours of competent personnel or no personnel with the competence needed. It is also used to minimize overall cost to deliver the maintenance product.
Quality	Quality of maintenance work is related to proper training (competence), proper tools and parts (bill of materials) and enough time (custody).
Maintenance Technical Library	Where all the detailed maintenance information is stored.

Table 2. **Technologies for Detecting Deterioration**

Technology	Primary situations	Notes
chemical analysis	analyze oil, other lubricant or water	Much knowledge is needed to analyze results. Heavy equipment is costly so contractors are used for expertise and specialized equipment. Widest variety of tests for specialized needs.
vibration analysis	rotating equipment	Highest learning curve. Equipment has come down in cost. Can be the first way to detect critical wear.
temperature measurement	electrical, process heat, roofing, energy efficiency	Easy to use and very easy to understand. Costs for low-end units have plummeted. High end coming down nicely.
ultrasonic	air/vacuum leaks, high voltage lines, thickness, cracks	Not expensive. Easy to use. Multi-use for predictive and troubleshooting.
visual	anything one would like to be able to see inside of like pipes, engines, gear boxes, etc	Used mostly when there is a known problem. This mode is an extension of the mechanics most developed senses.

Table 3. **Typical Maintenance Worker's Day – Reactive versus Proactive**

Item	Reactive without planning and scheduling, %	Proactive with planning and scheduling, %
receiving instructions	5	3
obtaining tools and materials	12	5
travel to and from job (both with and without tools and materials)	15	10
coordination delays	8	3
idle at job site	5	2
late starts and early quits	5	1
authorized breaks and relief	10	10
excess personal time (extra breaks, phone calls, smoke breaks, slow return from lunch and breaks, etc)	5	1
Subtotal	*65*	*35*
Direct actual work accomplished (as a percentage of the whole day)	*35*	*65*

Table 4. **Types of Learning**

Type	Observable Behavior	Performance Level
1. knowledge	is able to describe diagram, argue, etc.	answer x of 10 questions correctly
2. skills	demonstrate, show perform, solve	do in x minutes with no mistakes
3. attitude	comfort, without hesitation	to employer's own satisfaction