RELIABILITY THE MISSING LEG OF THE STOOL

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Abstract – All end-users within heavy industry focus on improving ‘Safety’ and some also work on improving ‘Operations Excellence,’ but there are only a few end-users who spend equally as much time on ‘Reliability.’ PCIC is an example of this culture where a standalone safety entity to focus on electrical safety was created. Unfortunately, in industry, we continue to see significant incidents with loss of life even with this enhanced focus on safety and operations excellence. A three-legged stool is inherently stable, but a stool with less than three legs cannot stand. The missing leg of this stool is reliability, which has not been a focus area of but a few end-users. In the companies that view reliability (all failures are preventable) on par with safety (all incidents are preventable), equipment failure is addressed proactively to prevent the ‘catastrophic failures’ that have led to significant incidents in facilities. This paper will provide a context of the methods for developing a world-class reliability-centric organization.

Index Terms — Safety, Operations Excellence, Reliability, Process Safety, Process Safety Management, Reliability Management Program, Reliability Centered Maintenance, Root Cause Analysis, Failure Modes and Effects Analysis, Preventative Maintenance, Predictive maintenance.

I. INTRODUCTION

In 1990 the US Congress passed the Clean Air Act Amendments which included a three-pronged approach to improve chemical accident prevention and increase public accountability for safety at companies and worksites involved in chemical production, processing, handling and storage in the United States.

The amendments to the clean air act gave new responsibilities to both the US Environmental Protection Agency (EPA) and the US Occupational Safety and Health Administration (OSHA). Also, it created a separate agency, the US Chemical Safety Board (CSB), to conduct independent investigations of major chemical accidents and publicly report the facts, conditions, circumstances and the cause or probable cause of the accident.

In addition, the industry founded the Center for Chemical Process Safety (CCPS) as a response to the methyl isocyanate release in Bhopal, India, in 1984 that killed over 2,000 people and injured tens of thousands.

In 1999 a news article [1] was entered into the congressional record (S 8235), which described 14 major chemical accidents in the United States that occurred between 1987 and 1991, which together resulted in 79 fatalities, nearly 1000 injuries, and over $2 billion in damages. [2] The incidents occurred at refining and chemical companies [1][3].

It has become apparent since the 2005 vapor cloud explosion at Texas City [4] as well as other industrial incidents that significant accidents continue to occur, and that safety or process safety is still an issue today. The Texas City Refinery explosion occurred on March 23, 2005, when a hydrocarbon vapor cloud was ignited and violently exploded at the isomerization process unit at a large refinery, killing 15 workers, injuring more than 180 others and severely damaging the refinery. Many within industry, as well as safety professionals, had hoped that Process Safety Management (PSM) and Safety Based regulations would reduce significant process events by more than 80%, but this has proven to be an unfulfilled aspiration.

The Baker Panel [5], which convened following the incident in Texas City, developed recommendations around leadership, incentives, safety culture, maintenance & reliability and more effective implementation of PSM systems.

During several of the significant incident investigations, there have been several lessons for the corporate management of process operations. Visscher stated “one is that most large companies monitor the performance of individual units, facilities, operations, and managers by statistical measures. These numerical indicators are used not only to monitor performance, but also to improve performance, by basing pay and bonuses, budgets, or other types of recognition” [2], on these indicators or Key Performance Indicators (KPI). Therefore, as the saying goes “what gets measured gets managed,” and what we report to management is what the front-line leaders focus their attention and emphasize to their teams, especially when it impacts pay and performance incentives. As one moves up the management ladder, this becomes magnified since bonus, and stock options begin at a sum equal to 50% or more of an individual’s base pay up to multiple times the base pay for executives. Most company’s performance measurement and incentive systems for safety performance are focused almost exclusively on injury rates, and do not include measurement of process safety performance metrics. As a result, safety programs focus on personal safety initiatives, and company management receives reports on trends in safety performance based on injury rates, even as overall process safety, asset integrity, maintenance, and reliability deteriorates, and consequently contributes to a higher risk of major accidents. Per Visscher, “a principal lesson coming out of the Texas City refinery disaster is the importance of these additional process safety indicators, in addition to personal safety measures, to monitor performance at any facility at which hazardous chemicals are used, processed or handled" [2].

Engineers must learn from previous incidents to reduce the likelihood of them recurring. If not, the likelihood of accidents continuing to occur is high as the incidents discussed, demonstrate that small mistakes have disastrous consequences.

II. ACCIDENT CAUSAL MODEL

Incidents rarely have only one cause or failure mode. Ness stated, "For many years, safety experts have used the Swiss cheese model [7] to help managers and workers in the process industries understand the events, failures, and decisions that can lead to a catastrophic incident or near miss. According to this model (Fig.1), each layer of protection depicted as a slice of Swiss cheese, and the holes in the cheese represent potential failures in the protection layers, such as:

- Human errors
- Single-point equipment failures or malfunctions
- Asset integrity
- Maintenance practice
- Reliability
- Knowledge deficiencies
- Management decisions
- Management system inadequacies
- Failure to perform hazard analyses
- Failure to recognize and manage changes
- Inadequate follow-up on previously experienced incidents warning signs" [6]

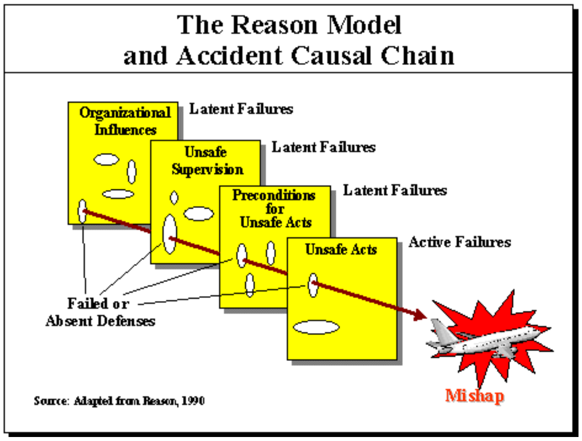

Fig. 1 Reason or "Swiss Cheese" Model [7]

As depicted in Fig 1, incidents are the result of more than one failure to effectively address hazards, which are represented by the holes aligning in consecutive slices. The result of the alignment of these hazards typically is a catastrophic incident. End-user companies employ various types of management systems that include physical devices, planned activities such as preventive or predictive maintenance that protect and guard against equipment failure. Therefore, organizations that have an effective PSM, asset integrity, maintenance and reliability systems will reduce "the number of holes and the sizes of the holes in each of the system's layers, thereby reducing the likelihood that the holes they will align." [6]

III. RELIABILITY = SAFETY

As discussed previously, management performance is measured by KPIs; unfortunately, one of these numerical indicators tends to be the budgets, which include funding for maintenance, engineering and reliability programs. The author of this paper has experienced pressure to cut maintenance budgets over consecutive years at more than one employer to meet overall financial goals.

Organizations invoke budget cuts by arbitrary percentages across the board without due consideration to the effects of these cuts or reflecting on the real impact of continuously cutting cost over time as an organization adds assets. Management never makes a request to reduce the amount spent on safety! If an organization is not willing to cut its safety budget, then likewise it should not lower its maintenance, engineering and reliability program budgets.

It is unfortunate that not everyone grasps the concept that reliability and safety are dependent on each other. One needs to consider that most accidents don't occur when things are running smoothly, and the equipment has a high level of reliability. Accidents happen when we are in the reactive maintenance realm where assets fail unexpectedly, and there is a rush to get the process operational quickly.

Manufacturing facilities are an asset-intensive environment where an integral part of Safety is Reliability, in simple terms as reliability increases so does safety. The author has had the opportunity to work for a global chemical company that implemented a best in class reliability program. During those years we were able to see the results of the reliability initiatives and their positive effect on equipment, people, and processes. In addition, the safety KPIs also improved with several periods exceeding 300 plus safe workdays. One might ask, "why does this happen, and which comes first safety or reliability?" Another way to relate reliability to safety is that as assets become more reliable, end-users are servicing them less often; thus the workforce is exposed to hazards less frequently. It is evident when we look at the continued occurrence of significant industrial incidents, organizations without a reliability-focused approach will continue to have incidents which impact safety. When working in a reliable and safe environment, people are positive and not stressed in their respective roles because the processes are under reliable control and safety is one of the positive side effects of reliability.

There are three maintenance methods that asset intensive organizations can use. The first is Reactive Maintenance where all behavior is reactive. Reliability is low, and there is no planned maintenance or failure mode prevention activities; thus, all maintenance activities are reactive, or breakdown initiated. In this environment, per Isleifsson, "Safety is instinctive; that is to say when a problem arises instincts are what drives the situation more than anything else. Instincts say that one can react to the problem in a particular way, unfortunately often ignoring or not noticing the dangers that are present" [8].

In Planned Maintenance all behavior is guided through the planning and scheduling process. Safety procedures are embedded in the maintenance plan and thus enforced. Reliability is intentionally planned, and scheduled maintenance activities can support reliability initiatives. Focusing maintenance activities on expected failure modes, preventing failures obviously contributes to increased reliability. However, individuals need to be aware that excessive maintenance can backfire. Focusing on the wrong maintenance activities or merely creating a time-based system with no focus on process criticality, equipment reliability or actual maintenance needs can result in a system that is not focused on the failure modes and can overextend the two critical resources of an organization (workforce and budget).

Finally, there is the Pro-active Maintenance where the behaviors are based on a self-disciplined focus on continuous reliability improvement with embedded safety in all aspects of the maintenance and production environment. There is a continuous improvement approach to Reliability. Maintenance activities are not only performed but implemented in a way that focuses on how they can be improved. There is a strong focus on condition monitoring and only intervening when predictive failure mode measurements are trending up.

Safety is embedded and in a pro-active environment safety conscience is second nature where responsibility for safety is everyone's role and viewed as an added value to the business.

Safety should be a critical value to any company. An excellent safety record preserves the organization's reputation and worker morale, minimizes insurance, workers' compensation, and legal costs, and reduces process downtime. To some, it might appear unreasonable to suggest that putting resources into reliability could be an investment in safety. Studies by Okoh & Haugen, "Maintenance-related major accidents: Classification of causes and case study" [9] have found the following for the hydrocarbon and chemical process industries:

- 30-40 percent of major industrial incidents determined maintenance was a factor.
- Includes both preparation and performance of maintenance.
- Contains incidents caused by the lack of proper maintenance.
- 76% of incidents related to maintenance performance occurred during the maintenance activity.
- 24% occurred during site preparation or transition to or from production activities.
- Maintenance activities expose workers to higher risks because of changes in work activities and locations.

As one can see Reliability, and Safety have a strong correlation. By focusing on increased Reliability, it will promote the correct behaviors and result in better safety KPIs. In addition, it will also have a positive impact on the productivity and therefore profitability.

IV. Reliability Management Program

A reliability management program (RMP) can minimize hazards by improving a company's control over asset life and maintenance or repair cycles. But, to achieve best in class results that will significantly reduce the hazards associated with shorter maintenance cycles, a reliability program must move beyond merely keeping the equipment running. While preventive maintenance (PM) includes repairing or replacing worn parts before they fail this does not address the failure mode it only restores the equipment for the short term. The failure mode must be resolved to prevent parts from continuing to fail. An RMP will extend the time between maintenance or repair cycles by reducing or removing the sources of equipment defects.

Organizations with a mature safety culture will find the same basic principles used in targeting safety incidents and exploring methods to reduce them are utilized to focus and examine reliability incidents. A reliability program uses risk assessments or Failure Modes and Effects Analysis (FMEA) as well as statistical analysis of equipment and system failures to determine which areas pose the highest risk of failure, associated costs in downtime and repair/replace efforts. An FMEA can include personnel risk assessments; thus safety is built into an RMP.

Predictive maintenance (PdM) is one of the most valuable components of an RMP; unfortunately, most view it as a tool for merely determining the optimal time for performing maintenance. While using PdM data for condition monitoring and analysis, PdM methods can be used to assess the quality of a repair, which can result in improved repair techniques, thus leading to longer Mean Time Between Failures (MTBF) and subsequently less exposure to employees.

Reliability and safety have the same goal; 'all' reliability and safety incidents should be prevented.

V. RELIABILITY CENTERED MAINTENANCE

Reliability centered maintenance (RCM) is a corporate-level maintenance strategy that is implemented and supported to optimize the maintenance program of a company or facility. The final result of an RCM program is the implementation of a specific maintenance strategy on each of the assets of the facility.

Often when end-user companies utilize RCM, Root Cause Analysis (RCA), and Reliability Measures techniques, they are addressed or used as separate and distinct topics instead of being incorporated into an overall RMP program. There are those individuals who believe that one tool is all that is required, apply it to everything and all of the failures will be solved. One must understand that each method is a separate and distinct tool having their own benefits.

Following the merger of two large chemical companies in the late nineties, the author saw first hand the effects of applying RCM to every piece of equipment in a plant. A chemical complex from the company were on opposite sides of a road. One site had just begun the process of implementing RMP and had limited PMs while the complex on the other side of the road had experienced a catastrophic incident with significant loss of life and had performed a PM on every asset in the facility. One would expect the reliability of the facility that implemented consistent PMs on all assets to be higher than the other site with limited PMs, but that proved to be an incorrect expectation. Both sites had comparable facility reliability metrics but, in the end, did not achieve equal reliability, why? The facility with PMs on all assets did not have enough manpower and administratively closed the ones not completed each month. This is a process used to close PMs that are not going to be implemented.

Therefore, the blind utilization of these techniques (i.e. blanket implementation of PMs) will not garner the results that end-users are seeking. What each method accomplishes is providing the end-user with tools that will help to advance the reliability efforts.

RCM is a reliability tool whose intent is to develop a complete maintenance strategy for a facility, plant, process or individual piece of equipment. While an RCM analysis can be performed on any asset, this process and implementation are best suited to focus on the highest return on investment due to companies primary limiting factors being workforce and capital. Some end-users are well versed in implementing an RCM analysis, but most are not. It requires a trained facilitator and a cross-functional team of subject matter experts. The team should consist of engineers, mechanics, technicians, and operators. The typical analysis of 100 to 200 failure modes will take an experienced team approximately one week to accomplish.

RCM is a structured process that consists of the following:

1. Analysis preparation work
2. Analysis
3. Analysis implementation

All three components require dedicated resources for the process to function properly. Without the appropriate amount of preparation, the analysis team will be delayed, resulting in frustration, and potentially failure. With no analysis, there can be no analysis implementation; therefore, there will be no change in maintenance performance or results. This will result in a lack of support for the RCM effort, and eventually failure.

Analysis Preparation consists of the following: selection of a process, determining meeting schedule and location, agreeing to the expected outputs of the study, who will implement the analysis tasks, forming then training the team, gathering of information to conduct the analysis and consensus to these steps. To often this step is skipped which can lead to less than optimal results.

Process Flow Diagrams, Piping and Instrument Drawings, OEM manuals, policies, procedures, and an Operational History Data should also be collected. The Operational History Data should provide sufficient operational data to determine the current operating conditions.

Once all of the analysis preparation steps have been agreed to and communicated, everyone involved is aware of the objectives and should be committed to meeting them.

The next step in the RCM process is to perform an RCM Analysis that also requires structure and discipline.

By meeting daily, one can complete the analysis quickly which helps the team stay focused and eliminates wasted time that results from an extended meeting schedule.

An RCM analysis of an asset requires the completion of nine steps in a specific order to develop a complete maintenance strategy.

The following are the nine steps:

1. List process functions.
2. List the functional failures.
3. List the failure modes.
4. List the probability that each failure will occur.
5. List the effects of the failure.
6. List the consequences of the failure.
7. Run the failure mode through the RCM Decision Process.
8. Develop a Maintenance Task, Redesign, or Consequence Reduction Task.
9. Run the failed part through the RCM Spare Parts Decision Process.

The RCM Facilitator should note components designated as having a high failure rate and a medium to high consequence rating. These components are candidates for conducting RCA, which will focus on the possible component failures, including those that are physical, human, and latent. By completing these steps in order, the maintenance strategy for the asset analyzed will be complete. This includes the creation of several types of maintenance tasks:

- On-Condition Maintenance Tasks (Vibration Analysis, Thermographic, and Partial Discharge Analysis, etc.)
- PM Tasks (Scheduled Rework, Discard, and Inspection)
- Failure Finding Tasks
- Recommended Redesigns
- Consequence Reduction Tasks (for components where run-to-failure is the maintenance strategy)

The RCM analysis will find high failure rate and medium to high consequence assets. When conducting RCA to determine component failures modes, there will be instances where redesign is the only maintenance strategy to eliminate a failure. As an example, the author leads an RCA on a hydrogen compressor that had an MTBF of less than 50 days and required several days to rebuild working around the clock. The failure mode identified was rings and rider bands. We implemented a design change which extended the MTBF to allow the compressor to operate without failure during the normal operating period between turnarounds. This is an example of utilizing redesign to enhance reliability and improve safety by elimination of repetitive shutdown maintenance.

All procedures for the tasks must be clearly written and specific in content. When an undesired condition exists, they should state clearly what the individual performing the task should observe, measure, record, and do.

Implementation of the RCM analysis is the final step in the process. This is the step where the rubber meets the road, and by implementing the tasks, the RCM process generates benefits.

Implementation consists of four steps:

1. Prioritize the tasks based on probability and consequence.
2. Assign a specific person responsible for the task.
3. Assign a due date for task implementation.
4. Track and report the progress of implementation.

Following the completion of the implementation step, the expected results from performing the RCM analysis are:

- Improved asset reliability and availability
- Lower maintenance costs
- Lower unit cost of the product
- Reduction in health, safety, and environmental incidents
- Improved quality
- Reduced emergency maintenance
- Reduced spare parts
- Reduced turnaround time

Once completed and implemented this process can easily save millions of dollars. As an example, the hydrogen compressor previously discussed had annual maintenance costs of approximately a million dollars per year, which was eliminated, and did not take into consideration the repeated safety exposure. The key is to utilize these reliability tools comprehensively to maximize the benefits of RCM.

VI. CRITICALITY

The purpose of determining the critical equipment is simple, at the end of the day; the limiting factor in all companies is workforce and funding. By defining what is critical to operations, we focus both of these limited resources on those critical assets. This is how to establish a methodology by which equipment can be classified for the criticality classification to be used to set priorities for preventive and predictive maintenance programs, spare parts, reporting and other reliability efforts.

This section describes the method for determining equipment criticality classification and how critical equipment lists are developed and maintained.

Critical Equipment can be classified as equipment that contains, controls, or processes hazardous substances, which, in the event of a failure, might lead to a danger of injury to persons both within and outside the workplace. Some companies also classify equipment as critical if, as a result of the equipment's unavailability or malfunction, goals are not attained for the environment, production, business, or quality. Permanently installed equipment may be defined as critical if used to mitigate the hazards of loss of containment or control.

Before discussing the criticality classification example requires some context associated with process hazard analysis (PHA) and assessment of the potential hazards. A PHA (or process hazard evaluation) is a set of organized and systematic assessments of the potential hazards associated with an industrial process. The assessment of the potential hazards utilizing the application of risk assessment methodology including consequence categorization is the process used by many end-user companies to mitigate risk. A consequence is the ultimate result of a deviation or multiple deviations. The category structure below and appendix A are examples of consequence categorization levels that are utilized to mitigate risk:

- Category V - (Most Severe)
- Category IV
- Category III
- Category II
- Category I - (Least Severe)

The following are an example set of Criticality Classification:

Safety Critical: An electrical, instrument or mechanical device which is a component of an active safety system or a process case pressure relief device designed to mitigate an action level risk with a Category IV or V personnel, community, or environmental consequence, and provides an independent protection layer.

Environmental Critical: An electrical, instrumental or mechanical device, which is a component of active process control or monitoring system or safety system, designed to mitigate an action level risk with a Category IV or V environmental consequence and provides an independent protection layer.

And, or any equipment identified by facility operating permits as required to maintain compliance with environmental regulations and or permits can be added to the Environmental Critical List.

Environmentally critical equipment includes, but is not limited to the following:

- Emissions control; abatement or treatment equipment such as flares, vent scrubbers; waste collection devices; and wastewater treatment equipment.
- Devices or systems that monitor, measure, or record emissions information required to demonstrate compliance.

Accounting (Inventory) Critical: Equipment is classified as “Accounting Critical” when failure will result in an inability to meet the conditions of a contract (such as custody transfer meters per the Corporate Volumetric Control Policy or compliance requirements such as Foreign Trade Zone).

Quality Critical: Equipment is classified as “Quality Critical” when the site is solely dependent on it to maintain product quality that upon failure will produce an out-of-specification product, without any indication of non-conformance (as defined by quality certification system.

Health Safety and Environmental (HSE) Critical: Equipment is classified as “HSE Critical” when it is intended to reduce the size of an HSE consequence after it occurs.

- Fire Suppression System (foam, sprinkler, deluge, fire monitors and firewater distribution, mobile fire equipment, fireproofing and fixed Halon systems).
- Emergency Alarm System
- Fire and Gas Detection Systems
- Safety Equipment (respirators, SCBA’s, breathing air equipment, safety showers, fire extinguishers and fire hoses).
- Health Surveillance Equipment.

Production Critical: An electrical, instrumental or mechanical device, which is a component of active process control or monitoring system or safety system, designed to mitigate an action level risk with a Category IV or V facility impact and provides an independent protection layer.

A reliability-based study (i.e., FMEA) can be used to identify Production Critical equipment that upon failure will result in a significant reduction or a loss of production. Also, this failure could cause significant equipment damage and repair cost. It is the plant’s responsibility to define what constitutes a significant reduction for their site. Production critical equipment should make up a small percentage (approx. 5%) of the total equipment population. For example; non-spared or single train equipment such as an Olefin plant’s crack gas compressor, a Propylene Oxide plant’s recycle compressor, a non-redundant electrical distribution system, or a Polymers plant’s hyper compressor.

Criticality Identification is a precise estimation and evaluation of consequence of failure, which shall be performed using an appropriate risk-based methodology. Equipment or functional locations may be classified using one or more classifications, although maintenance work, preventive/predictive maintenance (PPM) programs and other reliability efforts will be assigned to equipment based on the highest consequence of failure and or classification of this equipment.

Once we determine the criticality, all of the equipment with a “criticality classification” value (Safety, Environmental, Quality, Accounting/Inventory, HSE, and Production) is to receive heightened attention in the areas of preventative/predictive maintenance (PPM) programs and spare parts availability requirements. Each operating facility’s management system shall clearly define this process. Equipment history and actual data must be incorporated into the criticality assessment to determine PPM tasks and frequencies better as well as to assess the availability requirements for spare parts.

VII. PREVENTIVE MAINTENANCE

A. History

Preventive Maintenance (PM) is any maintenance activity that is performed to prevent a piece of equipment from failing. Preventive maintenance activities may take several forms, but all of the forms of PM are intended to do one of two things, either prevent the next occurrence of a failure or at least detect the presence of an impending failure.

Performing preventive maintenance on a fixed interval is another defining factor which many refer to it as calendar-driven. Most end-users base the interval on operating time (days, weeks, months, or years); however, process throughput (barrels of product produced, gallons of fuel burned, hours of run time, etc.) can be the basis. In both methods, PM activities occur at fixed intervals. Therefore, any activity one performs on-demand is not a PM activity.

Some companies still subscribe to one of the original styles of maintenance were the technician or mechanics is assigned to continuously survey the assets to detect any issues that may need repair. This method has a significant drawback in that the defect has to be very late in its failure progression to be detected.

In the late 1960s, this style of maintenance was found to be too costly and produce too much non-productive downtime due to not knowing what was going to break next and how long it would take to fix.

In the early 1970s, this method gave way to a different PM execution model, which was the concept of time-based replacement. There was a belief that all failures were a function of time or throughput and were therefore predictable. Organizations thought they could organize their preventive maintenance strategy to replace parts or components at fixed intervals. This method was not the panacea that it was perceived to be as maintenance costs increased and system reliability was unchanged. Merely tracking hours to failure is a lagging indicator and will rarely point to the failure mode; therefore, a system of only implementing time-based replacement is not the answer.

Another type of PM utilized was a hybrid of the previous styles. This method involved scheduling a PM for an asset, disassemble it, and fix whatever the technician determined required repair. This PM style is utilized by many end-users today. The type of PM has a high level of variability based on knowledge and skill level of the technician.

The source of the problem is a lack of understanding of failure modes driven by time or cycles and the ones that are random.

B. *Ground Breaking PM Development*

United Airlines in 1974 was commissioned by the US Department of Defense to write a report on the processes used in the civil aviation industry to develop maintenance programs for aircraft. This report [10], written by Stan Nowlan and Howard Heap and published in 1978, was entitled ‘Reliability Centered Maintenance’ and has become the basis of all subsequent RCM approaches.

Per Nowlan and Heal, in the RCM system, all maintenance tasks are driven by a specific failure mode and have a specific strategy based on the impact of failure and type of failure mode. Failure modes may be random or may wear out with respect to time (see Fig. 2).

Nowlan and Heal’s research also found these key factors. That random failure modes require inspections, and the corrective work is performed based on the condition of the defect at the time of the inspection. Why are infant failures considered random? To answer that question requires us to understand the definition of random. The definition of random is “having no specific pattern.” Occasionally, infant mortality failures happen following maintenance on an asset, but this does not occur after every initial start-up or after every maintenance activity. These failures sometimes occur after start-up or maintenance, and sometimes they do not; therefore, that is why they are considered random failures. Wear out failure modes do not require frequent inspections, as this failure propagation is predictable as they are time or use related. This RCM report which created a new thought process on failure modes, defects, and strategies is perfect for preventive maintenance systems even after 30 plus years and remains the standard for reliability system design for maintenance.

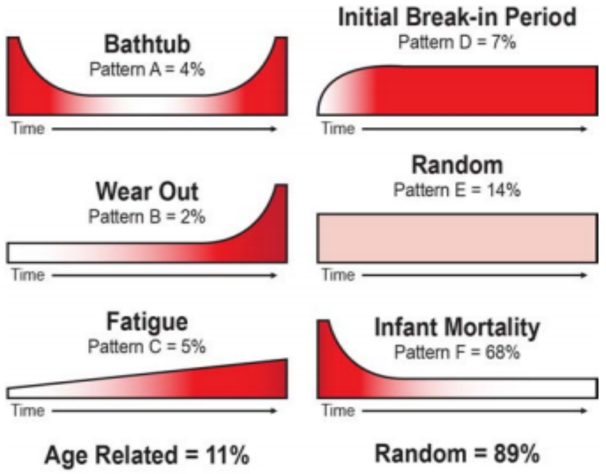

Fig. 2: RCM Failure Curves from Nowlan & Heap [10]

Determining whether or not a maintenance task is to remain in an equipment maintenance plan is based on the RCM system, which requires reviewing these questions for each task.

- Does the task prevent a failure mode?
- Does the task detect the presence of a failure mode?
- Does the task address regulatory or statutory requirements?

The purpose of these tests is to help us determine whether the task adds value and whether it should remain in the maintenance strategy. Frequently, non-value adding tasks creep into the program over time. This creep in the PM program tends to inflate cost and personnel loading, and overtime is not effective. The typical scenario that creates PM creep is similar to scope creep in a large project or turnaround. Companies that experience a failure believe they can PM their way to reliability, thus adding more tasks to the PM, increasing the frequency, and sometimes adding people. Of course, this does not address the problem. As mentioned earlier the author has seen this methodology implemented at one of his past employers who implemented it in response to a catastrophic incident. The fallacy to just adding PMs is that the nature of most failures is random, and a time-based replacement strategy is not effective at all in dealing with random problems.

To understand this phenomenon, we must first define a few terms. A ‘failure mode’ is the local effect of a failure mechanism according to the American Society for Testing and Materials (ASTM). An example might be just “bent,” “broken,” or “leaking.” For the reliability engineer, this is not descriptive enough to identify the problem and solve it. Therefore we modify the definition of failure mode to describe it as the part, the problem, and the reason (i.e., Bearing – Fatigued – Misalignment). This failure mode would be as follows: The bearing was fatigued due to misalignment. This description of the failure mode provides the information necessary to remedy future failures effectively. Once we understand the failure modes, we can then assign one of the six failure curves found in Fig. 2. The first three curves (A-C) denote an interval-based failure and are best suited for an interval-based replacement strategy. The last three curves (D-F) are random failures, and an interval-based strategy will not work. In fact, it will cost significantly more money and will result in no higher availability.

The answer to random failures is an inspection-based strategy where the component is inspected at some regular frequency, and the repair is implemented based on the condition of the component, regardless of time. The P-F Curve [10] graphically encompasses all of the concepts of reliability in a concise, articulate manner.

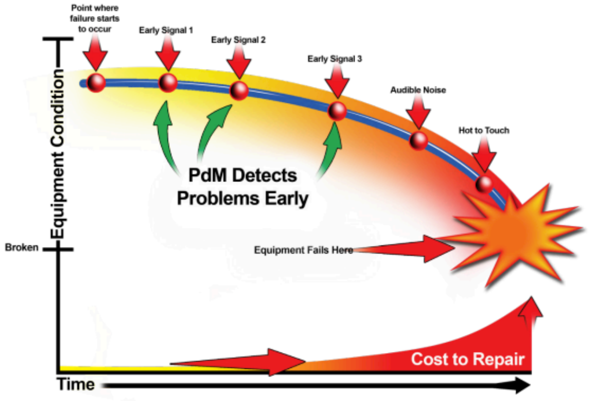

Fig. 3: P-F Curve

As defects propagate, the indications these defects give off change as the defect passes through its severity progression cycle. The indications are different early in a defect's life versus later in its life. These indicators can inform the inspector as to the condition of the defect, which makes planning and scheduling to eliminate the defect straightforward and specific. If an organization can mitigate the defect as close to Point P as possible, it creates many advantages: lower repair costs, longer lead time for planning and scheduling, lower probability of failure, and a lower necessity for keeping spare parts in stock as opposed to ordering them as needed. The concept of reliability is expressed by these advantages; therefore the development of P-F Curve is the single most important concept in the field of reliability.

C. P-F Curve

The P-F is a simplistic concept; the P stands for the point of a defect in the asset, as before this point the asset is healthy or defect-free. The F stands for the point of functional failure or loss of function of the asset. Therefore, the P-F Curve has the following implications for PM and PdM programs. Inspections, whether PM or PdM need to be performed close to Point P to identify the defect which increases the advantages to the end-user. So by using various PdM technologies (i.e., ultrasound, vibration, partial discharge, etc.) to find early defects provides the organization with an extended window (depending on asset typically an average of 90 days) to respond to the problem.

The P-F Curve also gives us an excellent indicator of the frequency with which PM and PdM inspections should occur. For random failures, the inspection interval is less than one half of the P-F interval, which ensures that there is sufficient time to find the defect before failure. This rule applies to PM as well as PdM programs, yet when the defects are no longer random, and there is sufficiently strong wear out mechanism producing the defect, this rule no longer applies. The end-user has to decide on what degree of risk they are willing to take with an interval-based replacement strategy. For non-random failures, the value of the PM program becomes significant, as it is the only failure-preventing task employed against that failure mode.

It is essential to understand that criticality is a methodology which allows us to focus the organization's resources and the level of scrutiny that we employ, but it has no bearing whatsoever on the inspection frequency. This is a common error for end-users, which is ingrained in poor inspection techniques and the organization's inability to effectively identify the defect. The basis of the inspection interval is the estimated P-F interval. The criticality of the piece of equipment does determine the number of inspection methods utilized for a given failure mode. In some instances, the end-user may choose to run assets to failure (RTF), which is an acceptable maintenance strategy.

It is essential that end-users understand that often nothing is found when performing PMs. Once end-users achieve a higher level of reliability, they must be resistant in making a business decision to save money by cutting the frequency of inspections. In fact, if the reliability effort is doing its job, then the inspections are not going to return any defects. The purpose of conducting the PMs on a set frequency is to mitigate risk. Risk must remain a part of the decision matrix. As the number of inspections increases without yielding any defect, then the nature of the inspections and the inspection criteria should be evaluated to ensure accuracy. This should be the only caveat, leave the inspection interval alone. If the end-user has conducted six inspections without finding a defect it means that the I-P interval (I = Point of Installation, so the I-P interval is the failure-free period) has lengthened (see Fig. 4), it does not mean that the P-F interval has changed. It is the P-F interval that determines inspection frequency, not the length of the I-P interval.

Fig. 4: I-P-F Interval

VIII. CONCLUSIONS

As premised earlier, a three-legged stool is inherently stable. As such an organization, which focuses on 'Safety,' 'Operations Excellence,' and 'Reliability' will also exhibit similar stability. In the companies that view reliability (all failures are preventable) on par with safety (all incidents are preventable) equipment failure is addressed proactively to prevent the 'catastrophic failures' that has led to significant incidents in facilities.

The ultimate objective of any industrial asset-intensive enterprise is to maximize and control safety, and operational profitability in real time. As the speed of industrial business continues to increase it is becoming even more critically important to focus on these objectives.

It turns out that what we need isn't more advanced technology. What we need to do is rethink how we address this age-old issue, and that begins with how we measure asset reliability in the first place.

Today with the continuous advancements in technology (Industrial Internet of Things (IIoT), data science, the proliferation of condition and process measurements) in industrial operations are making the direct real-time measurement utilizing PdM of asset reliability cost effective. By empowering today's industrial workforce with real-time operational profitability data, along with process control and real-time reliability risk information we will enable asset owners to enhance operations and business performance. Operators will be able to make operational changes and see the impact of these adjustments not only in the process but also on the profitability and reliability of the assets. They can then apply this feedback to make operating and business decisions, which maximize operational profitability without significantly increasing reliability risk. Likewise, plant maintenance personnel can determine their maintenance activities from the profitability and reliability risk information provided by the various systems, and adjust their actions and responses accordingly. Since the common objective of both operators and maintenance personnel is to improve operational profitability, they will work much more collaboratively.

It is clear that a profitable reliability approach that combines real-time control of reliability risk and operational profitability with a higher-level of reliability management will go a long way toward helping end-users meet their short and long-term operations and business objectives. Profitable reliability control is the next evolution of maintenance technology solutions. The result will be higher levels of operational profitability, safety, and reliability.

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X. VITAE

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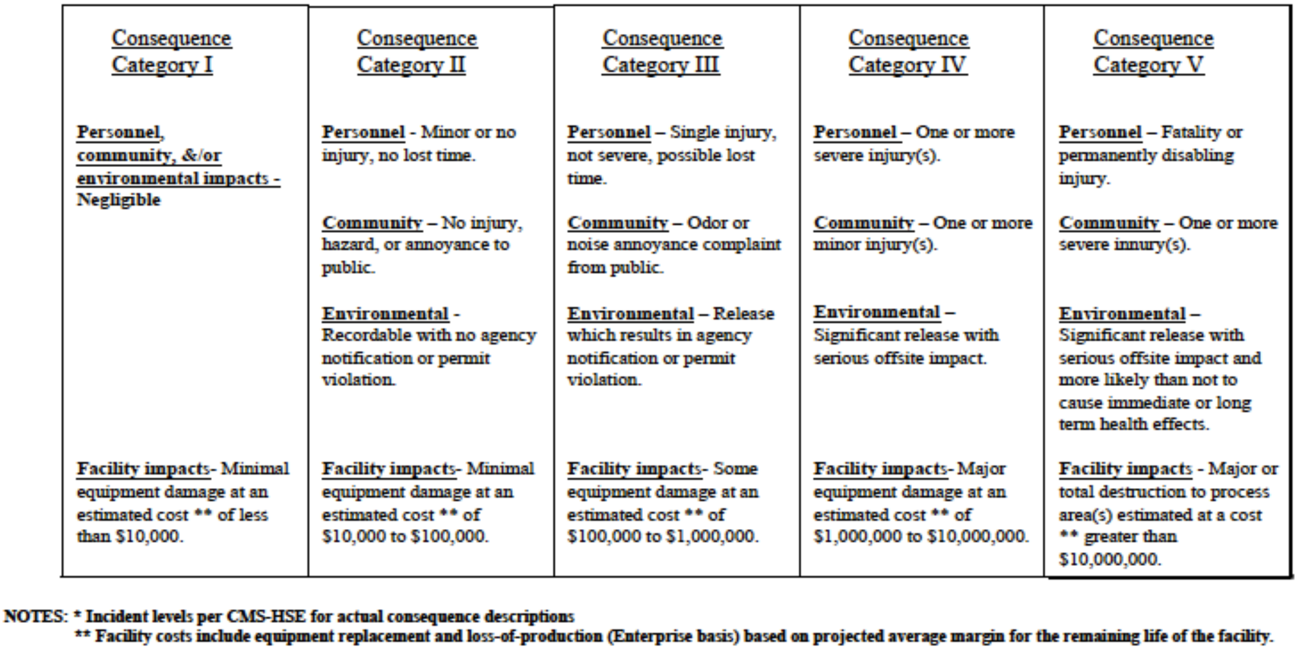
APPENDIX A

RISK CONSEQUENCE CATEGORY EXAMPLE



Consequence Category I	Consequence Category II	Consequence Category III	Consequence Category IV	Consequence Category V
Personnel, community, &/or environmental impacts - Negligible	**Personnel** - Minor or no injury, no lost time. **Community** – No injury, hazard, or annoyance to public. **Environmental** - Recordable with no agency notification or permit violation.	**Personnel** – Single injury, not severe, possible lost time. **Community** – Odor or noise annoyance complaint from public. **Environmental** – Release which results in agency notification or permit violation.	**Personnel** – One or more severe injury(s). **Community** – One or more minor injury(s). **Environmental** – Significant release with serious offsite impact.	**Personnel** – Fatality or permanently disabling injury. **Community** – One or more severe innury(s). **Environmental** – Significant release with serious offsite impact and more likely than not to cause immediate or long term health effects.
Facility impacts- Minimal equipment damage at an estimated cost ** of less than $10,000.	**Facility impacts**- Minimal equipment damage at an estimated cost ** of $10,000 to $100,000.	**Facility impacts**- Some equipment damage at an estimated cost ** of $100,000 to $1,000,000.	**Facility impacts**- Major equipment damage at an estimated cost ** of $1,000,000 to $10,000,000.	**Facility impacts** - Major or total destruction to process area(s) estimated at a cost ** greater than $10,000,000.

NOTES: * Incident levels per CMS-HSE for actual consequence descriptions
**** Facility costs include equipment replacement and loss-of-production (Enterprise basis) based on projected average margin for the remaining life of the facility.**

Fig. A-1