Perspectives on Equipment Prioritization for PM Development

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ABSTRACT

Various methods in use for developing Preventive Maintenance (PM) programs for industrial equipment share the need to prioritize equipment so that an appropriate level of resources is spent on repetitive PM activities. This need is universal regardless of the approach used in subsequent steps to determine appropriate PM tasks and intervals. Although Reliability Centered Maintenance (RCM) has become the gold standard methodology for this purpose, its use is limited by the extensive analysis resources it requires, part of which are expended in the equipment prioritization step. Other methods, such as Risk Based Inspection (RBI) prevalent in the oil refining and chemical process industries, are also fairly resource-intensive while taking a completely different approach to risk evaluation. PM Template technology used in the electric power industry takes the view that resources spent on risk evaluation should match the limitations imposed by PM development, and not exceed them. Despite the refinement of quantitative risk methods to a fine art by the nuclear part of the industry, the power industry makes little use of them for PM development purposes. Oddly, RCM also recognizes these limitations but not until after equipment prioritization has been performed, and thus misses an opportunity to become more efficient in execution. This paper examines these and related issues in some detail as a preparation for input to a new API Standard (API-691) in which existing RBI methodology will be extended from its current emphasis on passive equipment to active equipment, especially turbo-machinery. The purpose is to describe issues of importance derived from experience in other high risk industries and to explain their technical rationale, as preparation for input to standards development in the Oil and Gas industry.

1. Background

When developing effective PM programs in an industrial context, there is usually a need at an early stage to prioritize the large amount of in-scope equipment so that an appropriate level of resources is spent on expensive, repetitive PM activities for high risk equipment, while a much lower level of resources (or zero) is given to the rest of the equipment. This need for some kind of prioritization is universal, regardless of the approach used in subsequent steps of the methodology to determine appropriate PM tasks and intervals.

The motivation for this paper is preparation for a new API Recommended Practice (API-691) on PM development for active equipment, especially turbo-machinery, to supplement an existing Risk Based Inspection standard that has emphasis on passive equipment. The paper only examines the approaches to risk prioritization taken in Reliability Centered Maintenance (RCM), Risk Based Inspection (RBI), and PM Template methodology and the rationale for each, in light of the historical needs of commercial aviation, oil refining, and nuclear power industries. These are good examples of their potential fields of use. In particular, although this paper addresses risk, it focuses almost exclusively on risk prioritization of equipment in the early stages of a PM program development effort, and not on the level of risk mitigation achieved by the selected PM tasks.

Risk evaluation methods have become quite sophisticated and are fairly well known. Therefore, the risk prioritization step presents mainly the logistical challenge to be practical in using limited analysis resources when applied to a large number of active equipment items which, in principle, could be in the range 10,000 to 100,000. The main technical challenge of this step is to identify the subset of this equipment that presents sufficient risk to justify PM development, without missing any of them. Any omissions can subject a plant to unacceptably high risk.

2. Comparison of Three PM Development Methods

This section compares the risk prioritization features of the Risk Based Inspection, Reliability Centered Maintenance, and PM Template methods used in PM development. These are all “single failure” analysis methods. Thus we exclude Reliability Block modeling, Fault Tree and Event Tree modeling, and similar technologies. This is because they are most suited to the more complex requirements of design development and safety analysis where careful account must be taken of multiple failure scenarios, systems interactions, the physical processes of accident scenarios, and external events such as fires, tornados, and floods. Such considerations are not pertinent to PM development, which is focused on operation and maintenance of single items of equipment. Even though equipment reliability is a major input to multiple failure methodologies, and itself depends strongly on the quality of maintenance, it should be clear that PM is primarily just an input to such advanced techniques. Other features of RCM, RBI and PM Templates beyond equipment risk prioritization are not addressed in this paper, apart from occasional references that provide context.

2.1 Risk Based Inspection

RBI methodology espoused in API-580 [1] and API-581 [2] takes a conventional two dimensional view of risk as being composed of both frequency and consequence components in which both are evaluated to some practical degree whether it be qualitative or semi-quantitative.

The value is that for decision making, this two-dimensional decision space can be simplified by use of a Risk Matrix (a table in which rows represent frequency bins, columns represent consequence bins). The table entries are pre-assigned from a one-dimensional scale of risk (the Risk Rank) according to management directives. These matrices can range from 3x3 to 6x6 but the risk scale is typically binned into 3 or 4 Risk Ranks. Decisions are typically made according to this single parameter, neatly avoiding having to make decisions directly on frequency and consequence. Apart from the considerable effort that goes into evaluating the frequency and consequences of equipment failures, this is a sound approach conceptually.

It is quite useful to note that risk ranking and use of some kind of risk matrix is most useful when frequencies and consequences of events each range over several orders of magnitude, typical of issues confronting design engineers and safety analysts. This is because multiple failure events obviously drive down the frequencies of scenarios of interest. For PM applications, by definition, this does not happen for single failures of active equipment.

The RBI risk assessed is based on inspections and condition known to date, and the risk that would apply as time in service progresses without additional inspections. The real question to be answered in subsequent steps of the methodology is therefore – "given that the in-service failure of this equipment presents a significant risk, what PM actions can be taken to reduce the risk to an adequate degree?" Central to answering this question is knowledge of how the equipment degrades and ultimately fails if nothing intervenes to prevent it.

To answer those questions, a Failure Modes and Effects Analysis (FMEA) is used to break the equipment down into subcomponents and their degradation mechanisms. The typical interest implicit in RBI methodology is usually a pressure boundary failure due to any of a variety of damage mechanisms. If some of the mechanisms have remarkably different degradation rates there would appear to be a need to assess the risk at the level of each such mechanism, rather than for the equipment as a whole. RBI follows this path.

RBI is intended to be applied to passive equipment such as tanks and structures. In general there is less work to quantify risk for passive equipment than active equipment because the former can have many fewer subcomponents of interest, and fewer damage mechanisms (by at least an order of magnitude) by which it degrades in service. This makes it just about practical to quantify risk for each degradation mechanism for passive equipment, though a single dominant failure mechanism will often drive the inspection program. It becomes prohibitively expensive to do this for large quantities of active equipment such as turbo-machinery.

Furthermore, although there is sometimes a pre-selection of process systems that are to be left out of an RBI study, it is more usual for all of the pressure vessels, storage tanks, and piping systems to be included. Consequently, risk evaluation is an intrinsic part of the inspection development process in RBI, but does not need to be used at an initial stage to prioritize or screen equipment for further study.

So RBI for passive equipment can get away with assessing *two* dimensions of risk for *each degradation mechanism* for *all* of the in-scope equipment. The categorization of probability of failure and of consequence is typically software assisted, but requires data collection and entry. Even so, the burden of this level of work still challenges what many practitioners and oil company managers would prefer. This paper will be focusing intensively on these issues as they apply to active equipment in general.

2.2 Reliability Centered Maintenance

RCM is conventionally viewed as the gold standard for PM development but it does not address risk at all. It does, however, focus intensively on functional failures and their consequences. How does it justify not addressing frequencies of failure? The RCM rationale for this is not easy to find, but Smith [3] correctly points out that credible failure rate data do not commonly exist for failure mechanisms of equipment, which is the level in the analysis at which PM actions are selected, and therefore it is pointless to attempt this quantification of frequency at the mechanism level. This is especially true of unmitigated failure frequencies for specific mechanisms for functionally important equipment. The JA1011 RCM standard [4] suggests that the only failure mechanisms to be included should be those known to have ever lead to a failure of the equipment, or those which *realistically* could be foreseen to do so within the life of the plant, without including events that are, as stated by Moubray [5], ‘wildly unlikely’. In other words if it can reasonably be expected to happen, conservatively assume that it will, without making the effort to quantify the occurrence frequency.

The rationale developed later in Section 2.5 shows that this approach is well justified. Perhaps for these reasons, Moubray and the JA1011 standard pay little explicit attention to risk prioritization, even at the level of the equipment as a whole. Smith advocates employing RCM only for engineered systems or subsystems that are known to constitute about 80% of the risk, as measured by practical (i.e. knowable) performance statistics such as lost production. He supplements this prioritization using the sophisticated functional analysis of RCM (like Moubray [5]) for equipment in those systems.

RCM's focus on functional failure to the exclusion of frequency is rather strange. If frequency quantification can be dismissed relatively easily, albeit with considerable justification, why put so much effort into functional failures in order to derive consequences? RCM arrives at an array of system functional failures through an analytical process, with consequences that are usually stated as maximum likely consequences. These are used to screen equipment as to whether or not equipment failure could cause any of them. The functional analysis requires a lot of tedious work from the whole cross-functional team of experienced plant personnel. The strategy for determining consequences is less onerous, being accomplished by informal questioning of the same team.

The array of functional failures and consequences that RCM produces would, in fact, be capable of discriminating risk at a fairly detailed level if the corresponding frequencies were also determined.

Furthermore, the RCM method does not do much with the consequences other than to decide if they exceed a threshold that makes it imperative to perform "applicable and effective" PM. If the consequences are sufficiently severe, applicable and effective PM is required. In the end, discrimination between the sizable array of functional failures with their specific consequences comes down to a binary choice in prioritizing the equipment. Do the consequences exceed certain thresholds or not?

The simple binary choice on consequences to identify "Critical" equipment turns out to be exactly what is needed (see next section). It avoids what might otherwise have been expected to require a graded range of PM responses, to match the range of consequences. Despite subsequent publications [6, 7] and extensive industrial applications beyond commercial airplane maintenance, RCM does not offer an explanation for spending a lot of effort identifying functional failures and their consequences, to a degree that is little used.

One additional qualification is that equipment, whose failure does not produce sufficiently consequential behavior to warrant applicable and effective PM, is further divided into equipment that requires minimal PM to prevent damage to the equipment itself, in contrast to that which can safely be run to failure (RTF).

2.3 PM Template Methodology

The version of PM Template methodology referred to here is that practiced in the nuclear power industry. The nuclear power industry is paranoid about risk (on the basis that the fate of the whole industry depends on the "weakest link"), and has developed advanced quantitative risk methods of Probabilistic Safety Analysis (PSA) that are applied by regulatory fiat to every operating nuclear power plant in the USA, France, and many other countries. PSA's use Fault Tree and Event Tree methodology to address multiple failure scenarios that include equipment failures, human errors, operator responses, and external events such as floods, tornados, and fires. The main objective of PSA is to determine the contribution that each equipment item makes to serious accidents resulting in a wide range of on-site and off-site consequences.

Multiple failure scenarios in PSA's involve frequencies down to 10^{-8}/year and below, with consequences that can include thousands of fatalities. This powerful capability, plus the presence of plant and headquarters personnel very experienced in its use, is universally available in US nuclear power plants and among the regulatory authorities. It has seen highly successful deployment over the past 30 years as a stop-rule to undue regulatory encroachment, as well as providing rational support for needed design and operational modifications. Despite this very favorable track record, quantitative risk is scarcely used at all in PM development.

After 10 years of effort [8,9,10,11,12,13] to apply RCM, sponsored by the Electric Power Research Institute (EPRI), [Disclosure: The author of this paper was the EPRI program manager], the industry retained the basic "reliability-based" tenet of RCM (i.e. the FMEA basis for the PM actions developed). However, the system functional analysis to arrive at system functional failures was abandoned in favor of directly listing the functional failures of importance, usually in terms of their consequences. In other words the electric power industry adopted a wide-ranging, top-down set of binary choices for equipment prioritization in the form of a checklist of "things you don't want to happen".

Other aspects of the PM Template approach are more fully addressed in another paper [14], and are briefly mentioned below for completeness. The practice of developing the FMEA for each equipment item in its specific operating context was abandoned in favor of developing a more detailed FMEA for the equipment *type* that encoded enough information so it could be applied over the full range of operating contexts for any application of that equipment type. Candidate high level PM tasks were derived directly from experience in a top-down manner and included *as columns within* the equipment type FMEA. Line item actions that together comprise the task content for a given high level PM task are indicated in the appropriate PM column, one for each row of the FMEA to which that PM task applies. However, the PM task *intervals* are listed, with other descriptive information about the task, in a *separate PM Template* table that displays the PM task interval recommendations as a function of the range of operating contexts. These measures were adopted to achieve rapid but comprehensive analysis.

Why can a top-down listing of important functional failures successfully substitute for the system functional analysis of RCM? One reason is that system functional failures are rarely specific to failure of an individual equipment or an individual failure mode or failure mechanism of such an item. Instead they are *classes* of such failures, in that many failures of various equipment items typically lead to a given system functional failure. This must be so or the number of system functional failures would equal the sum total of all the failure modes and mechanisms of all the equipment items, instead of being a vastly smaller number by orders of magnitude. The result is that a large number of equipment failures contribute to any system functional failure, so that over time the knowledge base for the system functional failures becomes rather well established.

Consequently, statistical analyses of failure events plus accumulated plant operating experience shows that system functional failures are not mysterious events that must be researched exhaustively just to discover what they might be. Instead, designers design around them so that anticipated plant upsets remain safe, safety and hazard analyses regularly encounter them, and above all, plant operators are usually well trained to respond to them as general classes of system failure. Production and QA managers are also well aware of the types of functional failure that cause production losses.

High risk industries usually possess a wealth of information about the important functional failures, much of it already documented. It is much more efficient, and may sometimes be more credible, to prepare the list of significant functional failures by simply interviewing a range of stakeholders, rather than developing it analytically (e.g. by RCM functional analysis). The interview process takes little time but the analytic effort can be exhausting. Recall that RCM was specifically developed in the 1960's for the new generation of wide body jets beginning with the Boeing 747 and subsequently including the Lockheed L1011 and the McDonnell-Douglas DC10, and essentially all others since then. There was no operating experience at that time for much of the technology employed in these aircraft, such as new engines, new fuselage design, and avionics. This made the analytic approach to functional failures essential for that application.

Another feature makes the direct approach to functional failures appealing. There is no longer an arbitrary differentiation between a system level effect and a plant level effect. The direct approach can list functional failures at any level, especially those that have consequences at the plant level, which is more likely the level at which the risk is important to management. There is no rigid definition of a system in RCM, and quite often a plant is not managed by reference to particular systems, but rather by reference to sections of the plant or production process. So the level of system treatment in RCM is mainly for the convenience of the analyst. If that happens to correspond to system designations in use at a plant, so much the better, but it is not a requirement of RCM. The result of this simplification, realized in the PM Template methodology, is a checklist of important plant-level consequences that correspond to the plant-level consequences of system functional failures in RCM.

The operational result of forming a checklist of potential plant level consequences and not being squeamish about whether or not they are functional failures or consequences, and whether or not they occur at the plant level or some intermediate level in the plant, is that they can quickly document the things that are important to stakeholders at various levels of management, and by inference to various regulatory bodies as well.

An additional operational benefit is that a trained operator plus a process or system engineer or equivalent, can quickly state whether or not failure of an item of equipment can lead to any of the things on the checklist. Plant operators in most industries have direct and frequent contact with essentially all the equipment in the plant, unlike the operating crew of an airplane in which most of the equipment is not even seen regularly or at all, by the pilot. You do not need a whole cross-functional team to spend weeks working on an open ended functional failure analysis followed by more weeks applying it to the equipment list.

Instead, it requires just a couple of experienced persons working through the in-scope equipment using the pre-prepared consequence checklist.

The need for applicable and effective PM for a piece of equipment simply follows from at least one item on the checklist getting checked. Multiple items can be checked quickly to fully document the rationale for requiring quality PM on that equipment. The checklist of significant issues is usually referred to as the “Criticality Checklist”.

For many years this process for equipment prioritization with almost no explicit reference to quantified risk has been approved for maintenance analysis by the Institute of Nuclear Power Operations (INPO), which is the nuclear power industry’s own regulatory authority, as well as by the US Nuclear Regulatory Commission. Both bodies regularly recommend its use to utility companies, as well as the database of equipment type FMEA’s and PM Templates that support the method.

The only item on the checklist (i.e. one of perhaps 20) that is derived from PSA analysis is an overall “risk significance” that is equivalent to the percent contribution that failure of the equipment item makes to the *frequency* of one serious accident consequence – that is damage to the nuclear fuel. The checklist item is whether or not the equipment is risk significant by virtue of the fact that this fraction exceeds 5% of the total “core damage frequency”. So this PSA-derived reference risk is itself a *binary decision* based on a threshold *frequency* referred to a single damage state (admittedly a crucial one for nuclear reactors), and it is only one of many other checklist items that make no explicit reference to risk.

The fact is that the prioritization checklist for this risk-obsessed industry is a collection of high level *consequences*. The frequency dimension is suppressed by virtue of all single failure frequencies being in a relatively narrow band equivalent to “at least once in the plant life”, as explained further in Section 2.5.

2.4 The Rationale for a Binary Risk Prioritization Scheme

Another really hard fact is that the capability to design PM programs to address different risk levels is severely limited. As RCM teaches, the options are basically, 1) do nothing (run-to-failure) for low risk cases, 2) do minimal PM to prevent damage to the equipment – or equivalent low level consequences, or 3) do quality (i.e. applicable and effective) PM for high risk equipment. This last case may usefully may be divided into two levels (often called Critical 1 and 2 – or A and B) depending on the existence of equipment redundancy. High risk single point failures then become Critical 1; redundant equipment serving a high risk function becomes Critical 2. The difference is thus decided by an immediately apparent design aspect, not explicitly by risk. As far as risk is concerned the decision is still binary – go or no-go. The redundancy question is one of only two concessions made to consideration of multiple failures. The other is the presumption of an existing failure when considering the function of protective equipment.

Of course other criteria can be brought to bear on this case, such as whether for a single equipment item more than one significant and diverse checklist item contributes. However, adding this kind of complexity is rarely worth the effort. Even with just two critical classes separated only by equipment redundancy it requires a lot of judgment to hit the right note in fitting the type and frequency of PM tasks to the criticality class, and you generally do not know if you have hit it or not. [Disclosure: We at APT have spent the past 10 years developing tools to predict the reliability and business consequences of different levels of PM, precisely to solve this problem. However, we do not expect this capability to affect the majority of industrial PM programs for a long time, and so we proceed here on the assumption that this capability will remain beyond the reach of most plants in most industries for a good many years.]

Consequently, it is certainly not worth employing a risk process that is fine-grained (i.e. has many risk categories). For PM application, you only need to know if failure presents a large risk (>X) or not. Although the risk step must not miss any equipment that presents significant risks, there is no value in developing more information in the risk evaluation than can be used in PM development.

A convenient, although approximate, way to distinguish between criticality classes is in terms of the appropriate objectives of applicable PM, as follows:

- High risk equipment would be classed as Critical 1 and would warrant comprehensive PM. The most expensive to replace may also benefit from remaining life assessment before replacement or major overhaul. For Critical 1 equipment the objective of PM should be to *prevent all failures* because the consequences of even a single failure are intolerable, even though it is recognized that preventing all failures by means of PM alone is not an attainable goal.

- For Critical 2 equipment the objective of PM is to *prevent most failures* because although a single failure may be tolerable, you cannot afford to have many of them. This is true of redundant equipment serving a Critical 1 function because when the backup equipment is required to work it must usually be very reliable as well as available.
- For Non-Critical equipment (i.e. of minor, but not negligible functional importance) the objective of PM is to *prevent some failures* – e.g. those that might damage the equipment or other equipment.
- When the risk from in-service failure is acceptable there is a conscious and documented decision to run to failure (RTF), and no PM at all is performed.

Examples of Criticality Checklist items roughly covering the range from Critical 1 (requiring the highest level of attention to PM) , to Minor Functional Importance (requiring only minimal PM) are:

- Loss of a product batch.
- Production line or plant unavailable.
- Reduction in production rate between 66% and 100%.
- Reduction in production rate between 33% and 66%.
- Reduction in production rate less than 33%.
- Unlikely reduction in production rate because equipment is redundant.
- Possible death or serious injury to plant personnel.
- Significant risk of fire or explosion.
- Possible loss of a high level safety function.
- Loss of one train of a multiple train safety function.
- Possible environmental release in excess of regulatory release limit.
- Environmental release in excess of plant administrative limit.
- Personnel toxic exposure in excess of plant administrative limit.
- Major impact on product quality, requires scrap or rework.
- Significant impact on product quality.
- Possible injury (requiring first aid) to plant personnel.
- Possible failure of another critical equipment item.
- Possible delay of startup schedule.
- Large total cost if equipment has to have major repair or be replaced.
- Significant impairment of routine operational or maintenance activities.

To assist in selecting which of these items are consequences of in-service failure of a given item of equipment, it obviously helps if checklist items are accompanied by statements that quantify them or that describe them in qualitative but familiar operational terms.

Although the level of effectiveness, i.e. risk reduction or mitigation achieved by PM is *not at all* the main topic of this paper (we are obviously trying hard to differentiate these two risk aspects), the following observations are worth bearing in mind.

a) The usual practice of testing for hidden failures, and seeking design changes when no applicable and effective PM can be found for critical equipment, should be followed. One aspect of testing for hidden failures is that the testing reduces the average unavailability of the failed equipment, and hence the risk posed by its failure to start when needed. This unavailability risk component for standby equipment is precisely and strongly limited by the testing frequency. Even so, the total risk cannot be reduced below the failure-to-run contribution, which is controlled by the other PM tasks that can be performed on the equipment.

b) For equipment that is normally operating, technically and economically effective risk reduction can usually be achieved by periodic PM tasks of various kinds, assuming the tasks address wearout mechanisms of failure. The most effective cases would be where the affected subcomponents (those that fail), 1) have a useful life that is accurately known (this is the time during which essentially no failures are expected via this mechanism, i.e. the time from as-new to when the failure time distribution becomes appreciably greater than zero), and 2) where the subcomponent's age is also well known. Periodic PM intervention can then be timed to occur conservatively at around the useful life, which is well before the average life is reached. In general for most equipment, the age is most likely to be known for large and expensive mechanical subcomponents that are known to have been in place since the plant or equipment was first installed. These are the least likely items one wants to discard before their full life is realized.

c) For most equipment the age of most subcomponents is not known at all, or at least this information is not researched and retrieved during normal PM. This 'random age' situation is the case for the vast majority of wearout mechanisms for the vast majority of equipment subcomponents. Knowledge of the useful life can still be used to set the PM interval, but still in a conservative way. This is because when the PM action is effective and the interval is correct, essentially all replacements (or restorations) of the subcomponent can be made during or as a result of the periodic PM, rather than during repairs after failure.

d) Random failure mechanisms and mechanisms for which the wearout time is not well known or is very dependent on uncontrollable factors, require monitoring of condition. Even then, random failure mechanisms can only be addressed this way when they present at least a short term signature of an incipient failure. Consideration of the time available between detection by condition monitoring and the time at which failure occurs is also required (the so-called P_f interval [5]) to determine whether effective restorative action could be completed within this time. Currently, the most widely accepted and common forms of condition monitoring are oil sampling and analysis, infra-red thermography, vibration monitoring and analysis, ultrasonic testing for material defects, various forms of electrical testing, and acoustic monitoring for electrical discharge and for the condition of grease in bearings and bushings. Most of these are performed on a frequent periodic basis, but continuous monitoring of vibration levels has also been in use for some time. New technology is providing more and more means of continuous monitoring, a trend that is increasingly becoming technically and economically feasible for high risk equipment.

e) Periodic use of condition monitoring techniques has been invaluable because they are relatively inexpensive to perform, often require no equipment outage, and are non-intrusive. They thus carry little or no risk of introducing failures through the performance of maintenance, even when performed fairly frequently.
f) Some condition monitoring techniques can be used to approach the full life of the equipment, which can be a large economic advantage in addition to those noted above. It is probably why many of these techniques are often referred to collectively as ‘predictive maintenance’, especially when the remaining life can be estimated.
g) In addition to knowledge of the relevant condition monitoring techniques, detailed consideration of their effectiveness requires special equipment and personnel training, and advanced techniques of data collection, processing, storage, and retrieval. Specialist input to the development of API-691 will address all of these predictive maintenance aspects.

2.5 The Rationale for Suppressing Frequencies

Given that a typical plant life is 40 to 60 years, by definition, all wearout failure mechanisms of interest occur within that period. Mechanisms that appear very quickly, i.e. within a few weeks, months or a year or two (e.g. clogged filters) are well known and absolutely have to be addressed with very effective PM actions. The useful life (initial period during which essentially no failures are expected) for other wearout failure mechanisms thus range from a few years to about 60 years – scarcely more than one order of magnitude. For this reason the information added by quantifying these unmitigated failure frequencies is not significant because the frequency range basically corresponds to them all being in the same frequency bin.

Random occurrence rates for the non-wearout mechanisms can in principle be much smaller in magnitude and might even approach rare event status. However, random events are even less quantifiable than wearout mechanisms and mostly fall into four categories, 1) those with human origins (e.g. maintenance and operational errors), 2) manufacturing or design defects, 3) are the result of multiple failure scenarios, or 4) are really wearout mechanisms that are so sensitive to the operating context that the useful wearout lifetimes are extremely uncertain and are best quantified as being random. Human originated random events are absolutely not rare events and fall in the same frequency range as the wearout mechanisms. It is questionable whether PM can even be expected to address design and manufacturing shortcomings, although these, too, are typically in the same quantitative range as the wearouts and are often at the short end of this spectrum (infant mortality). RCM is a single failure analysis, as are all other PM development processes, so multiple failure scenarios are beyond the scope of PM. Wearout mechanisms that have degradation rates that are too variable to be quantified are still subject to the same maximum likely limits on useful life as other wearout mechanisms.

There simply does not seem to be a strong justification for spending a lot of effort quantifying the occurrence frequencies for risk purposes, even for most Critical 1 equipment. Both RCM and the PM Template methodologies take advantage of that fact.

However, where the cost of failure and the cost of replacement are both exceedingly high, the economic motivation for remaining life assessment will oblige a quantitative assessment of the probability of failure as a function of continued time in service. This however, is a specialist activity, focused on dominant damage states for a relatively small number of important equipment items. This is not usually considered an aspect of preventive maintenance. The vital activity of remaining life assessment requires detailed technical knowledge of the physical processes affecting damage states in operational conditions. This is another area of API-691 development that will require input by specialists outside the realm of PM program development.

3. Conclusions

There are 6 conclusions of note from this paper that suggest the areas in which the methodology of Risk Based Inspection will need to be supplemented in order to develop a standard for PM development for turbo-machinery or active equipment in general. The characteristics of passive equipment enable RBI to be successful in a way that will not survive the need for application to an order of magnitude more subcomponents per equipment item, perhaps several orders of magnitude increase in the number of equipment items to be addressed, a wider range of degradation mechanisms, and a larger number of PM activities that are available to address them. RBI seems to do a good job within its range of application, but lessons can beneficially be taken from other high risk industries for extension to the larger numbers and increased complexity of active equipment.

RBI is a start, but the greater number of components and added damage mechanisms require both a more explicit and detailed use of FMEA and the dominant need to streamline and simplify as much of the process as possible. The use of FMEA has not been a focus of this paper but the use of FMEA as the reliability basis for PM is a bedrock requirement from RCM and has been made even more detailed and efficient in the Template methodology [14]. Efficiencies can be achieved by a focus on failures that can be mitigated by PM, using standard consequence types for prioritization, leveraging much of the detail by use of generic equipment types, and simply focusing on applicable PM strategies, all as facilitated by the PM Template approach. Most of the failure consequences will be economic and can be quickly estimated from the Criticality checklist selection with rough, typically generic, MTTR and an estimated system downtime cost.

There is a great deal of real world experience from the successes over many decades of RCM for commercial and military airplanes, and the PM Template methodology for nuclear power plants and the rest of the electric power industry, as well as application of both methods in general manufacturing and other industries. This experience demonstrates conclusively that:

1. The initial prioritization of equipment for PM development purposes does not require quantification of (unmitigated) occurrence frequencies for individual failure mechanisms, nor even for the equipment as a whole.

Close theoretical examination of equipment degradation types and time scales verifies that there are good reasons for this, as explained in this paper. Therefore:

2. Consequences alone, of in-service equipment failure, remain a good surrogate for relative risk in these circumstances.

This is because the equipment failure frequencies of concern fall in a relatively narrow range, accessible to simple investigations, assumptions, and reasonably appropriate statistical models. In the event that instances are discovered that contradict these conclusions it would probably be prudent to apply more advanced methods to deal with them in a focused way, thus preserving the more simple consequence-based approach for the vast majority of equipment items.

There is also industry-wide experience with PM Template methodology over a long time period, which verifies that:

3. A top-down list (the Criticality Checklist) of consequences that are important to a range of stakeholders is very practical and comprehensive and saves a lot of analysis effort in comparison with the kind of functional analysis contained in RCM. It is quick to develop and also quick to apply to the list of in-scope equipment.

In addition to the real world experience from the nuclear industry, this "Criticality Checklist" approach also has theoretical support in contexts where significant operating experience exists, and where plant operators are, 1) trained to respond to plant upsets and equipment failures, and 2) have direct contact with the equipment on a regular basis.

These complex issues are made easier to evaluate when risk prioritization done early in a PM development project is separated conceptually from the risk mitigation that is required later in the project to develop the recommended PM task intervals.

4. Risk prioritization should avoid over-specification of the consequences (risk) because fine structure in risk definition cannot be used when developing applicable and effective PM tasks and intervals. A binary decision structure (i.e. exceeds a consequence threshold or not) is sufficient to identify equipment requiring applicable and effective PM.

5. Equipment that requires applicable and effective PM can be further separated into two groups by equipment redundancy, which is quickly evident by design and is not explicitly a risk question.

6. The need for minor maintenance, failure finding, design changes, etc can be identified by other qualitative questions in the manner of RCM.

Even continuous monitoring, where it can be economically applied, is not 100% effective because it is not free of uncertainties and may be compromised in some cases by rapid deterioration after incipient failure is detected. The remarkable success to date of periodic condition monitoring does suggest that continuous monitoring will become the most effective PM defense of the future, and will become more and more essential for remaining life assessment. Even then, we should remain aware that even the most effective PM is not supposed to substitute for effective design, operation within design limits and quality repair practices, facts that are all the more true in high risk industries.

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References

1. "Risk Based Inspection. API Recommended Practice 580", 2nd Edition, November 2009, American Petroleum Institute.

2. "Risk Based Inspection Technology. API Recommended Practice 581", 2nd Edition, September 2008, American Petroleum Institute.

3. "Reliability Centered Maintenance", Anthony M. Smith, 1993, McGraw-Hill.

4. "Surface Vehicle/Aerospace Standard JA1011: Evaluation Criteria for Reliability-centered Maintenance Processes", 1999, Society of Automotive Engineers, Inc (SAE).

5. "Reliability-centered Maintenance", John Moubray, 1992, Industrial Press, Inc.

6. "RCM – Gateway To World Class Maintenance", Anthony M. Smith and Glenn R. Hinchcliffe, 2003, Elsevier, Inc.

7. "Reliability-centered Maintenance", Second Edition, John Moubray, 1997, Industrial Press, Inc.

8. "Application of Reliability-Centered Maintenance to Component Cooling Water System at Turkey Point Units 3 and 4", Electric Power Research Institute, EPRI Report NP-4271, October 1985.

9. "Use of Reliability Centered Maintenance for the McGuire Nuclear Station Feedwater System", Electric Power Research Institute, EPRI Report NP-4795, September 1986.

10. “Application of Reliability-Centered Maintenance San Onofre Units 2 and 3 Auxiliary Feedwater Systems”, Electric Power Research Institute, EPRI Report NP-5430, October 1987.

11. “Reliability Centered Maintenance Applied in the US Nuclear Commercial Nuclear Power Industry”, Proceedings of the 6th International Maintenance Conference, Institute of Industrial Engineers, October 1989.

12. “Comprehensive Low-Cost Reliability Centered Maintenance”, Electric Power Research Institute, EPRI Report TR-105365, 1995.

13. “Streamlined Reliability Centered Maintenance (SRCM) Implementation Guidelines”, Electric Power Research Institute, EPRI Report TR-109795 V2, 1998.

14. “PMEA’s and PM Templates for Preventive Maintenance Analysis”, David H. Worledge, Glenn R. Hinchcliffe, Mark S. Benak, Asset Performance Technologies, Inc.