PMEA’s and PM Templates
for
Preventive Maintenance Analysis

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1. Background, Needs, and Objectives

The development of Preventive Maintenance (PM) recommendations for industrial assets requires a methodology to prioritize PM resource allocation among the equipment, and to develop the PM frequencies and actions to be implemented. Resource allocation depends on the impact on stakeholders of loss of equipment function, whereas the maintenance actions to be performed require evaluation of how the equipment degrades over time.

Experience across many industries has shown that the technical basis for PM must be thorough and robust and it must be relatively easy to develop it within reasonable resource and time constraints, or the result risks being failure of the project, or a PM program that is neither thorough, robust, nor even economical to implement. Unfortunately, less-than-effective PM programs have earned a well deserved reputation for being unproductive cost centers rather than revenue enhancers that provide significant cost leverage.

A viable industrial scale approach to PM development must be applicable to a large number of equipment items of various types. The number of distinct equipment *types* (e.g. reciprocating compressor, diaphragm operated valve, level indicator) will typically be of order 100, whereas the number of items of equipment will be of order 1,000 to 10,000, or even more. The impact of these numbers on the methodology cannot be overstated. The methods must be efficient at every step to be successful on a large scale.

Whatever its problems, Reliability Centered Maintenance (RCM) has proved over the past 40 years that a convincing reliability basis for PM actions requires mapping the actions to degraded states of the equipment. This has become the canonical foundation for modern PM content development. This paper focuses on such FMEA’s and will briefly outline PM Template methodology in which the FMEA’s are mostly used. Template methodology, although not classical RCM, has been astonishingly successful on a large scale in the electric power industry for over two decades.

2. Outline of Template Methodology

The starting point is the estimation of risk for each of the equipment items (the unique instances, or equipment ID’s) in scope, when their functions are lost. The Template approach is not overly concerned with how the risk prioritization is performed. This is because risk evaluation methods have become quite sophisticated and therefore present mainly a logistical challenge, not a technical one. In fact, RCM only focuses on one dimension of risk – the consequences, but does it via a time-consuming functional analysis. The nuclear industry does it rapidly using a checklist of questions that span functional, economic, and safety issues. A traditional FMEA (with essentially one record per equipment ID) that evaluates risk of functional failure can also be used, similar to the oil and gas industry's RBI process (API 580 and 581). However, 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), 2) do minimal PM, or 3) do quality PM. The latter (high risk) case may be divided into two levels (often called Critical 1 and 2) depending on equipment redundancy, so the difference may be decided by design, not explicitly by risk. Other criteria can be brought to bear on this case but it requires a lot of judgment to hit the right note, and you generally do not know if you have hit it or not. Consequently, it is not worth employing a risk process that is fine-grained (i.e. has many risk categories). For PM application, you basically need to know if failure presents a large risk or not. The take-away point is that although the risk step must not miss any equipment that presents significant risks, you should not develop more information in the risk evaluation step than you can use in the PM development step.

Performance intervals for PM tasks depend on the manner and rate at which equipment degrades, which depend on the type of equipment, its duty cycle, and its service conditions. The duty cycle and service conditions are referred to collectively as the operating context. Only about 10% of the information in the FMEA is specific to the operating context. The other 90% is applicable to every instance of the same type of equipment, wherever and however it is applied in the plant. However, the 10% that is context-dependent can have a large impact on the resulting PM recommendations. When using conventional FMEA's, practitioners reuse those parts of the table that apply to all occurrences of the same equipment type, editing as needed to account for the context-specific aspects. This takes time and it is not easy to manage the proliferation of context-specific tables.

To be more efficient in application, the FMEA has to have new features beyond FMEA's with which most of us are familiar. This development of FMEA will be referred to as a PMEA (for Preventive Maintenance Equipment Analysis).

For each equipment type, the Template method develops just one PMEA that is independent of operating context from the outset. When this PMEA is applied to each instance of that equipment type, it may yield different PM recommendations for the different operating contexts. It is analogous to performing different calculations with an electronic calculator; the same calculator gives different results for different calculations. If done correctly, the PMEA for a given equipment type is then a single table that only needs to be updated every few years as new knowledge becomes available. The fact that this *single* table can be applied to a variety of operating contexts can be summed up by saying that the PMEA is deliberately constructed to be *context-invariant*, i.e. you don't need to make different versions of it when the duty cycle and service conditions change.

The PMEA now retains an identity and can become a permanent repository for accumulating corporate and industry knowledge and experience about degraded states of equipment and the mitigating power of PM. This enables a corporation or an industry to develop and maintain a library of such PMEA's.

When such a library exists, the aggregate PM knowledge will be available to the PM analyst at the start of his project. If developed using the resources of an industry, the depth and scope of this knowledge on most equipment types will be more consistent and superior in quality to that otherwise available to personnel at any operating plant.

A second part of such a library will consist of simple tables, referred to as PM Templates (one for each equipment type), which contain the recommended performance intervals for PM tasks, in columns that correspond to discrete combinations of the major risk categories, duty cycle, and service conditions. These are chosen to span the range of risk and operating contexts. Task interval recommendations are prepared just once, when the PM Template is developed. The technical basis for them resides in the associated PMEA. The Template approach is briefly illustrated in Figure 1 and Figure 2.

3. Elements of the PMEA

The purpose of this section is to describe the major parts of the PMEA that are essential to an understanding of how the methodology works.

3.1 Elevate Risk Aspects to the Risk Evaluation Step

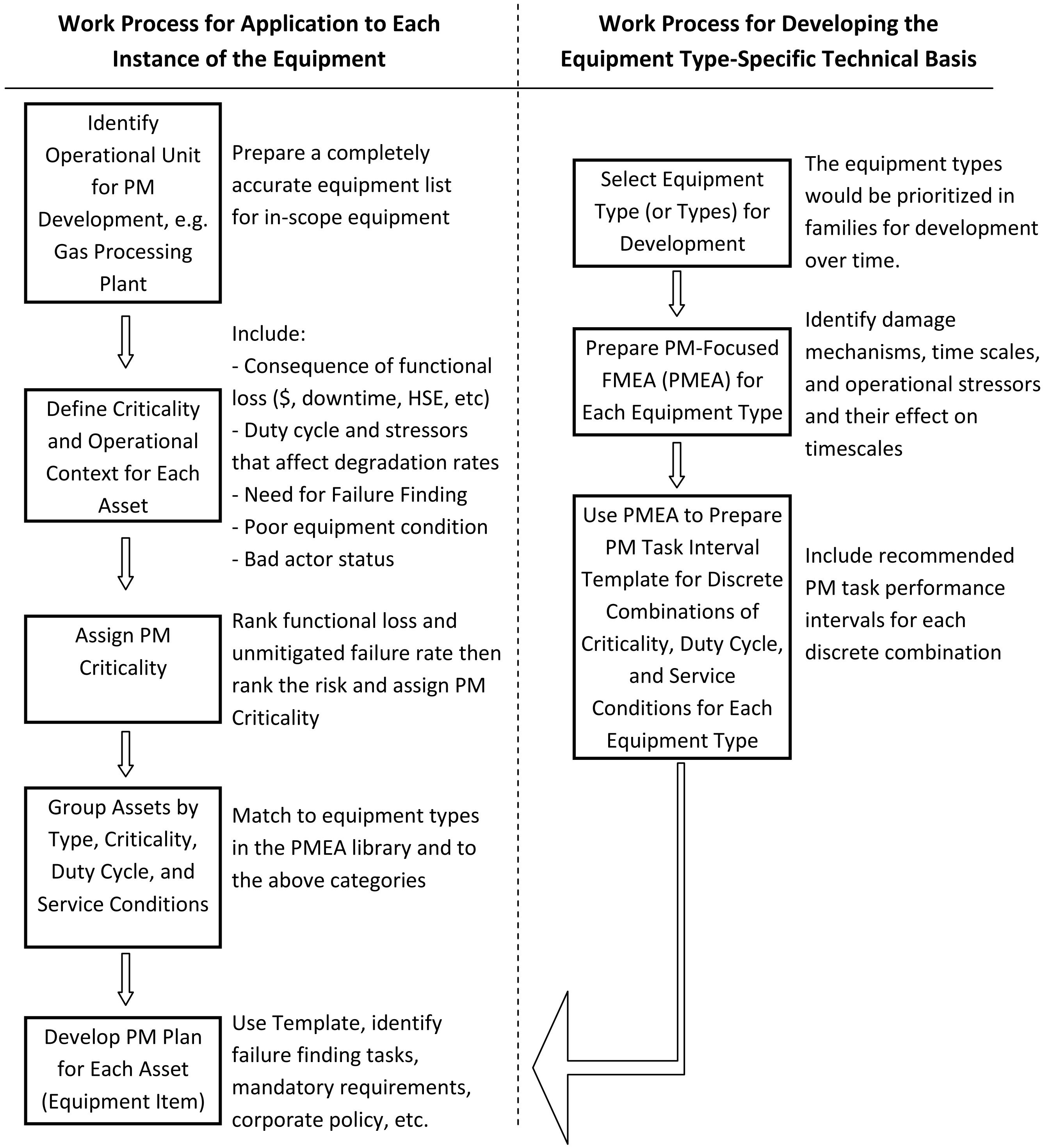
The prototype for the PMEA is the FMEA developed by RCM, but the rows in the PMEA focus intensively on *degradation mechanisms* and their causes; there are no *failure modes* in the table. The latter may be encountered in FMEA's for design studies, safety evaluations, RAM modeling, risk assessment, and so on, and are events such as "fails to start", "fails to run", "fails to open", "fails to close", etc. They are failed equipment configurations that affect system operation and risk, but none are maintainable conditions. To clarify this point, consider the degradation mechanism "valve stem", "binding", because of "inadequate lubrication". Valve stem binding can lead to failure in any position of the stem, hence the degraded condition maps directly and unambiguously to maintenance actions in a way that "fails to open", "fails to close" do not.

It is important to treat all risk aspects at the level of the equipment as a whole during the risk evaluation step, and not to assign risk for each degraded equipment state in the PMEA. The risk step will need to recognize the major functional modes in which the equipment can fail, such as failing to provide its primary function(s), failing to provide containment, or experiencing an energetic event such as a high pressure disruption. If these present significantly different risks, they must be documented in the risk step.

3.2 Degraded Equipment States

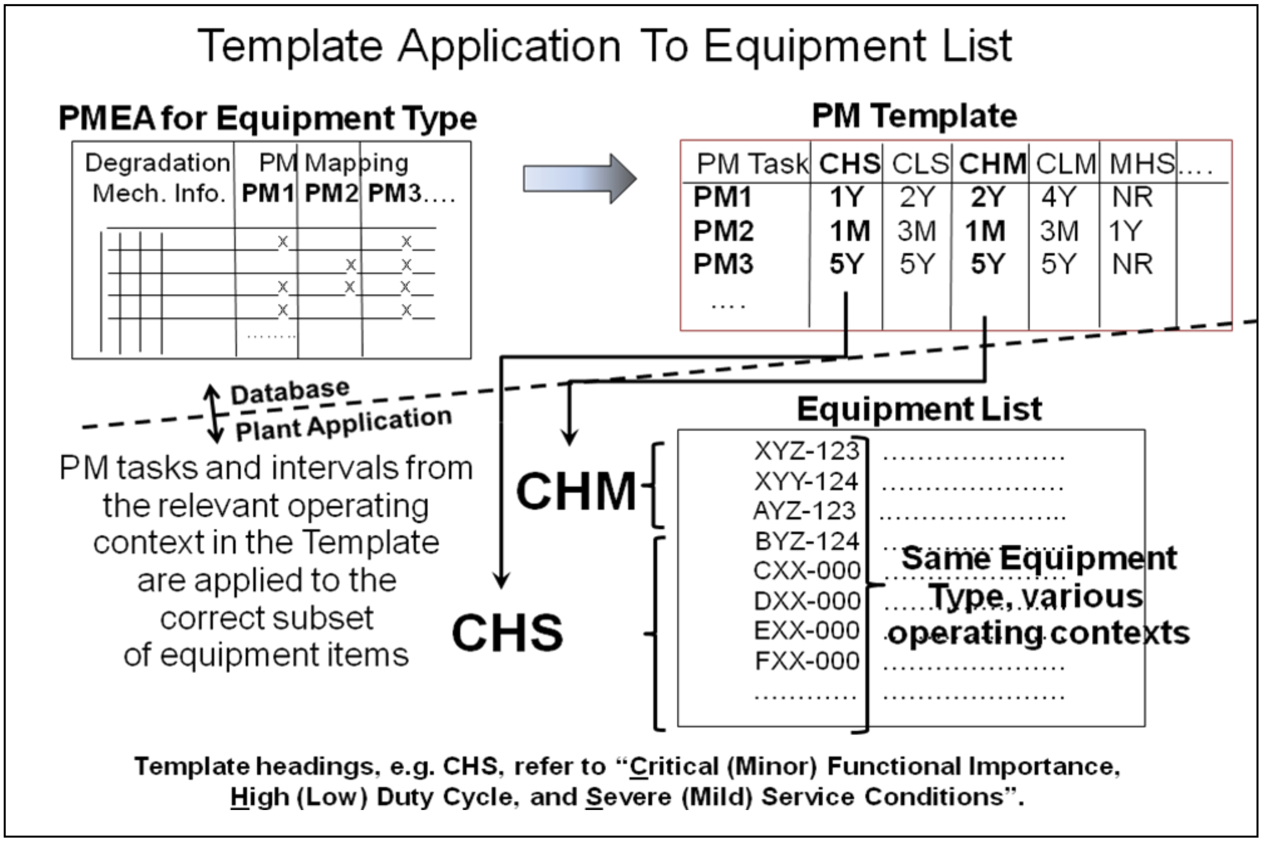
The PMEA lists each item of hardware that degrades, the mechanisms by which they degrade, the causes, the statistical failure pattern (i.e. random or wearout), and how long they take to reach the point of failure. It is absolutely necessary to identify the separate causes for each mechanism of degradation for each known point of failure in the hardware, because different causes for the same mechanism can cause the hardware to degrade at different rates and in a different statistical failure pattern. Since the

Figure 1*: Work Processes for Implementing the PM Template Process



* Tom Folk of Lloyd's Register provided the first draft of this figure.

Figure 2: Overview of PM Template Application



ultimate goal is to map each mechanism and its cause to the required PM task and task performance interval, it is necessary to write each combination of hardware, degradation mechanism, and cause with its development timescale, on a separate row in the table.

This is why the PMEA's have a lot of rows. For example, a horizontal, split case, multi-stage pump can have 25 failure locations, 42 degradation mechanisms, and 100 causes, arranged in combinations that form 143 rows in the table. A simple or passive equipment type such as a filter, tank, or a power cable may only have 5 to 20 rows. The entries in these data fields contain an average of about two words each, indicating the focus and specificity of the entries. This conciseness is possible provided the tendency to mix items together is avoided unless they truly behave the same way. The resulting format is compact and computer readable, with a high information density. For illustration, a small part of a PMEA for a Medium Voltage Motor is shown in Figure 3.

3.3 The Operating Context

The operating context can be summarized by a standard set of service stressors (e.g. temperature, vibration, moisture, etc) that easily can be assigned at the level of the equipment as a whole. The rates of degradation at the level of rows in the PMEA obviously depend on the service stressors. Then how is the PMEA made independent of the operating context of each equipment item?

Figure 3: Partial PMEA for a Medium Voltage Motor

Figure 4: Part of a PMEA for a Motor - Medium Voltage <15Kv - Horizontal - TEFC - Sleeve Bearing - Oil Lubed

Intrinsic Effectiveness of PM Strategies (H=High, M=Medium, L=Low)

Failure Location	Degradation Mechanism	Degradation Influence	Time Code	Stressor Groups	Discovery or Prevention Opportunity	Thermography	Vibration Monitoring	Oil Analysis	Electrical Testing	Electrical Inspection	Mechanical Inspection	System Owner Walkdown	Mechanical Refurbishment	Refurbishment	Operator Rounds	Calibration
Bearing Insulation	Broken / cracked	Improper handling	R		Inspection, Electrical tests								M	H		
Bearing Insulation	Insulation degradation	Contamination	W5_10	C	Inspection, Electrical tests						L		M	H		
Bearing Metering Orifice	Blocked	Contamination, Debris	R	C	Bearing temperature, Oil pressure, Oil level			M				M	M	H	M	
Bearing Metering Orifice	Blocked	Personnel Error	R		Bearing temperature, Oil pressure, Oil level			M				M	M	H	M	
Bearing Seals	Wear	Environment, debris	R	CF	Inspection	L	M	H				L	H	H	L	
Bearing Seals	Wear	Excessive oil	W0.5		Inspection							M	H	H	M	
Bearing Seals	Wear	Imbalance or misalignment	R		Inspection							M	H	H	M	
Bearing Seals	Wear	Improper installation	R		Inspection							M	H	H	M	
Bearing Seals	Wear	Incorrect lubricant	R		Inspection							M	H	H	M	
Bearing Seals	Wear	Material defect	R		Inspection							M	H	H	M	
Bearing Seals	Wear	Normal wear, duty cycle	UW10_15	D	Inspection							M	H	H	M	
Bearing Seals	Wear	Temperature excursions	R	T	Inspection							M	H	H	M	
Bearings - Sleeve	Wear	Babbitt imperfection / cold spot	R		Oil analysis, Bearing temperature, Vibration, Acoustic monitoring, Bearing inspection		M	H			H		H	H		
Bearings - Sleeve	Wear	Circulating electric currents	W0.5_2		Oil analysis, Insulation resistance checks, Vibration, Acoustic monitoring		M	H			M		H	H		

Within the PMEA, time scales for the development of degraded conditions should be quoted for nominally *unstressed* conditions. When the operating context contains certain stressors, these times must be reduced in a controlled way. So each row in the PMEA must document all the service stressors that can be significant. A single PMEA can then be applied to all relevant operating contexts for that equipment type, not because it ignores the context, but because it encompasses and accounts for the full range of it. Adjustment of these time scales depending on the specific context for any instance of the equipment type can be done by inspection, or even by software when the Template is created.

3.4 PM Task Effectiveness and Task Intervals

Most infrastructure equipment in industrial plants has a limited range of rather well known PM tasks that are candidates for inclusion in the PM program. These are tasks like inspections, calibrations, overhauls, scheduled replacements, many predictive and condition monitoring and testing techniques, functional tests, operational tests, walkdown inspections, and operator rounds, etc. Subject matter experts decide which of these are the useful candidates for the equipment type in question. When such a task is performed it will address many line items in the PMEA. The line items are the actions within each task that address specific degraded conditions.

Each candidate PM task is given a column in the table. Going down the column for a given PM task, the subject matter experts insert a marker in each row where the task would provide a significant likelihood of discovering the anomaly *if it were performed at the right time*. The markers are check marks or a code that shows the effectiveness of the activity (e.g. H, M, or L, for High, Medium, or Low). If task effectiveness is graded in this way, the above italicized condition preserves the context-invariant property of the PMEA.

When completed, the PMEA is the technical basis for each PM task. It shows which line item activities are required during the performance of each PM task, why, and when they are needed. However, actual task performance intervals will often fail to satisfy all the demands of the PMEA. The compromise will depend on the level of risk exposure. Thus the final act leading to application-independent PMEA's is to put the recommended task intervals into the PM Template, arranging them by criticality level, and keep them out of the PMEA.

4.0 Scope of Applications

The PM Template process based on context-invariant FMEA's has been used with great success by the US commercial electric power industry over the past 20 years. A database of such "PMEA's" and PM Templates has been developed in work sponsored by the Electric Power Research Institute (EPRI), with participation by utility subject matter experts. It now contains about 200 equipment types. Experience shows that the creation of a single PMEA and Template from scratch takes about 6 to 12 hours of team work depending on equipment complexity. Additional PMEA's addressing similar equipment types, or updates to existing PMEA's, proceed much more quickly.

The PMEA's are used mainly to develop PM Templates. It is the Templates that are most heavily used in PM improvement at a plant. The simplest applications use the Template recommendations directly, especially when resources are not available to apply detailed contextual information. However, modifications of the Template recommendations are often appropriate to accommodate poor failure history , poor condition, or aging equipment, etc. In the early stages of these developments the PM Templates were used by Commonwealth Edison Corporation (now Exelon with 17 nuclear units) to develop standardized PM tasks for all its nuclear power plants.

A very recent application was to an Emergency Diesel Generator Lube Oil system at a US nuclear power plant. This application was more demanding than most as the PMEA's had to be tailored to specific equipment models and combinations thereof, in order to address aging requirements. Even so, 39 PMEA's were generated in 12 days work on site, about half of which were modifications of existing PMEA's, the rest being created from scratch. PM tasks were then assigned to 224 equipment ID's in this system in about one week of further work.

Further customization around the Template recommendations can be performed by software tools acting directly on the PMEA. A light level of optimization giving reasonable cost reduction but retaining good equipment reliability was employed at an oil sand production facility for Suncor Energy Inc., in which 3100 PM Tasks were assigned to 650 items of rotating equipment using existing PMEA's in the database. Apart from the review process, essentially no time was required for the cross functional teams to develop PMEA's nor to generate PM recommendations. In fact the total 150 calendar hours of team time (< 4 hours a week from each of two teams)were spent on RCM functional analysis. This could have been reduced significantly by adopting a simpler approach to risk prioritization as recommended in Section 2. In contrast, using RCM for the whole project would have required the analysis team's participation for about a year, and would thus have needed to be spread over at least two years of calendar time instead of being completed in just a few months.

This much lower demand on the time of plant personnel can dramatically improve the chances of successfully completing and sustaining a PM improvement project for complex industrial assets.

5.0 Summary and Conclusion

Efficient and successful PM improvement on an industrial scale requires, 1) matching risk prioritization to the limited ability of PM to discriminate between levels of risk, and 2) a way to customize PM development using more or less permanent application-independent database objects.

To ensure the PMEA has these properties:

1) Assess functional importance (risk) at the level of the equipment as a whole, keeping failure modes and consequences out of the PMEA.
2) Discriminate between causes on separate rows in the PMEA because they affect failure pattern and time scale, and use sufficient data fields because using the PMEA is more efficient when it is in database format.
3) Bin the operating context to very few categories of risk, duty cycle, and service conditions.
4) Encode sufficient information about the service stressors and the timescale of degradation to address the range of operating contexts.

5) Map line-item PM actions to rows of the PMEA under pre-assigned PM Task headings.
6) Impose the condition "*if task is performed at the right time*" when it is desired to encode task effectiveness.
7) Recommend task intervals only in the PM Template, keeping them out of the PMEA.

The electric power industry database of PMEA's and PM Templates, sponsored by EPRI, is known as the PM Basis Database. It is in use at 84% of North American nuclear power plants, and others in Japan and South Korea, as well as by fossil fuel plants and the transmission and distribution sectors of the power industry. For nuclear power, a highly regulated and risk-focused industry like oil and gas, the database is recommended by both federal (NRC) and the industry's own (INPO) regulatory agencies. Commercial access to the database is provided under license to EPRI by the authors of this paper, who also maintain it and provide additional PMEA's (now 324), as well as automatic optimization tools.

Since this approach can incorporate various levels of detail, has been validated over a long period in a risk sensitive energy industry, and represents a huge step forward in PM improvement efficiency, it is suitable for wide application and is being considered for inclusion in a new API standard (API-691) on PM development for turbo machinery.