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Preventive Maintenance Task Deferral & Financial Risk Analysis

Using PM Basis Database to Evaluate Task Deferrals

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Technical Update, March, 2005

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ABSTRACT

Task deferral evaluation is focused on justifying a one-time deferral of a single task, rather than making a decision to increase the interval permanently. Because the deferral is limited to a single occasion, the level of risk is generally less than that which would accompany a permanent change. However, deferrals are often sought for purely logistical reasons, and historically have not always been supported by equipment condition information.

Objectives of the PM Deferral Process

- Ensure performance of components will remain acceptable if a PM is not performed prior to its late date.
- Ensure risks (probability x consequence) associated with deferring a PM activity beyond the assigned late date are acceptable.
- Ensure effective risk mitigation strategies are in place if risk is found to be unacceptable and the PM activity cannot be performed prior to the late date.
- Apply a graded approach to deferral of PM activities so that evaluation resources are first applied to the PM activities associated with the most critical components.

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1
PM TASK DEFERRAL EVALUATION PROCESS

1.1 Basic Assumptions

The following procedure assumes that you have no historical, adverse equipment condition information to suggest that the deferred task will lead to an unacceptable equipment condition or failure.

It will also be assumed that there is no specific reason to suspect that deferring the task will leave known failure mechanisms undefended. Nevertheless, since the possibility exists, two things will happen. Generically, there will be an increase in the failure rate, and an increase in the probability of experiencing a failure during the period of deferral. The failure rate increases with the proportion of the interval represented by the deferral. The probability of a failure increases with the failure rate and also with the length of deferral.

This suggests different treatment for critical and minor equipment. For an explanation of critical and minor equipment see Interval Evaluation.

For both critical and minor equipment it is assumed in this guideline that the increase in the absolute value of the probability of a failure during the lengthened interval should not be more than 0.1 (i.e. creates an extra 10% chance of a failure) as a result of the deferral. The value 0.1 is an arbitrary choice. In addition, for critical equipment it is also assumed that the failure rate should not be permitted to increase by more than a factor of two. This is because an increase of a basic event probability by a factor of two will cause a relative increase in the probability of significant damage, and therefore should be avoided. This should be acceptable on a one-time basis for a limited period except for the most risk significant equipment. It is assumed that PM tasks for very risk significant equipment would not be deferred without additional evaluation. The failure rate constraint is not applied in the case of minor equipment.

The following rules were derived from detailed failure rate calculations which took into account the generic number and distribution of failure mechanisms, random failures from non-wearout failure mechanisms, task effectiveness, and the proportion of wearout failures addressed by a PM task. The rules assumed the latter proportion was conservatively 100%. The calculations also assumed there is no conservatism in the existing PM program, so as to maximize the effects of deferrals.

1.2 Minor Equipment

Defer one time without further evaluation, up to the following limits. If the deferral is longer than these limits, it requires evaluation.

Interval (years)	Defer By (years)	A One-Time Deferred Interval May Thus Become (years)
1	1	2
1.5	1.5	3
2	2	4
5	3	8

1.3 Critical Equipment:

Defer one time without further evaluation, up to the following limits. If the deferral is longer than these limits, it requires evaluation. Tasks with intervals 1.5 years or less should not be deferred without evaluation.

Interval (years)	Defer By (years)	A One-Time Deferred Interval May Thus Become (years)
≤1.5	Requires Additional Evaluation	
2	1	3
3	1	4
>4.5	1.5	>6

1.4 Evaluation of Task Deferral for Critical and Minor Equipment

The above rules should cover almost all cases of interest without the need for further evaluation. However, any one of the following three methods may be used to justify task deferral outside the above limits:

1. Discover if the equipment condition has consistently been good enough to enable it to reach the deferred task execution time without failure. This requires data from plant specific experience.
2. If the interval is sufficiently less than the interval recommended in the Template, so that even with the deferral, the combined period does not exceed 125% of the Template interval, defer the task. This requires a current task interval that is conservative.
3. Evaluate the limit in the above tables using the Vulnerability tool with specific input data on criticality, duty cycle, service conditions, and all the task intervals.

2
STEPS OF THE DEFERRAL PROCESS

2.1 Determine if a PM Deferral is Required

- A PM Deferral is required when a PM activity is not going to be performed prior to the end of its grace period.
- A PM Deferral is not required when a permanent change in PM frequency is more appropriate. This would be a permanent change and would be made in accordance with the PM Change Request Process.
- A PM Deferral is not required for the following types of activities:
- Support activities, such as installation of scaffolding in support of a PM or refueling outage preparations.
- PM activities that have been “turned off” because the related equipment is out of service and there is no need to perform the PM from a technical perspective, such as filter changes when the system is out of service and there are no external influences that would clog or damage the filter. The justification to not perform these PM activities will be contained in the PM Basis.
- Administrative activities, such as verifying welding certifications.

2.2 Gather Background Information

The following information will typically be gathered to support this evaluation. To be efficient this information should be gathered from plant and industry sources in a format to make evaluation less resource intrusive.

- Component criticality, duty cycles and service conditions.
- Current scope and basis for the preventive maintenance activity being proposed for deferral (including failure modes and commitments to performance of the PM being proposed for deferral).
- Previous Maintenance Feedback for the PM being proposed for deferral.
- Previous deferrals of the PM being proposed for deferral.
- Status of other PMs on the components being addressed by the PM being proposed for deferral and previous Maintenance Feedback on those components?
- Site specific failure history associated with this and similar components.
- Industry operating experience associated with this type of component.

If the answer to this evaluation is that a deferral is not required, perform an Interval Evaluation in accordance with Chapter X.

2.3 Conduct the Deferral Evaluation of this PM

Conduct a review of the background information to determine the risk associated with component failing while waiting for the late PM to be performed. The level of rigor that goes into this review and remaining steps of this guide should be based on the criticality of the affected component.

The following steps will help to determine the risk (probability and consequence) associated with the failure of the components affected by the PM requested to be deferred.

1. Document criticality, duty cycles and service conditions for the affected component(s). This information was developed as part of criticality determinations. If not, this information should be estimated by the Evaluator. The criticality in this step will be used to determine the consequence of failure (Table 2). Duty cycles and service conditions are used to aid in determination of the probability of failure.

2. Review the PM Basis to determine if there is anything in the current PM Basis that would indicate that the PM should not be deferred. For example, does the PM Basis include a statement that this PM should not be deferred based on previous as-found condition?

3. Are there any commitments that would prevent deferral of this PM? If so, action will be need to be taken with the commitment before the deferral can be acted upon.

4. Does the PM being proposed address significant and likely failure modes? If not, it is much easier to defer this PM from a risk perspective; elimination of the PM may be prudent if it is not addressing significant and likely failure modes. The risk associated with deferring this PM will be much higher if the PM is addressing significant failure modes.

5. Does previous feedback on this PM indicate degraded conditions that would indicate that the PM should not be deferred? If so, the risk associated with this deferral is higher. If the previous question was answered yes, the PM addresses significant failure modes, and the answer to this question, the last feedback was degraded condition, then the risk associated with deferring this PM is high.

6. Has this PM already been deferred? A second deferral of this PM could significantly increase the risk associated with the failure of this component.

7. Are other PMs on this component up to date and does feedback indicate that it is ok to defer this PM? The overall reliability of a component will be based on the sum of preventive maintenance being performed. Not performing those PMs or finding degradation in as-found conditions of those other PMs will increase the risk associated with deferral of this PM.

8. Are there any performance issues in health reports that would indicate that this PM should not be deferred? System and component type health reports may include information related to the degradation of the component affected by this PM that would increase the risk associated with deferral of this PM.

9. Does the site specific and industry failure history of this component (and similar components) associated with failure modes being addressed by this PM indicate that this PM should not be deferred?

10. Based on response to the questions above, what is the probability of this component failing after the late date and prior to the planned performance of this PM? (Low, Medium or High)

11. Based on responses above, determine if the technical risk of deferral is acceptable. This will be a qualitative decision based on the answers to previous questions. Not all of these questions are equal. Some are more important than others. Document the basis, or thinking, behind this decision. If additional room is required, attach a document with the additional information.

12. What is the cost if the component associated with this PM fails prior to the PM activity is performed. This could be qualitative and or quantitative costs.

13. Is the cost consequence of deferral of this PM acceptable? As with technical risk assessment, the assessment of cost is a qualitative one based on this component failing before the PM is performed. Document the basis, or thinking, behind this decision. If additional room is required, attach a document with the additional information.

14. Review the costs to perform the PM if this request were to be disapproved.

15. Plant trip – failure of this component will cause a turbine trip.

16. Failure of a criticality 1 component.

17. Is the cost consequence associated with this deferral acceptable?

2.4 Action After Deferral is approved

Alert Operations that this PM activity is being deferred and that closer attention should be paid to this component during operator rounds and log readings. Specific additional monitoring information may be appropriate to ensure focused attention on the likely failure mode(s). If risks of deferral are unacceptable and adequate risk mitigation strategy actions cannot be put into place, the request for deferral should be disapproved. Proceed to the next step of this guide to document this decision.

- Change the due date on the PM to that approved in Table 1.
- If the deferral request has been approved without risk mitigation strategies change the due date on the PM and complete the PM by the new due date in Table 1.
- Follow-up to Ensure Effectiveness of the Process.
- Monitor the performance measures established in the PM Deferral Monitoring Health Report. Take action to improve performance based on the results of this monitoring.
- Conduct a self-assessment of the PM Deferral Process to ensure the process is working as designed and expected results are being obtained.
- Evaluate the lessons learned and implement improvement actions as required.

3
INTERVAL EVALUATION

3.1 Context

Before proceeding with Interval Evaluation, you are recommended to examine the sample procedure described in the flow chart PM Optimization. This procedure is one example of an approach to PM optimization which considers criticality, failure history, vendor recommendations, current PM tasks and intervals, and the acceptability of the EPRI recommendations. The flow chart makes reference to both PM Task Evaluation and Interval Evaluation and serves as an introduction to how a plant PM optimization project can use these evaluation processes. The Interval Evaluation process can also be used to address issues concerning individual task intervals.

Interval Evaluation selects and evaluates PM task intervals to provide adequate protection against component failures. Evaluation of whether the tasks themselves are technically applicable and cost-effective is done separately using PM Task Evaluation. Do not attempt to evaluate or change a task interval in response to concerns about equipment condition or reliability, until you are sure that the correct PM tasks are being performed. Evaluation of a task interval should be carried out in the context of other PM tasks which are being performed on the component. The main reasons for these evaluations could be, 1) to optimize tasks and intervals as part of a programmatic improvement in which a large number of tasks and components are addressed, 2) to change individual task intervals in response to poor reliability, 3) to change individual task intervals in response to unacceptable or consistently good material condition, or 4) to justify deferring a task. Evaluating the intervals follows the same general process regardless of the reason for the evaluation, however, a version that is focused on justifying task deferrals can be found at Task Deferral.

The Interval Evaluation requires the answers to a set of questions. Each question is handled in two parts. The first (What?) explains what the issue is about and why it is important. The second (Answer?) shows the user how to get the answer to the question, most often using the EPRI PM Basis Database.

3.2 Questions Outside The Scope Of This Evaluation

There are also three initial questions that should always be considered when evaluating a PM task interval, but they can not be answered by the database. They all presume a specific task interval is being evaluated.

1. Is this task interval specified by the plant operating license such as for Technical Specifications, EQ, Appendix R, etc?
2. Is this task interval specified by a relevant code or standard such as ASME Section XI?
3. Is this task interval part of a management commitment to regulators, insurance, etc?

If the answer to any of these questions is “Yes”, you will probably continue to implement the existing task interval in the short term. However, further evaluation of the interval may suggest that changing the requirement would add value.

3.3 Interval Evaluation Process

A. Is this a Critical, Minor, or Run-To-Failure component?
B. Which intervals are recommended by the EPRI PM Basis Database?
C. Is there a technical reason why the interval is longer or shorter than the EPRI PM Basis Database recommendation?
D. Should the current interval be extended or reduced?

3.3.1 Interpretation of the Questions

This Section explains what is meant by each question and why it is worth answering it.

A. Is this a Critical, Minor, or Run-To-Failure component?

The objective of PM could be to prevent all or most failures of a component as far as possible, or alternatively could be to prevent only some failures. Components with these two PM objectives may be stated in PM optimization processes to be “Critical” and “Minor”, respectively. Both cases lead you to consider doing some PM tasks. If neither of these objectives apply to this component, it should be classed as Run-To-Failure (RTF) which means that no PM tasks of any kind should be performed on it.

The PM objective for critical components is to prevent all or most failures that are known to occur and are expected to occur at least once in the life of the equipment. Critical components must therefore have sufficient PM coverage in scope and frequency to address a wide spectrum of possible failure mechanisms, and certainly all the common failure mechanisms.

Components that lack important functions may simply be allowed to fail if there are no serious consequences. They can be repaired after they fail but they would not merit expenditure of maintenance resources to prevent the failure. Such components would be classed as Run-To-Failure and they would literally be run to failure.

However, many components fall between these extremes. For example, they might cause significant costs when they fail even though such costs are not nearly on the scale of a loss of production. This could be a result of self or secondary damage, increased waste disposal costs, additional testing or requalification of other equipment, or because of significant radiation or other occupational exposure during repair (more than during PM). All such components are classed as Minor and they would ideally receive some level of limited, inexpensive PM.

Therefore, components receive a wide range of different levels of PM. It is convenient to think of the more comprehensive end of this range of PM coverage as corresponding to the objective of preventing all or most failures. Even within this category it is possible to distinguish failures which individually create huge costs every time they occur from those which can be (barely) tolerated providing a high reliability target is reached, e.g. where only a single failure is likely to be experienced in an extended period of operation. The former category could be referred to as Critical A components, whereas the second category could be referred to as Critical B components. Both are critical in the sense that they command that extensive PM effort be made to prevent them. Preventing most failures rather than all of them is appropriate for redundant equipment where the combination of two or more train failures would represent a critical loss of function. In this case, each train needs to be maintained at a high level of reliability or there is no point in designing in the redundancy. Clearly, in a nuclear power context, the level of Critical B PM provided for 2-train safety configurations may easily rival that for Critical A components (which might trip the plant or result in an in-plant fatality). Logically, the PM requirements become less demanding as the redundancy level increases above 2, and as the risk significance of the individual failures decreases. Even the nuclear power plant Maintenance Rule contains provisions to allow one or sometimes two failures for some critical components in a two year period.

At the other extreme, minor components might need a PM task to address just one or two catastrophic failure mechanisms if the objective involves preventing expensive damage to the component, or to another component.

You may not be able to find cost-effective PM tasks for minor components. This does not mean they revert to the Run-To-Failure category. They are still Minor components but you are then running them to failure. In these cases you have to accept the cost of the failure. In some cases you may even be unable to find cost-effective PM tasks for a Critical component. In this situation you should seek a design change, but if a practical design change can not be implemented you may be forced to run this component to failure, even though it is still a Critical component.

B. Which intervals are recommended by the EPRI PM Basis Database?

Task intervals recommended by the Database may depend on criticality, duty cycle, and service conditions. You should be aware that the tasks in the Database may not be packaged in the same way as current tasks, that is, certain line item activities may be performed as part of another task, and tasks which have similar names may differ appreciably in scope.

C. Is there a technical reason why the interval is longer or shorter than the EPRI PM Basis Database recommendation?

Constraints such as previous failures or reports of adverse or consistently good equipment condition may have influenced the existing interval. Differences in equipment design or peculiarities in application or operation may also have influenced the existing interval.

D. Should the current interval be extended or reduced?

The expert panel of utility and vendor personnel which recommended the tasks and intervals in the Template made the recommendations as being moderately conservative choices which could be applied by a utility with little operating experience, or with limited corporate memory of its failure history. The purpose of this step is to permit you to be guided by the recommendation, but to apply insight related to the conditions and history at your plant. The most important factors to be considered are your history of component failures and reports of component condition.

3.4 Interval Evaluation Process

This section explains how to obtain answers to the questions.

3.4.1 A. Is this a Critical, Minor, or Run-To-Failure component?

The answer to this question will already be known if the PM Task Evaluation process has been completed. A further aid to assigning criticality is to use the Criticality Checklist which can be found for any component type by pressing the PM Assessment button on the **Source** form and pressing the Determine Criticality button. Note that there is a second page to this checklist which addresses programmatic aspects of criticality assignments.

3.4.2 B. Which intervals are recommended by the EPRI PM Basis Database?

The set of intervals recommended by the Database can be seen most easily in the **Template** form which shows the range of tasks and intervals recommended for eight combinations of Critical, Minor, High and Low Duty Cycle, and Severe and Mild Service Conditions.

Select the column which corresponds to the Critical (C), Minor (M), High Duty Cycle (H), Low Duty Cycle (L), Severe Service Condition (S), or Mild Service Condition (M). Check the definitions of these terms in the *Definitions: Criticality, Duty Cycle, Service Condition* field of the **Definitions** Form to select the combination which applies to the component in question. A quicker way to see these definitions is to click anywhere on the header of the Template. To be sure that you are seeking an interval for the appropriate task name in the Template, check the task scope, outlined in the *Task Contents* field of the **PM Basis** Form. A quicker way to see this information is to click anywhere on the task row in the **Template** form, or to click on the *EPRI Task* field in the **PM Assessment** or **Plant PM Program** forms.

Be aware that the recommended intervals are moderately conservative and could be significantly modified after careful consideration of the CM and PM history of the components.

3.4.3 C. Is there a technical reason why the interval is longer or shorter than the EPRI PM Basis Database recommendation?

The task interval appropriate for your plant may differ from the database recommendation. It might be shorter if you have experienced one or more failures, or poor equipment condition during previous PM task intervals. It might already be longer if past as-found equipment condition was invariably good at previous task intervals, and if you experienced no failures.

If the current interval is shorter than the EPRI recommendation, check that there is no technical reason in the history of the equipment that is responsible, e.g. failures or adverse equipment condition or trend. If there is no technical justification for limiting the current interval, proceed at once to increase the interval to the EPRI recommended value, even if the change is greater than 25%. The EPRI value will then be the value used until further as-found evidence justifies changing it. If there is a valid technical reason to restrict the interval you should retain the current interval.

Remember that time-directed PM tasks can not provide a valid and effective defense against truly random failure mechanisms, i.e. those for which you do not expect any kind of failure free period - they can happen any time, even to a new component. Therefore, if a time-directed task interval is shorter than the EPRI recommendation due to past failures, or poor equipment condition, or adverse trend in condition, be sure that the task is indeed applicable to the relevant failure mechanism. You can check this by scrolling down the *Task and Program Effectiveness* column after clicking the Task Effectiveness button on the **Baseline Statistics** or **Custom Statistics** forms. Entries containing an upper case H or M before the slash (as in H/ or hM/ or M/) show the failure mechanisms which are addressed by the task with high or medium overall effectiveness.

If an upper case L appears it means that the task is not very effective against that mechanism. If the L is *not* preceded by a lower case h or m it means the task is intrinsically of low effectiveness for that mechanism, even if the task is performed at the right time. If the L is preceded by a lower case h or m, the task could in principle be effective (h or m), but is actually of low effectiveness because it is not being performed often enough.

You will usually find many entries containing an “R” in the *Time Code* column, which indicates randomly occurring mechanisms. In these cases, if the effectiveness entry is hL or mL it means that although the task can detect these degradations if performed when they happen to occur, you should not expect to optimize this particular task interval on the basis of these degraded conditions unless the task is capable of being performed more frequently than annually. Nor should you permit the occasional failure from these random failure mechanisms to influence the choice of the task interval if it is a time-directed task with an interval much longer than 1 year. The longer interval will be determined by longer term wearout mechanisms, not by the short term random mechanisms. Instead, select condition monitoring type tasks to form the main defense against random failure mechanisms.

If the current interval is equal to or longer than the EPRI interval, check that there is no valid technical reason in the history of the equipment to prevent a further increase in interval from being considered, e.g.

previous failures or adverse as-found equipment condition, or adverse trend in condition, which may have caused it to be reduced to the current value. Absent such evidence, proceed to the next step (D).

3.4.4 D. Should the current interval be extended or reduced?

3.4.4.1 Decrease The Interval:

The prime indicator of a need to decrease the interval is poor component condition. You should decrease the interval if the component condition has deteriorated to the point where you have little confidence that, even after it has been restored, it will remain unfailed through the following unchanged interval. Sometimes an adverse trend in equipment condition can be extrapolated to show the likely condition by the end of the interval. See the As-Found Condition section of this Application Guideline (1).

If you have already experienced one or more failures, or have experienced a severely degraded condition, you need to establish the cause of failure or degradation to be sure that it is a degradation mechanism that the task in question is supposed to address, i.e. to be able to detect before failure occurs. In addition, the degradation must be of the wearout kind, for a time-directed task to have any significant chance of improving the situation. You can check which mechanisms are the wearout kind by looking for an entry containing a W or UW in the *Time Code* field after pressing the Cause Evaluation button on the **Source** Form. Be sure that the task was actually performed the last time it should have been.

Also, be aware that a certain amount of degradation is expected to occur between PM tasks. A PM task is normally performed to detect such degradation if it is present, and the task often contains restorative actions regardless of whether degradation is detected. Consider decreasing the interval if, 1) experience shows that the degradation is so advanced by the time the task is performed, that you judge there may be a significant chance of a failure in the future if the interval remains the same, or if, 2) you judge for any other reason that maintenance action should have been taken sooner.

3.4.4.2 Increase The Interval:

1. If there is convincing evidence that the equipment condition at the existing interval is invariably good enough to enable an extension of the interval by the proposed amount, usually at least by 25% but not normally more than 2 years at one time, and
2. If no relevant failures have been experienced using the existing interval. The time period over which the equipment should be free of failures should not be too long ($<1/\lambda$),) but it should be long enough to contain at least several task intervals. This number of task intervals of experience may be accumulated over a group of like components.

Note that the equipment condition requirement is necessary for a confident increase in interval, and that it requires a judgement that the condition is not merely good, but good enough to regularly last to the extended interval. There will be a more confident condition assessment if the condition of a number of similar components is observed, if the observer knows what kind of degradation to look for, and if some measured parameter can be trended. When a group of similar components is available for interval extension it is beneficial to stagger the initiation of the interval increase among components so that some components can deliver condition information at the extended interval before the others reach the extended interval.

Read the *Progression of Degradation in Time,* and *Support for the Task Interval and Relation to Other Tasks* fields of the PM Basis Form to find clues to whether the recommended interval appears to have scope for interval extension. Sometimes this is discussed explicitly in those fields, especially when there appears to be little scope for interval extension.

Residual failure rates when PM is effective (i.e. the interval is less than or equal to the shortest failure free interval), are normally low enough to give MTBF's in the region of 10 to 25 years, even when randomly occurring failure modes are factored in. Therefore, the fact that zero failures have been observed in 2 or 3 intervals, or in 10 or even more years, can not be taken by itself as a justification to increase the interval. Therefore, it is not valid to increase intervals by referring to the absence of failures over moderate periods of time, without also considering the condition of the equipment. If equipment condition information is gathered in the normal course of performing PM tasks, the quantity of timely information available on which to base interval extension decisions will greatly increased in quantity and quality. See the As-Found Condition section of this Application Guideline (1).

25% Increase

If equipment condition is satisfactory you should feel comfortable increasing the interval by about 25% without further analysis. This is because in the worst case where the original interval is optimal (i.e. the interval is already set at the shortest failure free interval of all the relevant wearout failure mechanisms), and some failure modes become unprotected by the change, the failure rate is unlikely to increase by more than 15% to 30%. This happens because the failure free period only indicates the gradual beginning of the failure time distribution, which usually extends over a long time, and because only one or a minority of failure modes will be so affected. The importance of good equipment condition at the existing interval is that it adds a significant measure of conservatism to this estimate by making it much less likely that the worst case applies.

Larger Increases (i.e. >>25%)

When increases are constrained for practical reasons to be larger than 25%, for example when 1.5 years would be changed to 3 years because access would be impossible at power, this 100% increase in interval may increase the failure rate by 125% to 250% (i.e. the new rate could be several times the old rate) in the above worst case, i.e. when you start at the optimum and failure modes become unprotected. However, this result is not only the worst case, but also supposes you do not have any prior knowledge of whether failure modes will become unprotected by the increase in interval. Observing consistently good equipment condition at the existing interval is one way to be sure you are not in the very worst condition of uncovering failure mechanisms for even modest increases in interval. Judging that the condition will remain good for the duration of a large proposed increase can be more demanding.

To add additional confidence that a large increase will not result in unacceptable failures, you should prospectively try to assure that one or more of the relevant failure modes do not lose their PM protection. The form obtained by selecting a task in the Task Effectiveness combo box on the **Baseline Statistics** or **Custom Statistics** forms will display the *Failure Locations*, and *Degradation Mechanisms* that are addressed by the task, and will show an upper or lower case H, M, L, h, m, or l in the *Task And Program Effectiveness* column. The smallest failure free period, or range of periods, after a W or a UW in the *Time Code* column will give an idea of the optimal interval with regard to that mechanism. Consider however, that not every failure mode is relevant, i.e. needs to be addressed, as the following list illustrates:

1. For minor components you only need to defend against failure causes which have occurred before at this plant, and against the most likely degraded conditions, and maybe not all of these, depending on economic factors. Find the most common degraded conditions by pressing the Most Likely Degraded Conditions button on the either of the **Statistics** forms (reached from the Vulnerability Evaluation).
2. Random failure mechanisms can not be effectively defended against by tasks with intervals longer than 1 year and should be ignored for these tasks; they should be included when considering intervals for condition monitoring tasks.

3. Even for critical components you could leave certain failure mechanisms unprotected if you believe that there is a technical reason (e.g. design, operating conditions) why they would not influence your equipment. You can look at the factors which influence the degradation by finding the *Degradation Influences* field on the **Degradation** form. Depending on the situation, some of the wearout failure mechanisms (i.e. those with a failure free interval and a W or UW time code) could nevertheless be left unprotected provided:
   - They are not among the most common failure causes (see item 1), and
   - They are not ones which have occurred before (see item 1), and
   - There is not a significant likelihood that the influences driving them will arise. This will be true of random mechanisms whenever stressors (such as heat, vibration, moisture) are not applicable.
4. Failure modes may not need to be protected by the task in question if they are adequately protected by another PM task that is performed at an appropriate interval. Check the other task columns on the **Degradation** form.

The **Vulnerability** and **Statistics** forms provide a powerful tool to analyze the strengths and weaknesses of a PM program for a specific component type. As you modify task intervals the effectiveness of the tasks for individual failure mechanisms will vary in ways which depend on the type of mechanism.

The effectiveness of your task choices can be seen using the following procedure, which will first be described *assuming the complete set of recommended tasks is performed at the recommended intervals*. These task and interval choices are referred to as the Baseline case, and the results for these choices are available as soon as you press the Vulnerability button on any of the main database forms (e.g. such as **Source** or **PM Basis**). After understanding what the results mean, you can make custom choices of tasks and intervals using the **Custom Dialog** form reached by pressing the Perform Custom Vulnerability button on the **Baseline Statistics** form.

Press the Vulnerability button, select a Template category and add applicable stressors for a severe service condition. To find out more about stressors go to Stressors. Quite a variety of results representing the effects of the recommended PM program are displayed on the **Baseline Statistics** form:

1) The colored blocks in the center of the form should be the first results to notice. Press the buttons alongside:
   a. Red failure mechanisms have poor protection from the set of tasks, or none at all.
   b. Orange failure mechanisms have no PM task which has more than medium overall effectiveness.
   c. Yellow failure mechanisms have only one PM task with a high overall effectiveness.
   d. Green failure mechanisms have at least two tasks with a high overall effectiveness.
2) Red and orange records in the baseline calculation may resist improvement, because even the recommended PM program does not protect them well.
3) If your failure experience corresponds to yellow or green rows, you are evidently not performing the high effectiveness tasks, or not performing them effectively. You should be able to improve PM defenses against such failures by modifying your PM program to be closer to the recommendations.
4) If your failure experience corresponds to yellow or green rows, and you are currently performing the high effectiveness tasks, you should suspect that task scope or implementation might be improved.
5) A high percentage of red records (>15% - compare the number shown to the total of all failure mechanisms in the gray block at the bottom) indicates that even the recommended PM program gives limited protection. Any red records which are high on the lists of Most Likely Degraded Conditions or Most Likely Failure Causes, (both reached by adjacent buttons) or which are on

your priority list mean potential trouble. A large percentage of Red and Randoms would benefit from better coverage by condition monitoring techniques.

6) Any Red mechanisms which are also wearouts might be better protected at shorter task intervals.

7) To find the impact of individual PM tasks press the Task Effectiveness button and select one of the PM tasks to show just the failure mechanisms which that task is supposed to address and how well it achieves that goal.

8) Upper case H, M, L in the *Task And Program Effectiveness* column represent high (~97%), Medium (~80%), or Low(~50%) overall effectiveness of the task in addressing the failure mechanism when the task interval is taken into account. Lower case letters show the intrinsic effectiveness of the task if it had been done at the right time. So, an entry of hL means that the task could have been very effective against that particular combination of failure location, degradation mechanism, and degradation influence, but it was downgraded to a low overall effectiveness by the Vulnerability algorithm because the task interval was too long. A single upper case letter means that no downgrading was necessary because the task interval was short enough to retain the intrinsic effectiveness.

9) Looking down the *Task And Program Effectiveness* column, a pattern of many two-letter entries means that better protection can be obtained by shortening the interval. However, this may only be cost effective for Red records, and may not be practical in many cases.

10) Before leaving the **Baseline Statistics** form look at the numerical results at the top of the form.

    a. The top number shows the factor by which the baseline PM program reduces the failure rate compared to allowing the component to run to failure (RTF). If this number is not greater than a factor of ten it shows that even the recommended PM program has trouble attenuating the causes of failure.

    b. Next are displayed the two annual failure rates calculated by the Vulnerability evaluation – the RTF rate and the rate which the baseline PMs manage to achieve. The ratio of these two numbers is the above result in (a).

    c. The Average Repair Hours Per Failure averages over many different repair times, which each depend on the subcomponent which failed.

    d. The Total Annual Repair Hours multiplies the Repair Hours Per Failure by the failure rate.

Once you are confident that you understand why the recommended program has the characteristics shown by the **Baseline Statistics** form, proceed to repeat the analysis using your own selections of tasks and intervals.

Press the Perform Custom Vulnerability button to see the **Custom Dialog** form. Select a Template Category from the Custom combo box at the top of the form and applicable stressors for a severe service condition. The recommended task intervals are drawn into the *Custom Intervals In Years* column. Edit task intervals, which must be in units of years (e.g. 1.5, but with no following Y), against each task you wish to perform. Task intervals left blank will be interpreted as “Not Done”. When you have finished selecting tasks and intervals, press the “Calculate” button.

Interpret results on the **Custom Statistics** form exactly as described above for the baseline case. There are three additional results which are quite helpful. At the top, the **Custom Statistics** form now shows the factor by which failures – i.e. the failure rate – can be expected to increase in comparison with the baseline case. So, if you find that this factor is greater than about 1.25 for a critical component, or larger, you may want to improve your selections. Changes which are less than this 25% deterioration may not be too detrimental if the number of red records is not increased significantly. You can get guidance on task selections which meet these criteria by looking at the **Task Ranking** form, reached from the **Template** form.

If a task has been deleted or task intervals increased, the second helpful feature can be seen by pressing the Reds button. The **Poorly Protected Failure Mechanisms** form (i.e. Reds) may now show some items checked to indicate that these were not poorly protected in the baseline program. The items checked correspond to the increase in the number of red records shown on the **Custom Statistics** form. This deterioration was brought about by diminishing the level of PM protection. Before concluding that the increase in red records is important look in the Most Likely Failure Causes list. If they do not show up high on the list, the fact that they are now poorly protected is probably not too important.

The third additional result is the second numerical field at the top of the form labeled "Custom PM program provides" X "of the reliability benefit (compared to RTF) that the baseline provides". This statement can be illuminated by the diagram below which shows the failure rates for the run-to-failure case, a custom case where some tasks have been deleted or have had intervals increased, and the baseline:

The reliability benefit of performing the baseline PM's in relation to the RTF case can be represented by the value

$(\lambda_{RTF} - \lambda_{Baseline}) / \lambda_{RTF}$. The corresponding benefit for the custom case will be $(\lambda_{RTF} - \lambda_{Custom}) / \lambda_{RTF}$.

The ratio

$\lambda_{RTF} / \lambda_{Baseline}$ was displayed on the **Baseline Statistics** form as described above in paragraph 10(a). The ratio $\lambda_{Custom} / \lambda_{Baseline}$ is the factor by which the custom failure rate is greater than the baseline failure rate, and is given at the top of the **Custom Statistics** form as described above.

The value (X) appearing in the second box at the top of the **Custom Statistics** form is given by:

$$X = (\lambda_{RTF} - \lambda_{Custom}) / (\lambda_{RTF} - \lambda_{Baseline})$$

Thus, if $\lambda_{RTF} = 0.8$ failures per year, $\lambda_{Baseline} = 0.1$ failures per year, and $\lambda_{Custom} = 0.3$ failures per year the custom failure rate is 3 times the baseline value, the baseline PMs reduce the RTF failure rate by a factor of 8, and the custom PMs achieve (0.8-0.3)/(0.8-0.1) = 5/7 or 71% of the reliability benefit that the baseline program achieves.

4
REFERENCES

1. *Guideline for Application of the EPRI PM Basis Database*, EPRI, Palo Alto, CA, 2000, TR112500.

2. *EPRI PM Basis Database Client/Server Version 1.0; PMDB 6.0:* EPRI, Palo Alto, CA, 2004, 1009584.

A

A Strategy To Manage PM Tasks Within A Grace Period

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Background

Practical constraints result in some PM tasks at power plants being performed later than scheduled. This is unavoidable even in good maintenance programs where the PM intervals are optimal or conservative. To limit the risk of additional failures, most plants adopt a "grace period" for performing a PM task, limited to (for example) 25% beyond the scheduled time. PM tasks delayed longer than the grace period are reported as delinquent.

Some plants schedule the tasks at intervals which are 20% shorter than the technically optimal intervals so that a grace period 25% beyond the scheduled interval still meets the intent of the optimal interval. Consequently, most PM tasks get scheduled and performed considerably sooner than their optimal intervals in order to reduce almost to zero the number that become delinquent. This trend adds to PM costs and may harm reliability by introducing unnecessary maintenance error.

The objective of this paper is to generate a reasonable strategy from a reliability perspective, which plants can adopt as policy, regarding, 1) how long the grace period should be, 2) when tasks should be performed within the grace period, 3) how to track the plant performance in meeting this goal, and 4) the degree to which the overdue date might be exceeded.

The Appendix describes a generic numerical model to assess the impact of PM task intervals on reliability. The rest of the paper uses the model results to determine if current industry practice is reasonable, and how it might be improved.

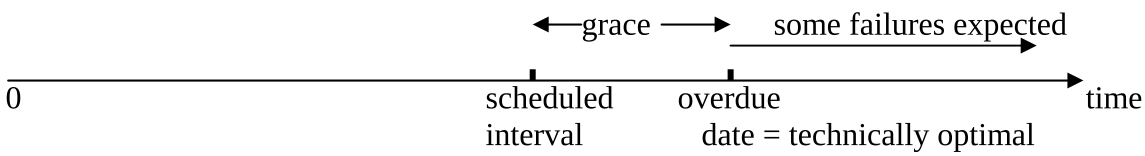
Length of Grace Period

Intrusive PM tasks performed before their technically optimal task intervals are likely to increase the failure rate because maintenance error and material defects are introduced more often. The effect (infant mortality) is commonplace for a wide range of equipment (e.g. switchgear, AOV's, check valves, relays), and is evidenced by significant levels of rework soon after a maintenance outage (Corio, Marie R. And Costantini, Lynn P., "Frequency and Severity of Forced Outages Immediately Following Planned And Maintenance Outages", Generating Availability Trends Summary Report, NERC, 1989). Therefore scheduling intrusive tasks too soon is detrimental. Nevertheless, to prevent many tasks from becoming delinquent it is a practical necessity to perform a significant proportion of all tasks before their optimal intervals.

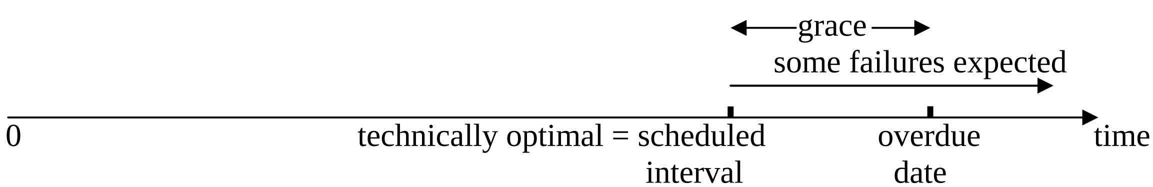
If an intrusive task is performed 20% earlier than its optimal interval, the infant mortality part of the failure rate, which is already roughly equal to the best failure rate that good PM can produce (see Appendix), will increase by a commensurate 20%, regardless of the fact that no "naturally occurring" failure modes are expected.

We distinguish two cases, in both of which the technically optimal interval is that beyond which wearout failure modes can be expected to occur.

In case A, conservatism is built into the scheduled intervals:



In case B, no conservatism is built into the scheduled intervals:



Because infant mortality erodes the benefits of good PM, in case A the degree of conservatism (and hence the grace period), should not exceed an amount which, following current industry practice, we will initially consider to be 20% of the technically optimal interval, (i.e. 25% of the scheduled interval). Less is better if it is also practical.

In case B, we also initially consider the grace period to be 25% of the scheduled interval, but in this case no infant mortality considerations arise. Instead, there is a concern that reliability may be worsened, because wearout failure modes could in principle occur during the grace period. We will assume that despite this residual concern, no wearout failure modes are actually *known* to occur with high probability within the grace period. This is a good assumption for grace periods in power plants.

Both cases are considered because they are common in the industry.

Task Performance Within The Grace Period

Case A: Within the grace period it is advantageous from a reliability perspective to perform intrusive tasks as close as possible to the end of the grace period (i.e. to the overdue date), so they are not performed too frequently. Condition monitoring tasks and other non-intrusive tasks may be performed sooner with little detrimental impact on reliability. Since some intrusive tasks must still be performed before others, it is better that these be the tasks with the longer intervals, because these will represent a smaller proportionate increase in failure rate. For example, 90 days before the overdue date is a 17% shortening for an 18 month interval, but only a 2.5% shortening for a 10 year interval.

Case B: Within the grace period it is advantageous from a reliability perspective to perform all tasks as close as possible to the start of the grace period (i.e. to the scheduled date). Since some tasks must be performed before others, it is better that these be the tasks with the longer intervals, because these will represent a smaller proportionate increase in failure rate. For example, 90 days before the overdue date is an 8.3% extension for an 18 month interval, but is a 22.5% extension for a 10 year interval.

Tracking Task Performance Within The Grace Period

In case A, performing PM tasks before their overdue date confers no reliability benefit. The sole benefit is the practical matter of avoiding too many overdue tasks. Consequently plants need track only those tasks approaching the overdue date, and only to the degree that it facilitates task implementation to avoid delinquency. For example, tracking tasks within 90 days of the overdue date could be a solution.

The number of tasks permitted to be within 90 days of their overdue date could be limited to somewhere in the range 50 to 200, depending on plant experience with getting tasks completed. There does not seem to be a useful purpose in limiting the overall number of tasks in the whole grace period, since there is no reliability penalty for being “in grace”.

In case B, performing PM tasks before their overdue date does reduce the reliability disbenefit of exceeding the scheduled date. The following section, “Exceeding The Due Date”, puts this concern into quantitative perspective, and demonstrates that performing tasks up to 25% beyond their due date does not lead to a significant reliability increase.

Tracking tasks that are within 90 days of the overdue date could be a practical solution. The number of tasks permitted to be within 90 days of their overdue date should also be limited, depending on plant experience with getting tasks completed. In this case, there is also a useful purpose in limiting the overall number of tasks in the whole grace period, since there is a reliability penalty for being “in grace”.

Exceeding the Due Date

As shown in the diagrams above, an optimal PM interval for a time-directed PM task corresponds to the onset of a non-zero probability of failure after an expected failure free interval. This probability distribution rises slowly. It will generally be many years before the chance of a failure has become a certainty. Consequently, to exceed the optimal interval does not result in immediate failures, but only an increase in failure rate. The accompanying model of failure rates, see Appendix, shows that a population of components with different task performance times in relation to their optimal intervals, can be permitted to extend past the technically optimal date to a considerable degree without causing a sudden large increase in failure rate. As a broad generalization, the increase in failure rate caused by exceeding the optimal intervals by a given percentage (<50%), is roughly similar in magnitude to that caused by infant mortality when shortening the intervals by the same percentage.

In case A, if the population of actual task performance times is centered anywhere between the scheduled intervals and the optimal task intervals (with standard deviation 12.5%), the average failure rate increases by about 6% at the most. In case B, if most of the population is positioned between the scheduled date and the overdue date but with 15% of the components in the grace period *past the overdue date*, the overall failure rate would be increased by only 20%.

Moreover, a specific component which does not get its task performed until 25% (this is 2 standard deviations if the mean is at the optimal interval) beyond the overdue date in case A, or 25% beyond the scheduled date in case B, experiences an increase in failure rate of no more than about 30%. In fact, it is the relatively slow response of failure rate to increasing interval which permits the possibility of finding the right interval by trial and error without excessive danger from overshooting.

The results indicate that it should be possible to permit a certain proportion of tasks to be performed beyond the optimal date without significant harmful effect. It is suggested that the strategy to be followed should avoid designating tasks as delinquent unless their performance times exceed some limit *beyond* the overdue date in case A. The model results show that even if 15% of the components in the grace period go past *125% of the overdue date* in case A, the overall failure rate would be increased by only 20%. In case B, a delinquent component should be one that has not received its PM task by the overdue date. Even then, if 15% of the components in the grace period become delinquent, the overall failure rate would be increased by only 20%.

Proposed Strategy

The proposed strategy would focus on completing, by the technically optimal date, (i.e. by the overdue date in case A, and by the scheduled date in case B) PM tasks which:

1. Are for risk significant components because their Fussel-Vesely (FV) parameter >0.5%.
2. Are technical specifications, surveillance tests, or code requirements.
3. Are for components in 10CFR50.65 (a)(1) (Maintenance Rule).
4. Are known to be needed to prevent a known *high* risk of failures, e.g. replacing head valves in reciprocating compressors at some plants.

<u>In case A</u>, the due date (date scheduled) would be programmed at no more than 20% less than the overdue date. The grace period would be the time between these dates. There would be no negative connotation attached to being in the grace period. The grace period exists only to focus on completing tasks by the overdue date. This case is more expensive to implement than case B, and does not contain as much conservatism as might be expected from the adoption of task intervals which are shorter than the technically optimal intervals. The negative impact on reliability of infant mortality is likely to cancel out the benefits of conservative task intervals.

<u>In case B</u>, the due date would be the technically optimal interval. The grace period would extend an additional 25% of this interval. There is a disbenefit to being in the grace period, but this is moderate and controlled by other steps. This case is less expensive to implement than case A.

In both cases, the number of tasks that are within 90 days of the overdue date could be tracked and limited to a number in the range 50 to 200, depending on plant experience. In case B only, the number of tasks that are in grace should also be limited to an overall maximum.

<u>In case A</u>, control workflow so that intrusive tasks with short intervals (e.g. 2 years or less) are preferentially completed during this 90 day window, and not before, i.e. as close as possible to the overdue date. Condition monitoring, and non-intrusive tasks could be performed earlier rather than later in the grace period to assist in work flow management.

<u>In case B</u>, control workflow so that tasks with longer intervals (e.g. 3 years or more) are preferentially completed before this 90 day window.

Screen tasks during the 90 day period before the overdue date so as to prevent tasks which are of the following type from going over the overdue date:

Tasks which:
1. Are for risk significant components because their Fussel-Vesely (FV) parameter >0.5%.
2. Are technical specifications, surveillance tests, or code requirements.
3. Are for components in 10CFR50.65 (a)(1) (Maintenance Rule).
4. Are known to be needed to prevent a *high* risk of failures, e.g. replacing head valves in reciprocating compressors at some plants.

In both cases, permit some of the other tasks normally in the grace period to go over the overdue date if necessary for practical reasons (e.g. spare parts not available), without being declared delinquent. Limit the total number of tasks to go beyond their overdue date to be no more than 15% of the total in the grace period.

Establish an upper time limit equal to the overdue date plus 25% in case A, and the overdue date plus 15% in case B, (note that this is a proportion of the scheduled interval, not an absolute number of days), beyond which any task would be declared delinquent.

KGB Model Of How Reliability Depends On PM Intervals

Basis For The KGB Approach

This treatment calculates the reliability of generic components as a function of preventive maintenance parameters. It includes the effects of PM intervals, the effectiveness of PM tasks, and both random and wearout failure mechanisms. It is applicable to either a single component with a single definite task interval, and also to a group of components, which may have different task intervals but whose actual task execution times are distributed around and shifted from the designated intervals.

The method depends on a few observations that stemmed from the EPRI PM Basis Database. A complex component (e.g. a motor or valve, etc.) has a large number of failure mechanisms, divided between wearout failure mechanisms (which have an expected period of failure free operation before failures start to be observed), and random failure mechanisms, which can occur at any time. Further, the expected failure free periods for the wearout mechanisms seem to occupy all time scales available, i.e. they range from less than one year to the design life of the equipment, say 40 years.

These failure mechanisms are actually a combination of a hardware (subcomponent) location of what fails (e.g. a switch), a physical mechanism (e.g. bent or damaged, misadjusted, worn, contaminated, or failed insulation), and of the influences that may drive these occurrences, such as maintenance error, normal use, dirty environment, heat, etc. We will use the term “mode” for each combination of circumstances. A complex component may have hundreds of such failure modes, although they can usually be grouped into about 20 major wearout modes and a similar number of random modes. The details depend on the component.

At the end of a failure free period a given wearout mode has some probability each year of producing a failure. If you waited long enough (this could be 100 years or more), and did no PM, you could be pretty certain that each mode would have produced a failure. Generally, modes with short failure free periods (e.g. 1 year) will have higher subsequent annual failure probabilities than modes with longer failure free periods (e.g. 15 years).

If you want to calculate the expected number of failures per year when no preventive maintenance is performed you would expect this failure time distribution to play a major role. Since no one normally possesses such information, such an RTF (run-to-failure) reliability prediction is not normally attempted. However, if a PM task is performed on a regular schedule, with an interval not too different from the failure free period, it is clear that a reliability calculation will depend far less on the details of the failure time distribution. This is because an effective PM task will discover emerging degradation and correct it, thus restoring the component to something approaching an as-new condition. This will take place in the early part of the failure time distribution so the bulk of its form and magnitude will scarcely be sampled in this situation.

Failure rates are also affected by whether the PM task is actually always performed, or performed on time, as well as by personnel errors which result in degradation not being recognized, repairs which are ineffective, defects and faults being introduced during the tasks, as well as by task intervals which are longer than they should be, and by modes which are not addressed by any task. Furthermore, although experienced maintenance personnel usually have a good idea of the most likely failure free periods to expect, modes can still be affected by many factors which change their failure free intervals in ways which are hard to predict.

These observations suggest that a realistic maintenance decision model could be constructed using a uniform distribution of failure free periods, and an overall effectiveness for each PM task. This effectiveness, E, would be the probability of diagnosing degradation and successfully correcting it, when such degradation exists and the task is performed. We would expect this parameter to be in the range 75% to 95%.

An individual wearout failure mode with failure free interval n years has a failure time distribution taken as uniform starting at n years and stretching out for another $2n$ years, so that normalization requires it to have an annual failure probability of $1/2n$ per year. All failure rates calculated in the model will be proportional to this probability, but the results are presented as ratios of failure rates so that the impact of this assumption is greatly reduced.

Assuming that N_w modes are active for a component, and that these have failure free periods uniformly distributed between some minimum, m years, and an upper limit of 40 years, there will be $N_w/(40\text{-}m)$ modes "starting up" each year on average.

Effective Maintenance Model - EM

Suppose a component is provided with a PM task at an interval of I years because it is known to begin experiencing failures from the shortest wearout mode at $m=I$ years. Such a component could be said to have the most effective PM possible because the task is not being done too often, but on the other hand, it is always done just in time to intercept degradation from the earliest failure mode. Even then, it is possible that the task is not done well, or is ill adapted to the failure mode. For this reason we assign a maintenance effectiveness, E to the task. This means that just after the task is performed, the degradation is still present with a probability $(1\text{-}E)$, and can continue to cause failures.

In the interval between I and $2I$, we expect to get $(1\text{-}E)/2n$ failures per year from any mode with failure free period, n, and these will endure for $(2I\text{-}n)$ years until the task is performed again. We expect this to happen every interval, so the failure rate for a single mode is thus

$$\Lambda_{e1} = (1\text{-}E)(2I\text{-}n)/2nI \qquad (1)$$

A chart of this relation against an accurate solution (using MBA software) to the underlying alternating renewal process is shown in Figure 1 for $I = 5$ years. Note that MBA gives a larger rate because it includes contributions of order $(1\text{-}E)^2$ and higher.

The chart shows that the model is only a few percent non-conservative (i.e. predicting low) for shorter modes, and becomes more so for longer modes. When this result is integrated across a spectrum of modes, the shorter ones dominate, giving a result, below, that is a reasonable representation (i.e. within a few percent) of the underlying renewal process.

Since $N_w.dn/(40\text{-}I)$ modes start up in dn years, the total contribution to the failure rate from all modes that can contribute is

$$\Lambda_e = [(1\text{-}E).\ N_w.\ /2I(40\text{-}I)]\ .\int_I^{2I} (2I - n)\ dn\ \ /n$$

$$\Lambda_e = (1\text{-}E).\ N_w.\ (2\ \ln 2 - 1) / 2(40\text{-}I) \ = \ 0.193\ (1\text{-}E).\ N_w / (40\text{-}I) \qquad (2)$$

Since I is usually much less than 40 years the dependence on task interval is weak. Equation (2) gives a failure rate of about 0.02 failures per year for effective PM with intervals up to 20 years, when $E=80\%$ and $N_w = 20$. This is close to experience.

To this must be added the random rate, which cannot be protected with time-directed PM tasks. If we assume that it is not cost effective to continue to reduce the wearout failures below the level of the remaining random component we would conclude that $\Lambda_r = B\Lambda_e$ with $B \sim 1$ or 2, so that the total effective maintenance failure rate must be close to $(1 + B)\ \Lambda_e \sim 0.04$ or 0.06 failures per year (i.e. 17 to 25 years between failures when well maintained).

Risk of Performing PM

Intrusive PM tasks run a risk of introducing additional failures. A simple treatment enables the most important conclusion to be drawn. Consider that performing an intrusive task introduces an additional failure with a probability P_{im} (subscript for infant mortality). This applies each time the task is performed so it increases the failure rate on average by $\Lambda_{im} = P_{im} / I$, where I is the task interval. The parameter P_{im} is likely to be in the range 5% to 15% for a wide range of equipment.

A value of $P_{im} = 0.1$ with a 5 year interval adds $\Lambda_{im} = 0.02$ failures /year to $(1 + B)\Lambda_e$, above; an amount that equals the effective maintenance failure rate. If the interval is unnecessarily decreased from 5 years to 4 years, Λ_{im} will increase by 20%, a significant erosion of effective PM. Other values of P_{im} and I give a similar conclusion

Run To Failure Model - RTF

When there is no PM, but failures are repaired in a time short compared to the mean time between failures, renewal theory provides an asymptotic solution for the above single mode that has a uniform time to failure distribution from n years to 3n years.

$$\Lambda_{RTF,1} = 2/(n + 3n) = 1/2n \qquad (3)$$

If this also is integrated over N_w modes:

$$\Lambda_{RTF} = [N_w / 2(40-m)]. \int_m^{40} dn \;/n$$

For $m \sim 1$ year we get

$$\Lambda_{RTF} = 0.047. N_w \qquad (4)$$

This gives ~ 1 per year for 20 modes and, with the result of equation (2), shows that effective PM reduces the failure rate by factors between 14 and 42 for E in the range 0.8 to 0.9 and B in the range 1 to 2, independent of the number of modes. This result underlines the immense value of an effective PM program.

$$\text{Failure Rate Reduction Factor By Effective PM} = 9.55 / (1-E)(1+B) \qquad (5)$$

These results are reasonable, but it is clear that we must account for the effectiveness of the task and also the level of random failures in the development which follows.

The general approach from this point is to develop a “Missed Modes Model” which will add the effect of failure modes which cause failures because the PM interval is too long. Such modes have nothing to prevent them from occurring and can greatly increase the failure rate. Armed with the Effective Maintenance and Missed Modes results we will impose a distribution of times at which the tasks actually get performed.

Missed Modes Model – MM

We envisage a single component with a set of failure modes, as before. The shortest failure free interval is at m years. The others are distributed uniformly between m and 40 years. Since the PM task interval is $I > m$, modes with $m <$ failure free interval $< I$ are “missed” by the task and so are not attenuated by the factor $(1-E)$. Modes with failure free interval $> I$ would be treated as effective maintenance in the manner shown above.

Failures will accrue in the first interval at $1/2n$ per year per mode, for a total of $(I-n)$ years. Integrating over all contributing modes gives a failure rate of:

$$\Lambda_m = [N_w. /2I(40\text{-}m)] . \int_m^I (I - n)\, dn\ /n$$

$$\Lambda_m = [N_w. /2(40\text{-}m)].[m/I - (1 + \ln(m/I)\,)\,] \qquad (6)$$

or $$\Lambda_m = [N_w. /2(40\text{-}\alpha I)].[\alpha - (1 + \ln \alpha\,)\,] \qquad \alpha = m/I$$

The modified effective maintenance contribution to be added to Λ_m is given by:

$$\Lambda_e^{'} = [(1\text{-}E).\ N_w /2I(40\text{-}m)] . \int_I^{2I} (2I - n)\, dn\ /n$$

so that $$\Lambda_m = [N_w /2(40\text{-}\alpha I)].[\alpha - (1 + \ln \alpha\,)\,] + \Lambda_e (40 - I)/(40 - \alpha I) \qquad (7)$$

We should also add the random contribution $(=B\Lambda_e)$ as before:

$$\Lambda_{Tm} = [N_w /2(40\text{-}\alpha I)].[\alpha - (1 + \ln \alpha\,)\,] + \Lambda_e [(40 - I)/(40 - \alpha I) + B] \qquad (8)$$

The ratio of this total rate to the effective maintenance and random rate is:

$$\text{Ratio} = \{[N_w /2(40\text{-}\alpha I)].[\alpha - (1+\ln\alpha)] + \Lambda_e [(40\text{–}I)/(40\text{–}\alpha I) + B]\} / \Lambda_e(1+B) \qquad (9)$$

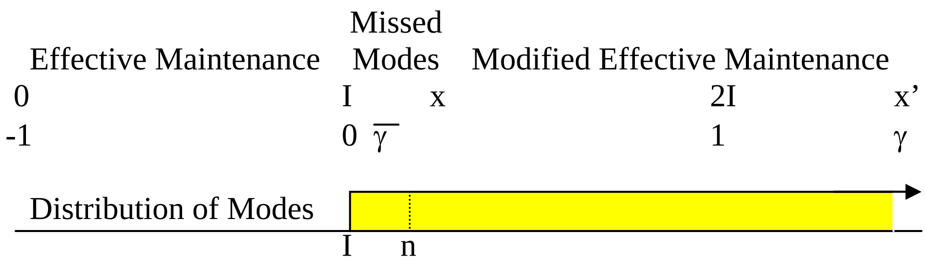
with Λ_e given by equation (2). The value of this ratio, minus 1, shows the fractional increase in the rate and is a prototype of the ratio we shall seek in the KGB population model.

KGB Model

The KGB model introduces a group of components which have individual task performance times, x_j, which do not necessarily equal their own task interval, I_j. Throughout, it will be convenient to use the dimensionless parameter $\gamma = (x_j - I_j)/I_j$ to represent the fraction by which any given task time exceeds its interval. Consequently, $\gamma = 0,1$ for all $x_j = I_j, 2I_j$, and κ is the standard deviation in the space of an assumed normal distribution of γ. There is no further need to use the subscripts j. We assume that the task interval represents the effective maintenance case, i.e. the shortest mode occurs at I. Components whose PM task is performed before this time are effectively being dealt with by effective maintenance because all modes are longer than the task time. Components whose task time is later than the designated interval possess missed modes, and so are treated with the missed mode model, plus a modified effective maintenance model for the modes which arise after the task performance.

Complications which arise include, 1) a normalization shift when the tails of the (infinite) normal distribution overlap the practical bounds of the problem at $x = 0$ and $x = 2I$, and 2) whether to correct the effective maintenance model to allow for the restricted range of modes since the shortest mode is at $I >$ task time.

Consider the following figure showing a task time of x to $(x + dx)$ for general guidance:



Missed Mode Contribution

When $x > I$ a missed mode at n provides an annual contribution of $1/2n$ failures for $(x - n)$ years. Modes with n from I to x contribute. The rate is thus:

$$\Lambda_m(x)' = [N_w / (2I.(40 - I)] . \int_I^x (x - n)\, dn \;/n$$

$$\Lambda_m(\gamma)' = [N_w / (2.(40 - I)] . [(1 + \gamma) \ln (1 + \gamma) - \gamma]$$

The average of this quantity over the N components contributing to it is:

$$\Lambda_m(\overline{\gamma}, \kappa) = [N/\phi]. \int_0^1 f(\gamma)\, \Lambda_m(\gamma)'\, d\gamma$$

where N is the number of components in the population, ϕ is a normalization adjustment, and $f(\gamma)$ is the population normal distribution. ϕ and $f(\gamma)$ are given by:

$$f(\gamma) = [1/(\kappa \sqrt{2\pi})]\exp [-(\gamma - \overline{\gamma})^2/\kappa^2]\; d\gamma$$

$$\phi = \int_{-1}^{+1} f(\gamma)\, d\gamma$$

Modified Effective Maintenance Contribution

The region to the right of x in the above diagram represents effective maintenance, but only for modes arising at times greater than x. Contributing modes each add failures for a time $(x + I - n)$ and these contributions should be integrated from x to $(x + I)$:

$$\Lambda_{e2}(x)' = [N_w .(1 - E) / (2I.(40 - I)] . \int_x^{x+I} (x + I - n)\, dn \;/n$$

$$\Lambda_{e2}(\gamma)' = [N_w .(1 - E) / (2.(40 - I)] . [(2 + \gamma) \ln \{(2 + \gamma)/(1 + \gamma)\} - 1]$$

The average of this quantity over the N components contributing to it is:

$$\Lambda_{e2}(\overline{\gamma}, \kappa) = [N/\phi].\ \int_0^{+1} f(\gamma)\,\Lambda_{e2}(\gamma)'\,d\gamma$$

Effective Maintenance Contribution

Components which have the PM task performed earlier than the shortest mode, i.e. with $x < I$, have effective PM with two qualifications. The first is that performing the task too frequently can add a significant number of failures, increasing N_w and B in a way that can not be modeled. The second is that when a mode adds failures, attenuated by the factor $(1-E)$, the modes that contribute are not the full spectrum from x to $(x + I)$, as before, because the shortest mode is at $I > x$. These two effects oppose each other. The second can be calculated but without the first, the failure rate would be artificially reduced.

Consequently, the contribution from these components has been assumed to be the normal effective maintenance rate of equation (2) times the number of components in this part of the group:

$$\Lambda_{e1}(\overline{\gamma}, \kappa) = [N\,\Lambda_e/\phi].\ \int_{-1}^{0} f(\gamma)d\gamma$$

Total Rate And Excess Ratio

The new total failure rate, $\Lambda_T(\overline{\gamma}, \kappa)$, is obtained by adding the separate rates:

$$\Lambda_T(\overline{\gamma}, \kappa) = \Lambda_{e1}(\overline{\gamma}, \kappa) + \Lambda_{e2}(\overline{\gamma}, \kappa) + \Lambda_m(\overline{\gamma}, \kappa) + BN\Lambda_e$$

These rates are all functions of N_w and N.

A fractional excess failure rate can be examined to find the percentage change in the rate compared to having all components maintained at the effective maintenance rate:

$$\text{Excess Ratio}\ (\overline{\gamma}, \kappa, B, E) = [\Lambda_T(\overline{\gamma}, \kappa) - (1 + B)N\Lambda_e] / (1 + B)N\Lambda_e$$

The Excess Ratio does not depend on N_w, nor on N, because they cancel in the ratio.

Note Added: The model is called the KGB model because it describes the effects of a population distribution whose main parameters are called K and GB (gamma bar) in the software.

Results

Figure 2 shows the percentage Excess Ratio for 4 sets of $E;B$ values as a function of standard deviation, when the population mean is in fact, equal to the designated task intervals.

When the population standard deviation is 25% of the designated intervals (25 on x axis), the worst case shown has an increase of 15% in the number of failures per year.

If the initial base case were less effective than an optimized PM program this change would be smaller. For 80% effective tasks, and a random contribution that is twice the effective maintenance rate, the population would need to spread to a standard deviation of more than 50% of the intervals in order to increase the failure rate by 15%.

Figures 3 and 4 show the general behavior of the Excess Ratio. Using these results and the fact that 16% of a normal distribution lies beyond one standard deviation, suggests the rule of thumb:

"Provided no more than 15% of PM tasks are executed beyond 125% of the optimal interval, the increase in failure rate will most likely be less than 20%."

Of course, these rules hold only as well as our assumptions about the values of E and B, a normal distribution of task execution times, and a uniform distribution of failure free periods for wearout failure modes. However, these were reasonable assumptions for generic PM programs and generic components. Furthermore, the baseline PM program was assumed to be well optimized to give the most sensitivity to the distribution of task times.

For PM programs which are not so well optimized, e.g. where task intervals already have a conservatism built into them, or where PM tasks are less effectively performed, where the random background of failures is higher, or where the infant mortality effects of decreased intervals is present, the effects of delayed PM tasks will be smaller than estimated above.

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