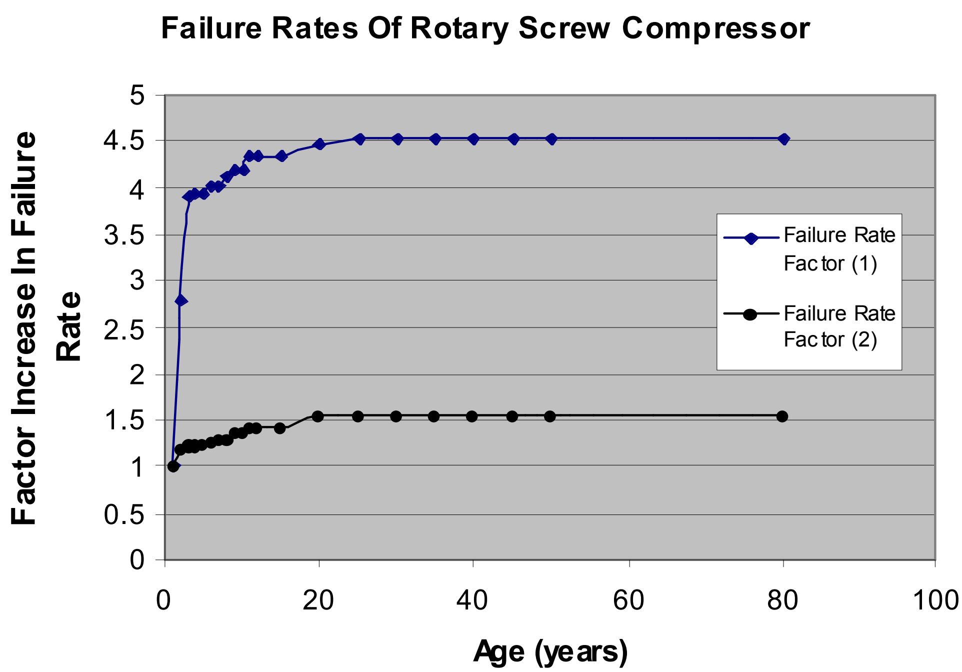
Guide for Predicting Long-Term Reliability of Nuclear Power Plant Systems, Structures and Components

Technical Report



Guide for Predicting Long-Term Reliability of Nuclear Power Plant Systems, Structures and Components

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REPORT SUMMARY

This report provides guidelines for predicting long-term reliability of nuclear power plant systems, structures, and components. The methods described will allow life cycle management planners to make improved estimates of lost generation and revenues, which play an important role in the choice of the economically optimum long-term maintenance plan for systems and components.

Background
As U.S. nuclear plants age, but continue to be valuable generation assets in a competitive industry, increased attention is being paid to improved safe and efficient operation. Developing the capability to quantify the probability of key component failure is becoming increasingly important. For passive and active systems, structures, and components (SSCs) important to safety and generation, this is difficult because of the lack of long-term experience data on component failures. EPRI has developed a Life Cycle Management (LCM) process for identifying the most effective and economical way to manage aging and obsolescence of important SSCs. Applications of the process have shown that, along with the price of electricity, estimates of long-term failure rates are the most uncertain inputs to LCM evaluations. These rates have significant effects on life cycle costs for corrective maintenance, replacement, and loss of generation due to component failures and on selecting optimum long-term maintenance plans.

Objective
To provide plant engineers with improved methods and guidance for predicting long-term failure rates for input to SSC life cycle management evaluations.

Approach
Researchers addressed both active and passive components and considered the effects of environment, aging, random failures, and maintenance on long-term failure rates. For active components, they used a “maintenance modeling” approach in which future failure rates are obtained by applying a calculated factor to the historical failure rate. For passive components, they used a “physical model” approach in which failure is predicted when physical parameters in an analytical model of aging degradation versus time reach threshold values. The model can be either single valued or stochastic.

Results

The report reviews generic industry databases and data types generally available (and unavailable). It also describes statistical methods for interpreting failure rate data. Long-term failure rate prediction methods are illustrated by example applications to compressors (active component) and buried service water piping (passive component) in the Wolf Creek nuclear power plant. The resulting methods are intended to help LCM planners improve the credibility and reduce the uncertainty of long-term SSC failure predictions.

EPRI Perspective

This project extends the technology in the EPRI LCM process [EPRI report 1000806], several plant-specific LCM plans [1003059, 1003060], and LCM sourcebooks of industry experience and data [1003058, 1006609, 1006616]. It improves LCM planners' ability to estimate future failure rates, which are so crucial for credible economic evaluations of long-term maintenance alternatives. It also is an important step in developing the industry's ability to apply risk-informed methods for managing aging and assets. The result of these improved methods in operating plants will be more effective LCM planning for optimizing equipment reliability and maximizing plant value while maintaining acceptable levels of safety.

Keywords

Life cycle management
Nuclear asset management
Component reliability
Aging

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1 INTRODUCTION

As U.S. nuclear plants age, and at the same time continue to be valuable generation assets, increased industry attention is being paid to improved methods of safe, efficient operation of these plants. EPRI has sponsored a process and extensive set of tools for identifying the most effective and economical way to manage the aging and obsolescence of important systems, structures and components (SSCs) known as Life Cycle Management (LCM). As documented in Reference [1], LCM integrates nuclear power plant engineering, operations, maintenance, regulatory, environmental and economic planning to 1) manage plant condition (including aging and obsolescence), 2) optimize operating life (including the options of early retirement and license renewal), and 3) maximize plant value while maintaining safety. References [1] through [4] represent a sample of the exhaustive EPRI literature on this topic.

A key element of LCM planning is the ability to quantitatively predict failure rates (or reliability) versus time of important SSCs under various operation and maintenance scenarios. Although this is a crucial need, it is the one aspect of LCM for which relatively little guidance exists at this time. Existing EPRI documents provide comprehensive checklists of the relevant aging mechanisms, stressors and influencing factors governing the aging of specific SSCs [1, 2, 3]. Other industry sources are also available on this topic, for example [5]. However, quantitative estimation of future failure rates remains one of the largest and most uncertain drivers in determining an optimum LCM plan alternative for a particular SSC. The other dominant driver is the price of power. The uncertainty band for predicting failure rates continues to grow as the prediction range approaches the end of the planned plant operating term. Long-term predictions are needed for this because plant valuation integrates cash flow over the entire remaining operating term.

This guide provides direction to LCM personnel who seek answers to the following three questions, when applied to a specific SSC:

1. With the current maintenance practices for the SSC, what will be the future failure rate?

2. If reliability is likely to deteriorate over time, what preventive and mitigative actions can be taken?

3. If these actions are taken, what will be the effect on the future failure rate?

The first step in answering these questions is to understand the current plant-specific failure rate and operating and maintenance history. For example, if the plant-specific failure rate, failure experience (e.g. maintenance rule performance against performance criteria), or other experience of equipment condition for a given SSC differs markedly from that experienced by like SSCs in the industry, it would seem prudent to understand the cause of the difference before attempting to foretell the future. If the difference turns out to be a deficiency in design or in preventive maintenance, that knowledge alone may point to beneficial actions that could be taken. Unfortunately, our ability directly to compare failure rates at different plants, and over time, is limited by factors explained in Section 4.

To supplement incomplete evidence from the comparison of failure rates, and indeed to make informed use of failure rate information, one needs to consider the operating conditions and maintenance history. In particular it will be necessary to know what the preventive maintenance program actually is, and has been, and if there are evident weaknesses in it. This will be one of the main differences between active and passive components, as the latter are often regarded as 'intrinsically reliable' components, which generally do not require preventive maintenance.

To project the failure rate behavior forward in time, it will be necessary to know whether there exist long-term failure mechanisms that are likely to produce future failures which have not yet been experienced at this plant, but which are known to occur in the industry. The capability of the current PM program to detect these degraded conditions in order to avert failures must be critically evaluated. Physical modeling and analysis of the PM program can assist in projecting failure rates forward in time, to complement any time-dependent failure-rate data that might be available. Methods that can be used to do this are a major focus of this guide.

Perceived weaknesses in the PM program, if there is a PM program, will suggest cost-effective improvements that might be made. Their effect on reducing the future failure rate may be examined using the same tools discussed above.

Plant-specific and generic data on failure rates have significant limitations and uncertainties, and so do the new tools to be described in the following sections. In practice, all sources of information need to be used to the fullest degree to make the best judgments about future reliability performance.

2
RELIABILITY PREDICTION NEEDS FOR LIFE CYCLE MANAGEMENT PROGRAMS

Some comments about estimating future failure rates have been published in Section 2.6 of the LCM Sourcebook Overview Report [1]. That reference lists some technical considerations, which are important in reliability data estimation, but does not give guidance on their relative importance or what to do about them. The following paragraphs illustrate the main features of common types of reliability information, and point to the appropriate, practical steps, which can be taken to use such information for LCM applications. Further information on the specific techniques is provided later in this guide.

2.1 Practical Context of Reliability Prediction

Reliability information includes descriptive data that describe the ways in which equipment can fail. Examples are: 1) failure mode, e.g. failed open, 2) failure location, e.g. valve stem, 3) degradation mechanism before the failure point is reached, e.g. binding, 4) the stressors which drive the mechanisms, e.g. vibration or temperature fluctuations, and 5) whether the event is an example of wearout in which failure is not experienced until at least a minimum time has passed, or is random in the sense that it can occur with equal likelihood at any time, even soon after the component is replaced or refurbished.

Reliability information also includes quantitative information which summarizes a group of failures, such as 1) the failure rate, or the probability of failure-on-demand, 2) the minimum life, i.e. the age at which the first wearout failures occur, 3) the characteristic life, i.e. the age at which 63% of the wearout failures have occurred, 4) the age at each failure, i.e. the failure times, and 5) the fraction of failures which have specific failure modes or causes. It is well to keep in mind that the failure rate and probability of failure-on-demand are no more than descriptions and measures of an aggregate of phenomena that defy more exact analysis. This description may be more or less adequate, but we should not approach this topic believing that there is a 'true' value of the failure rate in any particular case.

2.1.1 Qualitative Data

In general, it is not necessary to be very prescriptive concerning the definitions of the qualitative information so long as the reader can understand the events that have occurred. However, the following element of terminology may possibly cause some confusion unless the analyst is aware of the traditional and customary usage in related technical areas. Safety analysts view the term 'failure mode' as what the equipment *does* upon failure, such as 'fails closed', or 'fails open' (the Nuclear Power Plant Common Aging Terminology report [4] also adopts this usage), whereas in the maintenance world personnel commonly use failure mode to mean the cause-oriented description of the event, such as ‘binding of the valve stem from heat and corrosion’. The maintenance worker’s ‘failure mode’ is close to the safety analyst’s ‘failure cause’. Each tradition must be respected in order to communicate effectively with the two groups. However, this guide will use the term ‘failure mechanism’ to indicate jointly the failure location, degradation mechanism, and stressors, even though this represents a widening of the meaning of that term as defined in the Nuclear Power Plant Common Aging Terminology.

Complex, active equipment, such as a large pump will have a hundred or more failure mechanisms of the above type. Examples are provided for major equipment types in Appendix C. The more failure mechanisms that are not protected by PM tasks, the higher the failure rate will be. Indeed, there are a few types of active equipment that have a surprisingly large fraction of failure mechanisms (possibly as much as half the total) against which the PM tasks provide inadequate or very limited protection, even when good quality PM programs are applied.

The qualitative information can be used for the method of Maintenance Modeling (Section 5) in which the impact of preventive maintenance (PM) on failure rate is determined by accounting for new PM activities that provide protection against specific individual failure mechanisms. It can also provide a basis for extrapolating current failure rates to future times at which new specific failure mechanisms emerge, with or without changes to the PM program. In both cases one estimates the change in the failure rate, so the current failure rate is also needed to provide an absolute future value.

2.1.2 Quantitative Data

The failure rate in time and the probability of failure-on-demand are the most common of the quantitative parameters. The former supposes that the occurrence of failures can be related to the passage of time, i.e. time is the metric which ‘generates’ failures. The probability of failure-on-demand supposes that the occurrence of failures can be related to experiencing a number of tests or demands to perform a function – the number of demands is then the metric and time is irrelevant. In general, the methods in this report apply to both types of process, although the details often differ. When there is no danger of confusion, both terms will be represented simply by ‘failure rate’ in the rest of this report. Whenever the differences are important, the two processes are given separate treatments.

It is important to note that both the failure rate in time and the probability of failure-on-demand are alternative, imperfect, approaches to modeling the real world. It is perhaps obvious that the failure rate in time may be a function of age because time appears explicitly in the formalism. It is not so obvious that the probability of failure-on-demand can also be a function of age. This is because time is essentially a hidden variable for this parameter, not explicitly acknowledged by the model, but playing a role nonetheless.

The failure rate is typically represented as being constant in time. However, it is a strong function of service conditions, as well as preventive maintenance, and may also depend on duty cycle. Thus, failure rates can be stated specifically for high or low duty cycle equipment, and for severe or mild service conditions. The most likely of these factors to change over time is PM, often in response to the emergence of new failure mechanisms, but also in efforts to improve reliability, or to reduce costs. When new failure mechanisms are discovered, PM changes are often made to attenuate failures from the new causes. The initial increase in failure rate caused by the newly discovered failure mechanisms may not be measurable in the short term with any precision, and the failure rate over longer times often remains approximately constant because of the effectiveness of the new PM activities. If new PM activities were not brought to bear on the problem, the failure rate would increase over time.

Less often, PM is inadequate to attenuate the effects of new failure mechanisms. The impact of just one or two new mechanisms on the failure rate can then be considerable unless design changes can be introduced. The history of nuclear power equipment reliability generally shows that PM and design changes have compensated for the emergence of new failure mechanisms, so that reliability has generally improved, or at least held constant over time.

The maintenance influence can be represented in an indirect way by stating the importance of the equipment function. Equipment whose failure leads to extremely serious consequences, such as a personnel hazard, a plant trip, or loss of a safety function, is designated usually as “critical” equipment. Currently, in most nuclear plants this equipment will have a fairly comprehensive preventive maintenance (PM) program. Equipment that has significantly less functional significance is often designated as “non-critical” and therefore has a more superficial PM program. Equipment that has little or no functional significance will have no PM tasks and is designated as Run-To-Failure. The same piece of active equipment with the same duty cycle and service conditions is likely to have very different failure rates depending on its level of PM.

Passive components generally receive less PM than active components, but this is because their failure rates are usually sufficiently low even with little or no PM; they are “intrinsically reliable”. This is typically because there are far fewer failure mechanisms for passive rather than active components (perhaps ten, rather than hundreds). However, passive equipment that does receive PM may also differ significantly in failure rate depending on the PM performed. The use of cathodic protection and cleaning for heat exchangers is a good example. Therefore, some passive components will be amenable to the maintenance modeling approach for extrapolation of failure rates into the future, but will also lend themselves to Physical Modeling (Section 6) of new failure mechanisms, especially if these involve changes in material properties, or physical/chemical processes such as fatigue and corrosion.

If the PM program is made more comprehensive to account for higher duty cycle and more severe service conditions, the effects of these conditions on the failure rate can be minimized, at least for active components. Compensation by Such adjustments of the PM program in response to duty cycle and service conditions are usually applied for critical equipment, but are not applied to the same degree at most plants for non-critical equipment. Failure rates for critical equipment are therefore likely to exhibit smaller variations with duty cycle and service conditions than for non-critical equipment. Because this guide is focused specifically on critical equipment, the dominant influences on failure rates in the future for these components will be the emergence of new failure mechanisms, and the degree to which existing or new PM activities can protect against them.

Active, critical equipment subject to refurbishment, overhaul, or replacement therefore may not need an aging assessment because it will not reach the age at which new, long term failure mechanisms occur. Note, however, that much non-critical equipment of the same type may not have these tasks performed on it, even if replacements and overhauls are scheduled for the same equipment in critical applications. Even critical components may have had important PM tasks eliminated (in error) too recently for the negative effects on reliability to have become apparent.

If there are passive portions of active equipment that are not subject to refurbishments or replacements, these (e.g. valve bodies) are candidates for aging assessment. Equipment therefore needs to be scoped initially for the presence of such PM tasks, and also to determine the kind of reliability information that might be available. See Categorizing Equipment (Section 2.2)

Finally, despite the underlying the need for this guide in helping to discriminate between alternative courses of action, the actual value of the future failure rate itself may not always be an important quantity for Life Cycle Management. For example, in situations where it is known that equipment will certainly degrade at some time in the future by a mechanism which can not be well controlled by preventive maintenance, it may be more important to know when this might happen, than to estimate the resulting failure rate, because the equipment will need to be replaced before that time.

2.1.3 Sources of Data

Descriptive information on failure mechanisms that might appear at an advanced age can be sought from experienced maintenance personnel at older plants. Such subject matter experts can quickly provide detailed and relevant information when asked the right questions, (Section 5.3). Most nuclear plants will be able to gain access to the right kind of personnel at older fossil power plants in their utility's system with little effort or cost of manpower.

The adoption of as-found condition reporting schemes by plants that are currently trying to improve equipment reliability is a very positive development from the point of view of LCM. The ability to report an unusual degraded condition, well ahead of the time that failures occur, will improve the capability to be pro-active in maintenance and to avoid failures. However, as-found condition reporting is in its infancy, and presumes that PM tasks are performed to provide an opportunity to make such observations. The value of this approach will be decidedly less for passive components, which receive little PM attention.

The Maintenance Rule (10CFR50.65) and Probabilistic Safety Analysis (PSA) both provide opportunities to obtain reliability data. The value of the Maintenance Rule is that it provides a fairly uniform process for putting the spotlight on repetitive failures from the same cause, increases the knowledge and use of industry operating experience, and promotes finding early solutions to new failure mechanisms on an industry-wide basis. The focus on preventing repetitive failures is especially important to achieving the goals of preventive maintenance and to keeping failure rates constant over the long term. Although the Maintenance Rule will provide information to assist in quantifying failure rates (see below), the Maintenance Rule program itself has no direct capability to supply quantitative failure rates, because it mostly monitors small numbers of like components over short periods of time (~2 years). Maintenance Rule programs therefore do not normally calculate or trend failure rates.

Many plants have performed some kind of preventive maintenance optimization for active components, whether using Reliability Centered Maintenance (RCM), or a different approach. A large optimization project usually creates a database containing lists of components in each system, labeling the components that are critical, listing the PM tasks that are performed, and possibly providing a summary of significant corrective maintenance history. This information can contribute to understanding the PM program for the component, and how it evolved over time in response to plant events. However, the information is of the descriptive kind, and does not lead to a quantification of failure rates.

On the other hand, PSA is a practical source of failure rates for many active components that can be found in standby safety systems. Most plants improve their failure rate quantification by incorporating plant-specific information into the PSA every few years. Consequently, PSA personnel are usually the best source of knowledge at a plant on the status of plant-specific failure rates and of expertise in the methods used to update them. The Maintenance Rule has improved the recognition and timely reporting of functional failures, which should improve the quality of data included in plant-specific updates for PSAs, and will help to speed the process of performing the updates. Almost all critical components, both active and passive, are included in the Maintenance Rule failure reporting process.

Industry databases such as NPRDS, EPIX, NERC/GADS, IEEE 500, MIL HDBK 217E, NPRD2, and foreign databases such as OREDA, ERDS, ATV, and SAPHIR vary considerably in scope (Available Databases and Tools, Section 3), but all exhibit the general features of reliability data discussed above.

Given these characteristics, the most likely needs for LCM applications are, 1) to pool generic data from multiple sources, 2) to update generic data with plant-specific data, and 3) to characterize the time-dependent failure rate due to new emerging failure mechanisms, i.e. to extrapolate failure rates beyond current nuclear power experience, especially as a function of existing and new PM activities. For items (1) and (2) see Methods for the Use of Failure Rate Information, Section 4. For item (3) see Maintenance Modeling When Failure Rates Are Unavailable, Section 5. In addition to this guide, a useful modern overview of reliability theory, data analysis, available databases, and applications to safety and maintenance analysis in the nuclear industry can be found in Reference [6].

2.1.4 Improving Failure Rate Estimates Using Additional Data

Section 4 and Appendix A describe a number of techniques used to analyze and manipulate failure rate data. Several of these techniques are used to improve a given sample of data when additional data becomes available. If both samples of data are available in the form of raw information on the number of failures experienced in a certain time, or in a given number of demands, then the numbers of failures etc., can obviously be simply added together to create new estimates of the failure rate. What usually happens however is that the existing knowledge of the failure rate is in the form of a statistical distribution over a range of possible values of the failure rate, and the original numbers of failures and other raw data are not available. The new raw data (i.e. in terms of the number of failures experienced in a certain time, or in a given number of demands) then has to be combined with the previous (i.e. ‘prior’), failure rate distribution.

The most common application of these techniques is to improve generic data on the failure rate (obtained from nuclear industry sources, or from outside the nuclear power industry), with a local sample of recent failures more specifically representing the SSC in question. The need to do this is fairly evident: the generic data probably contains more statistical evidence, but its applicability to your SSC may be questionable. The local data is especially relevant, but it is unlikely to contain enough failures to be statistically meaningful by itself. Hence the need to combine the two sources. This process is accomplished by the Bayesian Updating procedure.

Because the plant specific data (i.e. the 'local' data or the 'new' data) is limited statistically, it is often not possible to know if it represents a run of good luck or bad luck, or the emergence of a potential problem, and whether the reliability it suggests will turn out to be applicable over the long term. The Bayesian Updating procedure automatically takes care of the 'strength' of the influence of the new data over the prior generic data, depending on the displacement of the medians between the two samples, and especially on the variance of the samples. Of course, the procedure can also be applied to improve any sample of data with the addition of any other data, as might be done when updating earlier estimates of the plant-specific failure rate with new plant-specific information.

This process is discussed further in Section 4 and in Appendix C. It is sufficient to know at this point that the combination can be carried out rather easily in many cases, and that the result is usually interpreted as the best way to characterize the failure rate of an SSC.

2.2 Identifying Important SSC Components and Subcomponents

The Introduction briefly stated that quantifying future failure rates would require the answers to the following questions:

1. With the current maintenance practices for the SSC, what will be the future failure rate?

2. If reliability is likely to deteriorate over time, what preventive and mitigative actions can be taken?

3. If these actions are taken, what will be the effect on the future failure rate?

The approach to answer these questions is formalized in the five steps below, and referenced to sections of this guide. The general approach is:

1. Screen the list of components associated with the SSC to establish which ones are likely to need failure rate prediction for future times.

2. For each component type requiring failure rate prediction, obtain the service conditions, duty cycle, and recent failure experience, and list the PM tasks and intervals. This needs to be done whether the equipment is active or passive.

3. Obtain the best possible failure rate information using Flowcharts A and B in Section 4.

4. For active equipment assess the effectiveness of the PM program and project the failure rate forward in time using the procedures of Section 5.

5. For passive equipment determine applicable failure mechanisms, develop the physical models described in Section 6, and use them to project the failure rate forward in time.

This approach to address the overall task of predicting future failure rates does not need to be implemented for every SSC; some screening can reduce the amount of work. The screening step, Step 1 above, accomplishes several objectives. First, it ensures that you know the boundary of each component type; second, it ensures you also consider auxiliary components that are not treated within the main component boundaries; third, it removes components that do not need LCM evaluation.

The screening step 1 and the compilation of current plant PM information and maintenance history of Step 2 are intended to be complementary to the screening described in the LCM process flowchart in reference [1]. The flowchart of reference [1] should be used to place these activities in the context of the overall LCM process.

To assist in performing Step 1, Table C-1 in Appendix C shows a list of approximately 70 major component types, and indicates the components that are normally included within the main component boundary and other associated components that should be considered, if present. They have been ordered so that passive components appear first, followed by active components. Within each category, the components that are **not** usually replaced on a periodic basis, nor receive any kind of refurbishment, nor thorough overhaul, appear first, followed by components that **are** likely to be replaced or refurbished on a periodic basis.

For any given component type, the fact that the component type usually is subject to periodic replacement or refurbishment (for critical function applications) does not mean that it does so in your case. Even if your PM program shows such a PM task in principle, it is important to discover from maintenance records, whether the task has actually been performed or not, if the equipment is old enough to have required it.

Most, if not all, smaller commodity type components as well as much larger equipment will be removed from consideration by the process of considering replacements and refurbishments. Examples are Electric Motors, Pumps, all I&C components, Control Relays, Terry Turbines, Main Turbine EHC Hydraulics, Switchgear, etc. In each case you should be careful to distinguish true refurbishments from more limited type overhaul tasks which will probably not result in the equipment being returned to an as new condition. An example of the latter type overhauls, are the approximately annual overhauls performed on reciprocating and rotary screw compressors. These distinctions have been made in Table C-1, in the interest of taking a conservative position on screening. However, component types that appear to have overhauls which may not be comprehensive, have been given a “No” response to this question, but have been left in position among the “Yes” responses so they are easy to identify.

The nature of the overhauls and refurbishments applied to any component type can always be found in the PM Basis Database [7] by looking in the PM Basis form at the Task Content field. Other data-fields on the PM Basis form also provide clues to what should actually be accomplished in the task. Despite this ready source of information, you should discover whether the overhauls as implemented in your plant correspond in scope to those described in the database.

The final screening activity is to identify passive components. When active equipment includes a significant passive component, such as valve bodies, pump casings, or heat exchangers the equipment in the EPRI PM Basis database is classed as active, and long term degradation mechanisms are included for the passive components. These are worth special scrutiny as described in Section 5; any additional long term degradation mechanisms that can be identified should be added to the database.

2.3 Applicable Degradation Mechanisms and Stressors

Appendix C contains four tables, mostly derived from the EPRI PM Basis Database

Table C-1 shows a list of approximately 70 major component types, and other data useful in the screening process.

Table C-2 shows typical degradation mechanisms for Reciprocating Compressors and Large Stationery Lead-Acid Batteries, to provide initial orientation on the wide range of possible degradation mechanisms.

Table C-3 shows typical degradation influences, or stressors, again for Reciprocating Compressors and Large Stationery Lead-Acid Batteries, to provide initial orientation on the wide range of possible stressors.

Table C-4 shows the combinations of failure locations, degradation mechanisms, and stressors, which represent long-term failure mechanisms on a variety of component types.

Note that no random failure mechanisms are included in Table C-4 because these have no particular relevance to long term planning, being just as likely to occur at any time, and contributing to a constant failure rate. Note also that no failure mechanisms are included that have initiating time scales up to 10 years, because it is expected that these will be adequately addressed by existing PM activities, or will be evident in the existing failure history, and be accounted for in the current failure rate. Section 5 discusses how the information in Table C-4 is used, and how to add new degradation mechanisms to the list.

Table C-4 data can be found in the EPRI PM Basis Database for all the other component types in the database by going to the Vulnerability form, then to the Degradation form, and by inspecting the Time Codes in the Time Code Column. This task is made easier by placing data filters on combinations such as *W*10* to isolate all wear-out mechanisms with time scales 10 years and longer, and repeating the filter for other obvious choices which can be seen in the list, e.g. *W*15*, and *W*40*. This is a good way to examine the failure causes that might exert an effect on the failure rate at long times.

3
AVAILABLE DATABASES AND TOOLS

Databases which may provide failure rate information are described below. Under each database title is a brief description of what it covers, its age, how to access it, and its apparent usefulness for providing data that can be used for addressing life cycle management needs regarding failure rates.

3.1 Existing Equipment Databases

3.1.1 EPIX (Equipment Performance Information Experience)

Equipment Performance Information Experience, EPIX, is the current name for the former Nuclear Plant Reliability Data System (NPRDS). It is supported and available to INPO members through the INPO website. EPIX is a collection of engineering, operational, and failure data on systems and components installed in US plants. It appears to have begun data collection in the early 1980's. Besides the failure event data it also has reports describing the root cause analysis of the failure. This kind of detail in a database is very useful in understanding what is behind the failure statistics. There have been some observations on performing searches that results appeared on only a few plants for failure events. There is a concern whether sufficient input on failure events is being provided by the broad utility membership.

The former NPRDS database contained at least 25,000 failure reports from 86 nuclear power reactors covering a wide range of components from 30 systems. Despite many shortcomings related to the quality and consistency of the data, this database was for more than 15 years, the primary source of reliability data for US nuclear plant components. It is not possible to extract meaningful time dependent information from this data.

The NPRDS system provided the service of notifying a plant when the failure rate for some component type became an outlier with respect to its peer plants or the industry in general. The NPRDS system issued CFAR reports summarizing failure rates, and pointing out the comparisons. It is expected that EPIX will resume an equivalent service at some point. However, benchmarking among peers is a valuable learning experience however it is performed.

It is possible to use the EPIX/NPRDS system to gain a gross picture of the effectiveness of a PM task on occasions when the NRC issues a new regulation that requires the industry to begin performing a specific PM activity, which a large part of the industry had previously not been performing. There are not many opportunities to observe this phenomenon, but it has been reported (Ref 37) that the annual number of switchgear failures, reported to NPRDS over a 12 year period, was reduced by about a factor of about 4 after the NRC started to require all plants to do overhauls. Since the population of breakers has remained fairly constant in the industry over the last two decades, a change of this kind, if it is not related to changes in reporting requirements, can serve as a gross indicator of the degree to which a PM task can affect failures.

A factor of this size is somewhat larger than, but broadly consistent with, estimates of the impact of major PM tasks made using the PM Basis Database. Indeed, if PM tasks did not have this kind of effect on reliability, there would be no justification for the large preventive maintenance costs incurred in many industries. Other examples might be provided by the introduction of MOVATS testing for MOVs, and erosion/corrosion programs for piping systems.

3.1.2 NERC-GADS (North American Electric Reliability Council-Generating Availability Data System)

The NERC-GADS database started in 1976 and went into computer form in 1982. It collects forced outage and forced derate event data on not only nuclear but also fossil, hydro and gas turbines power plants. The data are collected relative to the components that caused the forced outage or forced derate. The data for 1982 through 2000 covers forced outages on 143 nuclear plants across 58 power companies and contains over 40,158 forced outage and forced derate events associated with these plants. The components are not restricted to just the primary loop or safety systems but the entire plant through the service water. The nuclear plant related cause codes and their associated components are shown in Appendix B. A drawback of this database is that only the component that caused the forced outage is known and no other information is provided. Also, the cumulative plant service hours at the failure are not recorded. However the service hours at failure can be approximated since the operation hours per calendar quarter for the plant is known and the date of the forced outage event is known. The calendar time of the failure is included. There has been some concern about the accuracy of the reported data, but most all forced outage events seem to be reported. NERC-GADS is accessible through the PC-GAR program for a nominal cost to both data contributors and non-contributors alike.

With the MS Windows base PC-GAR program the batch sorting reports can be output for printing or for input into a spreadsheet program for the following report categories:

- Annual Unit Performance
- Unit-Year Statistical Report
- Component Cause Code
- Top 25 Cause Codes
- Individual Cause Codes
- Annual Unit Statistics
- Annual/Monthly Unit Summary
- Annual/Quarterly Unit Summary
- Unit Statistic Distributions
- Percentage of Period Hours
- Comparative Statistical Distributions
- Duration Probability

The variables that can be contained in these reports are as follows: The numeric outputs are expressed as means and standard deviations.

- Gross Maximum Capacity
- Net Maximum Capacity
- Gross Dependable Capacity
- Net Dependable Capacity
- Gross Actual Generation
- Net Actual Generation
- Units Service Hours
- Condensing Hours
- Reserve Shutdown Hours
- Total Available Hours
- Actual Unit Starts
- Attempted Unit Starts
- Forced Outage Hours
- Forced Outage Occurrences
- Planned Outage Hours
- Planned Outage Occurrences
- Maintenance Outage Hours
- Maintenance Outage Occurrences
- Total Unavailable Hours
- Equivalent Derated Hours
- Forced Derate Occurrences

The report output can include ranges of a number of the above variables including ranges for years forced outages to be examined and unit commission years.

It should be noted that NERC-GADS contains event data, not failure rates. Attempts to develop failure rates may require significant investigative effort.

3.1.3 EPRI PM Basis Database

The EPRI PM Basis Database was constructed in 1998 based on 39 nuclear plant component types. It now contains 60 component types, and many of the earlier components have since been updated by industry working groups. It provides recommended PM tasks and task intervals for these components in a variety of service environments, as well as the technical basis for the recommendations. It also provides detailed lists of failure mechanisms, times to failure for wearout failure mechanisms, the ability to analyze a PM program to find weaknesses, and to estimate the reliability impact of the weaknesses. However, the database is not a reliability database and provides no data on absolute failure rates, although examples given in Section 5 illustrate how it may be used to estimate relative changes in failure rates as a function of time. The database is now available through a website to EPRI member sponsors of the project, and as a Microsoft Access database to all utility members who sponsor the nuclear R&D program.

3.1.4 PRA Database

The PRA database is focused on failure and operation information from the primary sided of the nuclear power loop. It is a compilation of data from over 30 PRA projects conducted by PLG Consultants and is available through them. The database was begun in 1982.

3.1.5 Nuclear Component Reliability Data System

NCRDS is a recently formed component failure database under CRIEPI in Japan. This occurred because some earlier reliability analysis conducted in Japan with US data and compared to Japanese early data indicated that Japanese failure rates were significantly lower. This prompted the formation of this in-country database. The first publication of Japanese data for this database was 1997. To access this database CRIEPI would need to be contacted.

3.1.6 In-Plant Reliability Data System

The Institute of Electrical and Electronics Engineers (IEEE) began collecting data in 1977 from 10 nuclear power reactors by analyzing maintenance reports. Reports on valves and pumps had appeared as NUREG documents by 1983, and further data was published in 1986 on diesel generators, batteries, chargers and inverters. Some of this data formed the basis of a reliability data standard issued by IEEE in 1984 called IEEE Standard 500-1984 edition, which has been widely used and quoted.

The ANSI/IEEE Reliability Data for Pumps and Drivers, Valve Actuators, and Valves was published by John Wiley & Sons in 1986. The data apparently covers a broad range of application of these components and from all reports is quite useful.

3.1.7 Weibull Database

The Weibull Database consists of the Weibull failure distribution parameters and their ranges for components found in many general pieces of equipment as well as in many industries. It is available online at www.barringer1.com. The website points out that range of the parameters is quite broad, and indeed, for most components the uncertainty range of the data is so wide that it covers decreasing, constant, and increasing failure rates.

3.1.8 Offshore Reliability Data

The OREDA equipment reliability database is a membership organization of ten major oil companies that compile data on equipment for their offshore equipment. Even though this data is for oil production equipment in the harsh environment of the North Sea and Adriatic Sea it can have some applicability to equipment on the secondary side of nuclear plants. Generic data on failure rates has been published in a data handbook, covering, among other components, general equipment such as pumps, valves, heat exchangers, compressors, power equipment such as generators and transformers, and fire detection and fire fighting equipment. It was first published in 1984. The specific data is only available to OREDA members.

3.1.9 Non-electronic Parts Reliability Database

This is a report issued in 1981 by Rome Air Development Center (RADC), Griffiths Air Force Base, NY containing data on failure rates, confidence bounds, and effects of environmental factors for mechanical and electromechanical parts. It contains operating experience from NASA and US Navy facilities, which dates back to 1966. The most recent data update seems to be RADC TR 75-22. In addition, a Reliability Engineer's Toolkit (i.e. Handbook) was published in 1988 and includes useful insights on the US military's approach to the use of reliability data, including the use of adjustment factors for service condition and duty cycle effects - which are usually applied to electronic components.

The often quoted Military Handbook 217E (MIL HDBK 217E) contains data exclusively on electronic equipment.

3.1.10 Scandinavian Nuclear Power Reliability Data System (TUD)

Reliability information from 12 Swedish nuclear plants and from 2 Finnish nuclear plants has been collected since 1980, and was initially named the ATV system. It now contains over 245,000 failures covering 448,000 mechanical, electrical, and instrumentation components, and is administered by the TUD group, with representatives from the power companies and one from the Swedish Nuclear Power Inspectorate, SKI. Failure rates, probabilities of failure on demand, and repair times are included. The data is analyzed with advanced statistical methods, which include some ability to detect time dependence of failure rates. The failure rate data is published regularly in the TUD T-Book, which is publicly available at a cost of 5000 Swedish crowns. The latest publication was in 2000. Contact information is as follows:

TUD- Reliability, Maintenance and Operation
TUD Office
SwedPower AB
P.O. Box 527
SE-162 16 Stockholm
SWEDEN
Phone +46 8 739 73 20
Fax +46 8 739 62 26
E-mail: svenne.skagerman@swedpower.vattenfall.se

3.1.11 German System (ZEDB)

This system contains reliability parameters such as failure rates and probabilities of failure on demand for 16 nuclear power plant components drawn from 21 German plants. Parameters are provided for lognormal distributions of the relevant parameters. The latest publication was in 2000. It is available (in German) from:

VGB PowerTech Service GmbH, Verlag technisch-wissenschaftlicher Schriften, Postfach 10 39 32, D-45039 Essen, Germany.

3.1.12 European Reliability Data System (EIReDa)

This database addresses data from 2000 nuclear power plant components in the countries of the European Community. The database dates from about 1977 and contains estimates of failure rates and probabilities of failure-on-demand with their uncertainty distributions, as well as comparisons of the values with other sources. The publication is available as: European Industry Reliability Data Bank, H. Procaccia, S. Arsenis, P. Aufort, and G. Volta, 1998, Crete University Press.

3.1.13 NRC NUREG Publications

Some NUREG contractor reports contain items of failure rate information. These can be viewed and searched in the electronic reading room on the NRC's web site at http://www.nrc.gov/.

3.2 Equipment Databases Being Developed

3.2.1 Process Equipment Reliability Database

The Process Equipment Reliability database is a recent development of the Chemical Process Safety Institute. The database is still in the design phase. It is focused on process plant component failure.

3.2.2 Reliability, Availability and Maintainability Database

The RAM database is being developed by the Ship Operations Cooperative Program. The database is still in the design phase. It has a strong international membership.

3.3 Database Conclusions

In looking back over these databases from the nuclear plant equipment perspective for both primary and secondary side the following conclusions can be made.

- The Scandinavian Nuclear Power Reliability Data System, the EIReDa System, and the German ZEDB database are the most useful source of failure rates and probabilities of failure-on-demand because they represent the results of extensive analysis which has already been performed by the database administrators. In many cases other sources of data are referenced and values given, together with uncertainty bounds in terms of standard measures and distributions. Almost no time-dependent data is available from these sources.

- The PM Basis Database is a database that is a standard reference for US nuclear plants in providing information related to preventive maintenance tasks and intervals and their technical basis, but it is not intended as a source of quantitative failure rates derived from raw data. However, it does provide time dependent predictions of the change in failure rate from current values, for alternative PM assumptions. To produce absolute values of failure rate as a function of time it requires only the addition of the current failure rate (i.e. the failure rate produced by an existing PM program).
- The EPIX database has the strongest potential as a source of raw failure information for the nuclear industry. A concern is the rate of reporting of data by US plants. EPIX is currently an event-based database that requires extensive R&D effort beyond the boundaries of the database in order to extract failure rates. INPO personnel have declared their intentions to add the estimation of failure rates to the database sometime in the future.
- NERC-GADS seems to have the advantage of containing the most data covering the most equipment. It lists the equipment that caused the outage and therefore is usable for determining probability of failure versus time curves. Another advantage of this database is that data for components for other types of power plants can be included, where applicable, even though the concern may be a component in a nuclear plant. This is especially true on the secondary side. No failure rates are produced by NERC-GADS.
- The Nuclear Component Reliability Data System and the PRA database may be useful for primary side components but it appears that applicability in the case of the former and access in the latter may be a problem.
- Both the “ASNI/IEEE Reliability Data for Pumps and Drivers, Valve Actuators, and Valves” and the Weibull Database are readily available and may be useful in initial bounding estimates for LCM support analyses, although the Weibull database has such large uncertainties it may not, in fact, bound the estimates in a useful way.
- The applicability of the OREDA database may be questionable because of the harsh environment, even though some components may be similar to nuclear applications.

4
METHODS FOR USE OF FAILURE RATE INFORMATION

Failure rate estimation usually begins with a number of failures of like components, which are supposed to be representative of a larger group of similar components. Given the general characteristics of reliability data described in Section 2, the group of components for which failure rates are to be estimated, or for which quantitative failure data are to be combined or updated, should be reasonably homogeneous in preventive maintenance and other important stressors such as duty cycle and service environment. Furthermore, since the various failure modes for the same component may differ significantly in occurrence rate, the data should either correspond to the same failure mode (e.g. fails to open, leaks), or be sufficient in number to sum over all the failure modes of the equipment.

4.1 Methods for Manipulating Reliability Data

A set of raw failure data needs to be mathematically manipulated in order to obtain the desired results, usually a probability distribution of values of the failure rate, or of values of the probability of failure-on-demand. Reliability experts have developed many methods to accomplish these tasks. Appendix A attempts to provide sufficient technical information and examples so that non-reliability users can obtain the best possible values of the current failure rate, and the best predictions of the future failure rate. Generally, data are likely to be encountered as a single set, multiple sets needing integration, or a “new” set that can update existing values.

The remainder of Section 4 provides context and general guidance as to when and how the various methods described in Appendix A should be used. Section 4.1 lists the methods described in Appendix A. There is no need for the user to be completely familiar with Appendix A before reading the rest of Section 4, although some of the terminology used in the following list may be better understood by referring briefly to the relevant Appendix material.

Appendix A describes the following techniques:

A1 Estimation of parameter values and confidence intervals for a failure rate in time (either a run-time failure rate or a standby failure rate) starting from the number of failures and the amount of time the components were exposed to the operating environment.

A2 Estimation of a probability of failure-on-demand starting from the number of failures and the number of demands.

A3 Bayesian updating of generic knowledge of a failure rate using a sample of new data.

A4 Calculation of the likelihood for a new data sample consisting of times to failure (constant failure rate).

A5 Calculation of the likelihood for a new data sample consisting of times to failure (time dependent failure rate).

A6 Calculation of the likelihood for a new data sample consisting of a number of new failures (constant failure rate).

A7 Calculation of the likelihood for a new data sample consisting of a number of new failures (constant probability of failure on demand).

A8 Bayesian updating when the new data is a new distribution of the failure rate.

A9 Using a lognormal distribution as the prior.

A10 Benefits of a self-conjugate prior for a constant failure rate.

A11 Benefits of a self-conjugate prior for a constant probability of failure on demand.

A12 Using the method of moments to transform a given distribution to a self-conjugate prior.

A13 Deriving point estimates and confidence bounds from the posterior distribution.

A14 Weibull analysis of times to failure.

A15 Time dependent failure rates from linear regression.

A16 Using the EPRI PM Basis Database to compare reliability of similar component types.

These 16 sections provide a fairly comprehensive set of tools usable by those who are not expert in the field of reliability. The next two sections outline in general when these tools would be used, and introduce two flow charts which attempt to organize the process of reliability data improvement into a simple series of decisions. The user should be aware, however, that use of the flow charts may be over simplistic in some cases. The flow charts point to the use of specific tools from the Appendix as the need arises.

4.2 Use of Generic Data

Sections 2.1, and Appendix A, provide fairly detailed technical methods with which to address the generation or modification of failure rates or probabilities of failure-on-demand in the light of old and new data of various kinds. It remains only to indicate which of the methods would normally be used in certain situations. In practice, the choices are almost always very limited. Using plant-specific information has the sole advantage that you probably have detailed knowledge about the key parameters discussed in Section 2, i.e. the PM program, the duty cycle, and service conditions, and these factors are appropriate for your application. Generic data will most likely be superior in a strict statistical sense, but using it may require you to forego knowledge of these key parameters. The methods of Appendix A can be applied regardless of whether the data sources are generic or plant specific. Therefore, the most important issue in seeking and combining data sources is the above concern over homogeneity of the application.

However, for many nuclear plant components, generic nuclear plant sources may be reasonably homogeneous in PM program, the duty cycle, and service conditions because of the restricted application of the component types. For example, large, complex equipments such as pumps, motors, and medium or high voltage breakers will most probably receive a reasonable level of PM simply because of the high cost of repairing the equipment when it fails. Many components may also have reasonably similar service conditions. For example, charging pumps and instrument air compressors are likely to be positioned inside clean, air-conditioned buildings. Likewise, for many components, the duty cycle category will require only deciding if equipment is normally in standby, or is normally operating.

Precise statements about what constitutes a high or low duty cycle, and severe or mild service conditions are provided for 60 major component types in the EPRI PM Basis database in the Definitions Form, or by clicking on headers in the Source Form. Since LCM applications will almost always target only critical components, it can be assumed that these will usually have a comprehensive PM program because of their functional importance.

The likely needs are, 1) to combine different generic sources of data, each in the form of a given distribution over the parameter of interest, and 2) to update a generic or plant-specific distribution on the failure rate, or on the probability of failure-on-demand, with plant-specific data on numbers of failures, or failure times (failure rate only).

The following Chart A, focuses on the use of generic data to provide a baseline for the failure rate at the present time, and is therefore a good place to begin the process of future failure rate prediction.

In Chart A, the presumption is that if the available data sources include PSA data, you need to carefully consider the inclusion of the PSA data because it may well be the most applicable of all the sources, especially if it has already been updated with plant-specific data.

If Weibull parameters are available and applicable, use them directly to predict the failure rate in the future, but do not ignore the need for reasonable agreement between time-dependent and time-independent values for the current failure rate. The chart does not explicitly address the combination of multiple sets of Weibull parameters, nor the updating of Weibull parameters using new data, because of the low chance of needing to do this, and the need for expert statistical input when doing it. Chart A therefore includes the direct use of time dependent data as well as the use of generic data.

If Weibull parameters are not available, time-dependent data will consist of values of the failure rate for equipment at different ages. Use linear regression techniques to evaluate that kind of time-dependent data.

Chart A also addresses the case where no data is available for the equipment in question. In that case you need to identify another component that shares design features which make it likely that its failure rate could be used as a surrogate. Proceed to use the surrogate component data, but it may be necessary to modify the results using factors that account for remaining design differences. In this case such factors could be derived from the EPRI PM Basis database.

Combine time-independent generic data sources, providing they meet the applicability requirements discussed above, before updating the result with more recent plant-specific data which may also be available, described in Chart B. Use equation (18) to combine separate homogeneous source distributions. The symmetry of the right hand side of the equation shows that it does not matter which distribution you consider to be the prior and which the likelihood. Use equation (18) sequentially to combine more than two distributions, i.e. use the posterior obtained from combining the first two sources as the prior for combining the next. This procedure necessarily involves numerical analysis.

Do not assume that it is reasonable to combine sources of generic data just because the above procedure makes it possible. If one source has a much smaller variance (i.e. is much narrower) than another, it may be better to use the one with the narrower distribution on its own, because it will almost certainly include more failure experience derived from more homogeneous plant conditions. However, this is by no means a golden rule, because the narrower distribution may represent a set of conditions that is not a good match to the conditions appropriate for your application. If you do not know the application conditions for either distribution, you may benefit from using the wider distribution alone, in order to avoid too much specificity in the generic data. If the generic sources are not markedly different in this way, it is probably best to combine them all.

4.3 Updating a Prior Distribution with New Failure Data

The greatest controversy over the use of Bayes' method involves the introduction of a prior distribution when there is no initial information at all about the likely values of λ. The application to updating existing knowledge of constant failure rates or probabilities of failure-on-demand based on pre-existing industry data, generally avoids these concerns, but users updating Weibull parameters should exercise due caution in this regard and seek expert statistical input whenever the topic of "non-informative priors" arises.

In general, to include new data along with prior information on failure rates use equations 8 and 9 or their self-conjugate equivalents with the following procedure:

1. Decide whether the new data is generated from an exponential, Poisson, or binomial statistical process. Calculate the likelihood of getting the new data with this process, using equations (11), (15), or (17).

2. If the new data is generated from a Poisson or binomial statistical process you may use a gamma or beta self-conjugate prior, respectively. In that case, determine the parameters of the prior, by matching the mean and variance with those of the given prior distribution as described in A12. Modify the parameters of the gamma or beta priors to obtain the posterior distributions using equations (26) or (28). This procedure requires only a little algebra.

3. If the new data is not from a Poisson or binomial statistical process, or if you do not wish to use self-conjugate priors, use equations (8) and (9) directly to obtain the posterior distribution. This procedure necessarily involves numerical analysis.

4. Choose a representative point estimate from the posterior distribution, such as the mean. You may need to calculate the mean if the posterior is not a standard distribution. Calculate confidence bounds using equations (29) and (30), or by using (32) and (33) for a gamma distribution.

Chart A: Getting Started and Using Generic Data on Failure Rates

(References are sections in Appendix A)

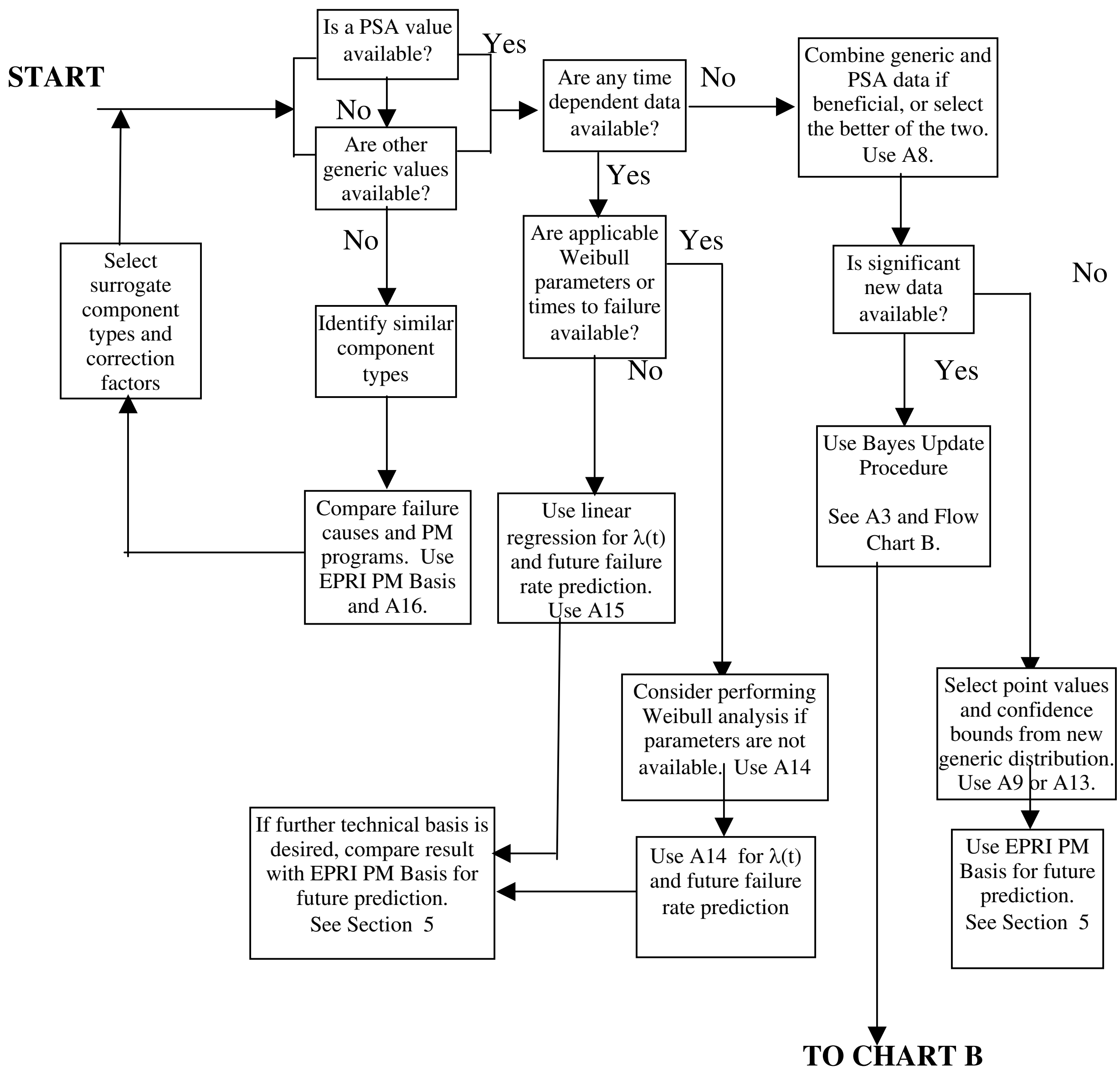
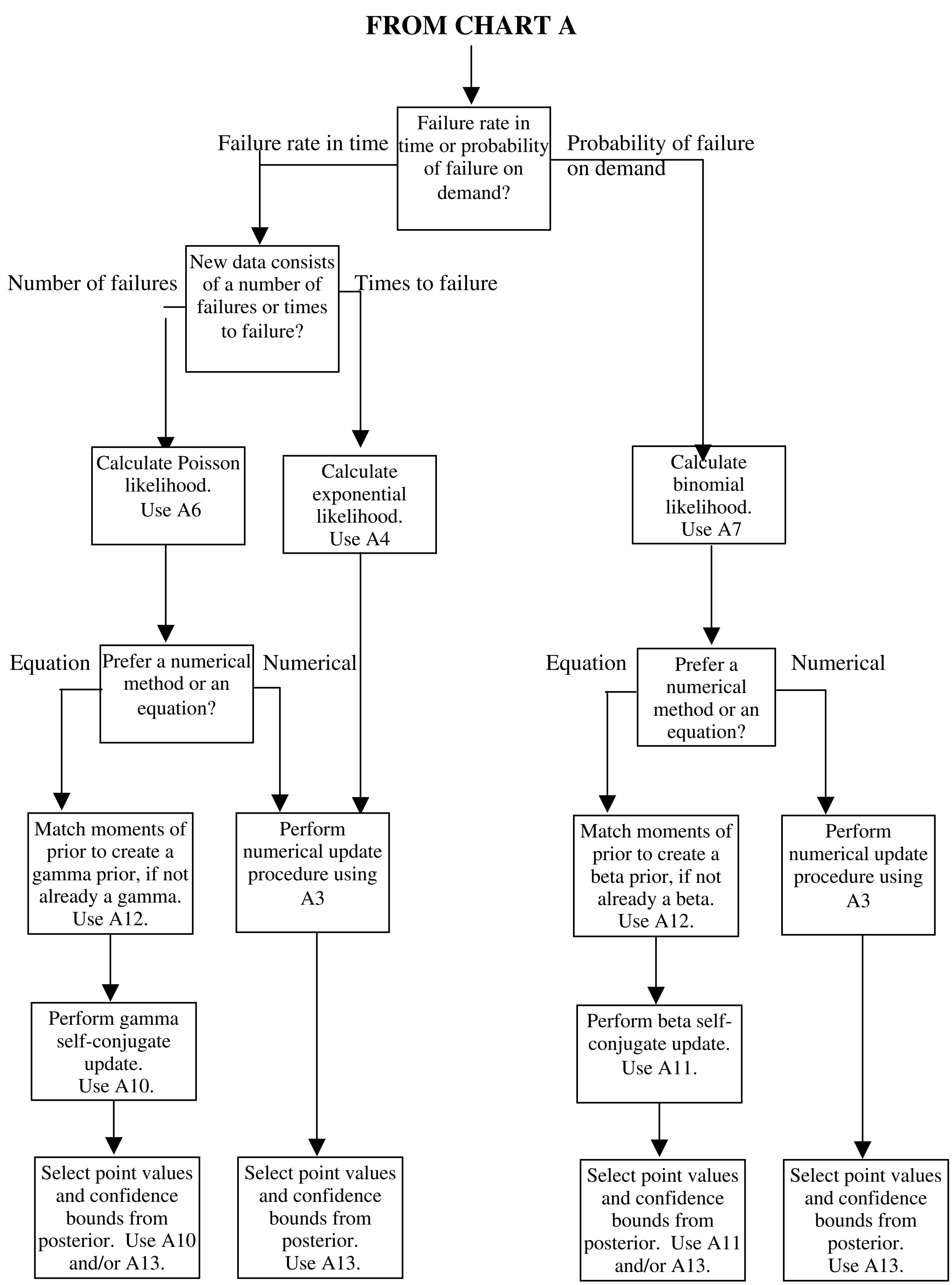


Chart B: Bayes Update of Generic Data



4.4 Time-Dependent Failure Rates

Chart A contains guidance on the case where time-dependent failure rate information is available. This is included for completeness, rather than from an expectation that such data will often be obtained. This section outlines several reasons why the availability of time dependent data would be an unusually fortuitous circumstance, and provides the rationale for the limited treatment of time dependent methods in Appendix A.

The first reason why time dependent failure rates are difficult to quantify is that active equipment is likely to be partly or completely refurbished or to be replaced at certain intervals. This makes tracking the age at failure a somewhat onerous task; one that has not yet been done systematically anywhere in the nuclear power industry. Further, most failure rate quantification in the industry has been done to provide failure rates for Probabilistic Safety Assessment models (PSA), and these have not required time dependent data.

Second, a complex piece of repairable equipment will be made up of many items, each of which has a number of failure mechanisms. A large fraction of these are random and therefore contribute directly to a constant failure rate. The rest will be wearout mechanisms with widely different times to the 'rising part of the bathtub curve' of failure rate versus age. A bathtub curve is shown in Figure 4-1, A. Some items will wear out and be replaced several times before the wearout characteristics of other items come into play. As a result the complex piece of equipment never wears out, and exhibits an approximately constant failure rate, as displayed by the flat parts of almost all the curves.

Figure 4-1 resulted from the analysis of a large quantity of data [8] from the airline industry in the 1960's, and amply demonstrates this point, i.e. that preventive maintenance removes the long term time dependence in all but a small proportion (6% to11%, see Figure 4-1, A, B, and C) of components, which happen to include aircraft reciprocating (B) and turbine engines (C). In Figure 4-1, time is plotted along the horizontal axis, failure rate along the vertical axis. Only in the subsets A, B, and C, would the long term time dependence conceivably be of interest to Life Cycle Management. This proportion is small but it is significant.

Third, most nuclear plant equipment is very reliable, and is not present in the very large populations typical of fleets of airplanes, motor vehicles, or consumer items. The consequent lack of failures makes failure rate estimation a very uncertain affair. The pressure is always to increase the sample size to increase the number of failures experienced in order to improve the accuracy of the estimate. This generally leads to the pooling of data from several plants, or even across the whole industry. At the least, this tends to mix data from different PM programs, duty cycles, and service conditions, as well as from different manufacturers and model lines. Influences on the failure rate from these effects tend to obscure trends with the age at failure.

Paradoxically, the effort to reduce the numerical uncertainty by increasing the sample size in failure rate analysis, leads to increased uncertainty over whether the result obtained from a wide range of different conditions actually applies to the particular component of interest. This is true regardless of whether the time dependence of the failure rate is in question. A 'pin-hole camera' analogy is instructive: the attempt to see the image more clearly by widening the hole to let more light through, only succeeds in defocusing and blurring the image.

Fourth, subdividing the failure experience into subgroups of different age to determine a trend of failure rate over time increases the uncertainty in the failure rate for each subgroup. Nevertheless, standard regression techniques can easily be applied to this kind of data to determine its time dependence. However, regression will only determine the time dependence within the range of the data. Furthermore, confidence intervals on regression parameters widen toward either end of the range of data. Consequently, the method is limited in its capability to extrapolate failure rates outside this range.

Weibull Analysis, the often-quoted method to determine time dependent failure rates, requires a significant fraction of the population to fail in order to provide reasonably accurate estimates of the Weibull parameters. This is not an impediment in a manufacturing environment where a number of items may be put on test, and the test is run until most have failed. But this situation seldom arises in the nuclear power industry where corrective and proactive actions must be taken as soon as the first failures occur on the same set of critical components in a plant, or even across the industry.

Weibull analysis, like regression analysis, mainly determines the time dependence within the range of the data. Consequently, when only a very small fraction of the population has failed, the predictive power of the technique outside that range is limited by the significant uncertainties that then accompany estimates of the Weibull parameters.

Weibull analysis is best applied to a single failure mechanism that can display a clear wear out effect, rather than to the whole failure rate of the equipment (see the above discussion of constant failure rate for complex, repairable equipment). Most texts on Weibull analysis (e.g. [9]) point out that as soon as four or five different wear-out mechanisms contribute to the data, the failure rate tends to take on the appearance of a constant failure rate.

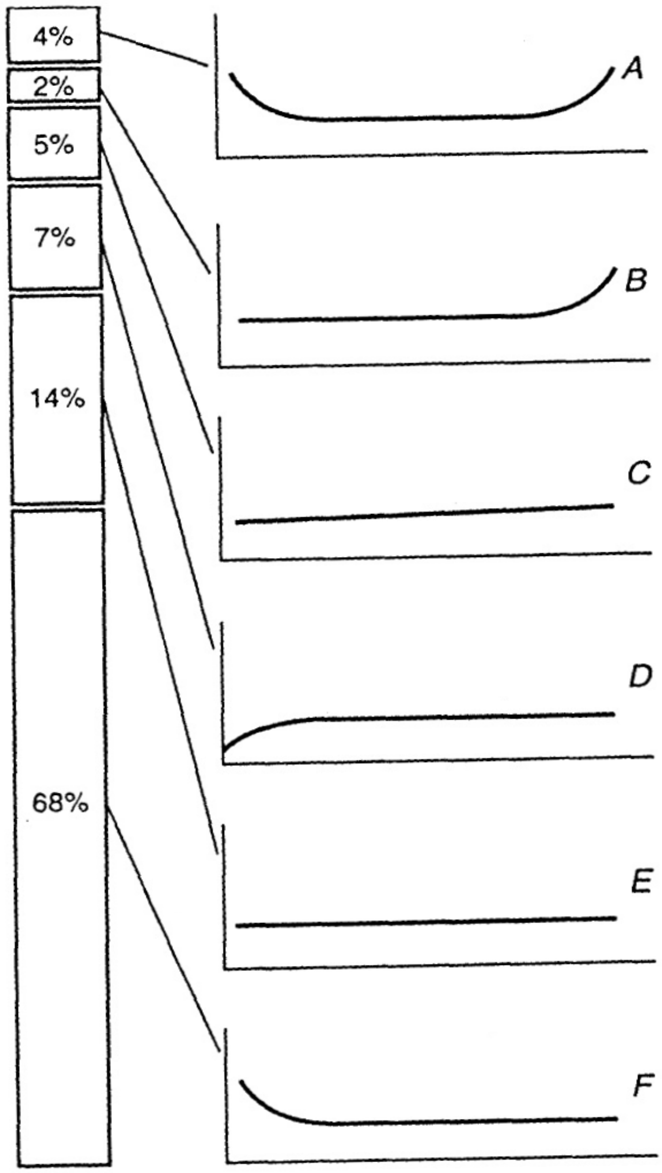


Figure 4-1
United Airlines Time Dependent Failure Rates

5

MAINTENANCE MODELING WHEN FAILURE RATES ARE NOT AVAILABLE (ACTIVE COMPONENTS)

5.1 Overview

In many cases, especially involving active equipment, neither the data available nor the methods described in Section 4 will be sufficient to project failure rates forward in time with adequate confidence. Two examples of such cases are (1) the appearance of new failure mechanisms in industry operating experience whose future effects are not reflected in the historical data, and (2)potential changes in maintenance strategy which suggest that the future may not resemble the past.

For passive components it is possible that the lack of failure rate data can be remedied by explicit modeling of the physical effects of a single new failure mechanism. This approach is described in Section 6.

When no physical model is at hand to describe the development of a new failure mode as a function of time or when there are too many such degradation processes to make modeling them a practical proposition as in the case of most active components, we may turn to the maintenance modeling approach described in this section. This approach acknowledges that decisions must be made in the absence of complete data on time dependent failure rates. The method estimates *changes* in failure rates over long time periods under simplifying assumptions. The future failure rate is obtained by applying a calculated factor to the historical failure rate (i.e. to the current value). This is a useful and valid procedure because, 1) knowledge of the historical failure rate should always far exceed anything we could say about future failure rates, which have not yet been experienced, and 2) even if time dependent failure rate data were available we would need to ensure it properly accounts for the current failure rate. Furthermore, the method has the advantage that it takes explicit and detailed account of long term industry operating experience regarding:

1. Existing hardware failures, degradation mechanisms, stressors, and their time of development to failure

2. Newly experienced hardware failures, degradation mechanisms, stressors, and their time of development to failure, providing they can be identified, usually by reference to analogous experience on older equipment, but possibly by engineering evaluation

3. The effectiveness of past, current, and future PM tasks and their dependence on task intervals in protecting against individual degradation mechanisms

4. The detailed interaction (e.g. overlap in coverage) between PM tasks

Consequently the approach provides estimates of the effect on the failure rate of introducing new degradation mechanisms, of changing existing PM tasks and intervals, and of introducing new PM strategies. Furthermore, the effects will be seen to be a function of time.

The data and calculational capabilities for maintenance modeling are available in an existing EPRI product called the EPRI PM Basis Database [7]. The database was developed over the last 5 years using input from numerous utility workshops to provide recommendations on PM tasks and task intervals for 60 major component types for a range of different duty cycles, service conditions, and functional criticality. The database also provides the technical basis supporting the PM recommendations. It does this by providing a detailed list of all the failure locations, degradation mechanisms, and stressors (called degradation influences) along with available information on, 1) whether the mechanisms are random or wear-out in nature, and 2) the minimum life for the wear-out cases. The database contains the quantitative effectiveness of each PM task for each degradation mechanism and time scale that it addresses, under the assumption that the task is performed at the right time.

This database is supported by EPRI and has been adopted by the industry as a long-term Preventive Maintenance Information Repository (PMIR). It is continually being updated with new information with the cooperation of industry groups such as the PM Coordinators Group (PMCG), the Nuclear Industry Check Valve Group (NIC), the Large Electric Motors User Group (LEMUG), various other NMAC and FMAC groups, and individual utilities. The database is also available via the PMIR (beta) website, operated by EPRI. The database is being converted for fossil plant applications over the next two years, which will provide a source of longer-term degradation mechanisms for consideration by nuclear LCM programs. The EPRI PM Basis database is also likely to benefit from its use by LCM analysts because it will be able to incorporate LCM program insights and findings on new long-term degradation mechanisms.

The database contains an application called the Vulnerability Evaluation, which is able to find strengths and weaknesses in any subset of the recommended comprehensive PM coverage. It also estimates the effect on the failure rate when the user changes the data or parameters. To do this, the PM task effectiveness data are retained or adjusted downward by the code depending on a comparison it makes between each user task interval and the time scale of development of the individual degradation mechanisms.

In this guide the Vulnerability Evaluation will be used to estimate future changes in failure rate that depend on, 1) gaps in the current PM program leading to poor equipment condition and thus to additional failures at future times, and, 2) new failure mechanisms expected to occur at later times, with or without enhanced PM activities to cope with them.

These applications of the database would benefit from modest enhancement of the current user features. A simple example is the ability of the user to add new degradation mechanisms to the database, since in current versions such additions require administrative access.

5.2 Maintenance Modeling Using the EPRI PM Basis Database

Use of the PM Basis database will be described assuming that any manipulation of the data that requires administrative access to the database, can be accomplished with the cooperation of the database administrators. Until the needs of LCM users can be assessed more completely by EPRI, and the relevant user features are added to the database, the database administrators can respond quickly to user requests by e-mailing modified database files.

Although the remainder of Sections 5.2 and 5.3 will best be appreciated by those who are already familiar with the PM Basis Database, the description is complete enough for new users to open the database and to follow the description screen by screen within the database. Readers who do not yet have access to the database will nevertheless be able to understand the methodology by reading the remainder of Section 5.

The user selects a component type of interest from the scroll box in the opening screen. All the forms that contain views of the data or perform calculations are accessible using command buttons on the forms. It is recommended that the user thoroughly examine, 1) the information in the 'Template' form, which provides an overview of the recommended PM tasks and intervals for various plant conditions, and 2) the information in the 'PM Basis' form that contains a summary of the technical basis for the PM recommendations. The user should then go to the 'Vulnerability' form. The Vulnerability and related forms present the results of an algorithm contained within the database, which assesses the effectiveness of all the tasks over all the failure mechanisms for the component type, and formulates a quantitative conclusion as to the effect on reliability.

Although the Vulnerability form displays some of the basic results, the results are usually too extensive to be viewed easily on the form. A superset of this information can be more easily viewed, and used, by pressing the 'Degradation' button. The Degradation datasheet displays all the failure mechanisms affecting all the important subcomponents of the equipment, each with information on its time of development, and each mapped one-to-one to the PM tasks. Important quantitative results such as the number of failure mechanisms which are not very well protected by the PM program can be seen by pressing the 'Statistics' button.

Each record (row) in the Vulnerability form (and in the Degradation datasheet) represents a specific failure location, degradation mechanism, degradation influence, (collectively a 'failure mechanism), and a set of overall PM task effectiveness values (High, Medium, Low). Each column at the right of the screen contains the effectiveness results for a specific PM task in the Template. Records are color coded to give a rough indication of which failure causes are well protected against by PM tasks, and which are poorly protected – or unprotected. Red rows have no task addressing them with better than a Low overall effectiveness. Orange rows have no task addressing them with better than a Medium overall effectiveness. Yellow rows have at least one task with a High overall effectiveness, and green rows have at least two tasks with a High level of overall effectiveness.

If a task is shown as having a two letter code, such as hM, it indicates that the effectiveness would have been High if the task were performed at the right time, but was downgraded to Medium because of consideration of the task interval versus timing of the degradation process. A PM task that is 'grayed out' is a task that is not performed on a regular schedule, and is ignored by the Vulnerability algorithm.

The Statistics form provides numerical results in terms of the numbers and percentages of opportunities for failures, represented by subsets of the data. The numerical value in the text box at the bottom right of the form, labeled "Failure Rate with the default PM program is proportional to:" is proportional to the number of failures *not* prevented by the PM program. These are the failures responsible for the residual unreliability experienced when using the analyzed PM program.

The Vulnerability results displayed at this point are the 'Default' results – i.e. under the assumption that all the recommended tasks will be performed at the recommended intervals. To perform the default calculation the code automatically selects from the Template the tasks and intervals for the most demanding application conditions. The particular set used is shown on the Vulnerability form – usually the 'Critical, High Duty Cycle, and Severe Service Condition' – unless there is some reason why these conditions do not apply to the component in question. The user can examine the effect of changes to these recommendations by pressing the 'Custom Vulnerability' button on the Vulnerability form.

The Custom Vulnerability calculation begins with a dialog form in which the user enters a choice of tasks and intervals (in years). A short-cut is provided if he or she wishes to begin by entering the same data as used for the default (i.e. to save time if only a simple change is needed). Deleting an interval means the task will not be done at all. Also shown is the Template data for the Default, and the actual task intervals that were used by the Default calculation (because some assumptions are made that go beyond the Template interval data).

When the user has made the changes to the tasks and intervals he desires, and hits the 'Calculate' button, the Vulnerability algorithm is re-applied. The Custom results are interpreted in an analogous way to the Default results with one exception. The Custom Vulnerability form now displays a factor (later referred to as the factor 'g'), by which the failure rate is expected to change between the Default PM program and the Custom PM program. For example, if it states that failures will increase by x 1.46, it means the failure rate will increase by 46% (i.e. g=1.46). If it states that failures will increase by x 0.73, it means the failure rate will decrease by 27% (i.e. g=0.73).

To evaluate the weaknesses in a PM program, run the Custom Vulnerability calculation for the tasks and intervals that represent your PM program for the component. If it appears that the failure rate is significantly higher for your program than for the default program, (i.e. the g factor >>1) you should look for the reasons. In any case, you should look at the Red records in the Vulnerability form to determine the specific degradation mechanisms against which you are not adequately protected. If any of these have time codes which include a "W", and an expected wear-out period of 10 years or more, e.g. W15, or W<40, or UW12_20, you have identified specific opportunities for the future failure rate to be higher than it is now.

If these poorly protected (Red) long-term wear-out records have two-letter designations of task effectiveness you may improve reliability by decreasing one or more task intervals – obviously the ones showing the decreased task effectiveness. If these red records have tasks "grayed out", you may improve reliability performance by adding these tasks to your PM program. If there do not appear to be any other tasks which can be modified in these ways you should seek additional activities which could be performed. Some of these might be found in the column headed "DiscovPreventOpprnty' which stands for Discovery or Prevention Opportunity. Most of the items in this field have already been incorporated into PM tasks, but occasionally an additional item may be found. If you believe a task's effectiveness can be improved by adding such an activity, which is not initially present, or if you need to add a completely new PM task, you should contact the database administrator (D. Worledge 505-890-1688 or G. Hinchcliffe 704-947-9424) to make the changes.

You may run the code after each change to discover the effect on the failure rate. Note that at each calculation the g factor records the factor by which the failure rate changes with respect to the new default calculation. Note that the new default is changed by virtue of additions of records to the database. To account for this use the "Failure Rate with the default PM program is proportional to: value" which can be found in the box at the bottom right of the Statistics form. Ratios of the "Failure Rate with the default PM program is proportional to: value" express the factor by which the failure rate is expected to change from one calculation to another.

Although the change in failure rate calculated by the Vulnerability algorithm sets the magnitude of the change that can be expected over time (i.e. by the factor g), no time scale is automatically attached to this change in the failure rate. The time scale has to be determined using successive runs of the code as described below.

5.3 Time Dependence of the Change in Failure Rate

To extract the time dependence of the g factor, the basic requirement is to run the Vulnerability calculation for a range of different PM task intervals with values of 1, 2, 3, 4, 5, 10, 15, 20, etc years – and longer if necessary. Record the increase in failure rate provided by Custom Vulnerability for each value of the task interval. The task acts as a kind of probe, which 'detects' the rising failure propensity as a function of time.

Consider the effect of a single degradation mechanism that has a failure time distribution which increases from zero at 5 years and which becomes zero again at 15 years (this means that the failure is certain to have occurred after age 15 years). Assume a PM task that addresses this failure mechanism with a given effectiveness is proposed as an addition to the PM program. If the task is regularly performed at an interval less than 5 years it attenuates, by the stated effectiveness, the failures which might arise after 5 years. So the estimate of the g factor is low (i.e. ~1.0), and will be insensitive to task intervals up to 5 years. From 5 years to 15 years, however, the effectiveness of the task decreases because it is not being done in time to prevent some failures from occurring. The failure rate will therefore increase at task intervals greater than 5 years to a larger value. When the task interval exceeds 15 years the task is completely unable to prevent any failures at all, and the failure rate will remain constant at its maximum value. The range of task intervals, over which the failure rate is calculated to become asymptotic to its value when the task is omitted, is thus the elapsed time period which is required to experience the full increase in the failure rate.

In practice, a PM task will address a significant number of wear-out degradation mechanisms, all with different time scales of development, as well as random degradation mechanisms, which average to the same rate all the time. The time behavior of the failure rate increase can then be quite complex. In most situations investigators will be studying the effect of a single PM task, for which the above procedure gives direct results for the change in g as a function of time, i.e. g(t). The absolute failure rate will be obtained by multiplying the factor g(t) by λ_0, where λ_0 is the current, or historical failure rate, obtained with the task performed at the interval, I_0. Obviously, Vulnerability gives g = 1 when $I = I_0$ as can be verified easily by running the Custom calculation with the same tasks and intervals as for the default case.

Users are advised to construct a table of the results, as in the examples below, and then represent them graphically, as implemented in the examples. This process may be executed automatically in a future version of the PM Basis Database if it gains acceptance by LCM users. The time points selected should start with the range suggested above, but other points can be added to explore the behavior when g is changing rapidly. Do not use time points less than 1 year because g will usually decrease significantly in the range below 6 months, accounting for the fact that such frequent execution of the task will provide significant protection against the random degradation mechanisms. This is valuable for the non-intrusive, condition monitoring type of PM task, but is not practical or cost-effective for intrusive tasks. If, out of curiosity, you explore the region below 1 year it is important that you ignore this region of decrease in g(t), and hence $\lambda(t)$, when considering $\lambda(t)$ going forward.

Example 1: Centrifugal compressors are usually given an overhaul about every 5 years for the purpose of replacing end-of-life components. What is the effect on compressor reliability if this task is suddenly discontinued, while continuing to perform all other PM tasks at their normal intervals?

When Custom Vulnerability is run for the time points in Table 5-1, the factors g(t) are obtained, shown graphically in Fig 4-1. $\lambda(t)$ assumes the failure rate at the 5 year interval is 0.05 failures/year.

Table 5-1
Failure Rate Increases after Increasing the Overhaul Task Interval for a Centrifugal Compressor

Time	g(t)	λ(t)
5	1	0.05
6	1.32	0.066
7	1.32	0.066
8	1.53	0.076
9	1.72	0.086
10	1.72	0.086
11	2.37	0.076
15	2.37	0.118
20	2.61	0.108
25	2.69	0.130
30	2.69	0.130
35	2.69	0.131
40	2.69	0.131
∞	2.82	0.142

The chart below shows that the failure rate does not increase for about 5 years, after which the full effects are felt gradually over the next 20 years. Note that the curve was roughly fit by eye. The jumps shown by the code, rather than the smooth behavior of the curve, are manifestations of the discrete ‘turning on’ of degradation mechanisms in the database. Although they may indeed indicate times of marked increase in the failure rate, such jumps are unlikely to be observable by actual measurements of the failure rate. Consequently, a smooth curve through the points may be the best way to represent the results.

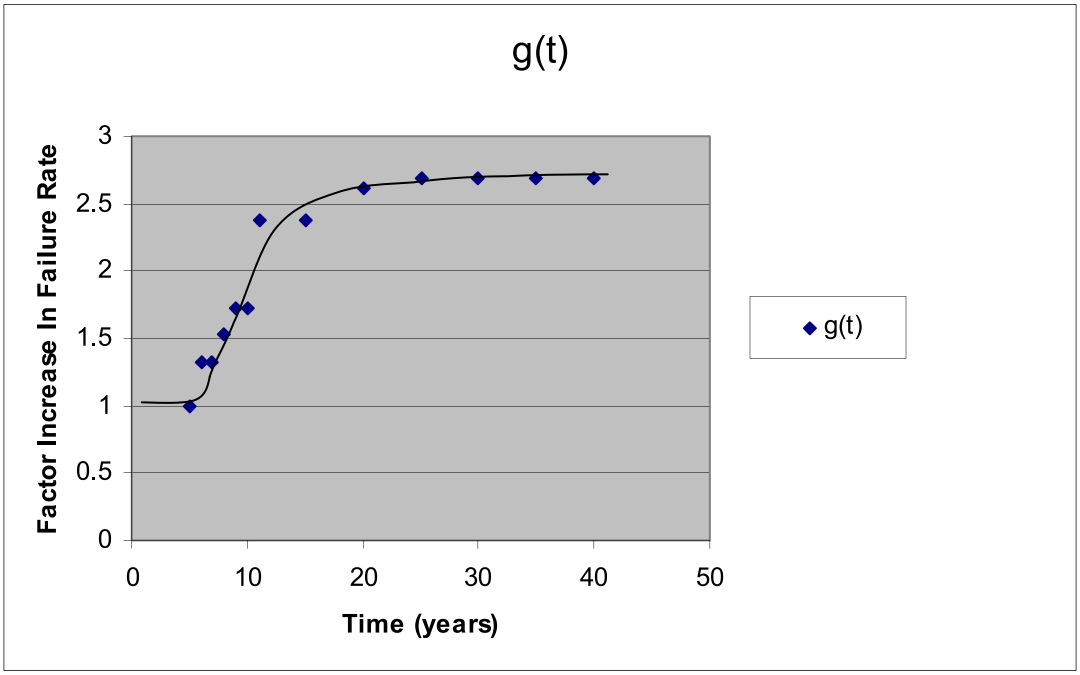


Figure 5-1
Effect on Failure Rate of Increasing the Centrifugal Compressor Overhaul Interval

The results can also be interpreted to look backwards in time if, for example, the overhauls were discontinued sometime in the past. If the task had been discontinued 7 years ago, the table shows that the failure rate is destined to continue to deteriorate over about the next 10 to 15 years as successive wear-out mechanisms come in to play. This is an opportunity to point out the difference between a theoretical failure rate estimate and the actual experience of failures. The deterioration in failure rate of 32% expected 7 years after the task was abandoned will probably not yet have been noted, as it is not a large change in relation to the uncertainties that attend failure rates. Furthermore, no extra failures at all may have occurred up to this time, or if they have, they may not have been recognized as the effect of deleting the task, leaving the whole increase by a factor of almost 3 as an unpleasant surprise in the future.

To compare failure rates when new degradation mechanisms are added, run the calculations again after the new data is added to the component table in the database. Obviously, if the new mechanisms of failure are well protected by existing PM tasks, the changes to the failure rate will be rather small.

However, if there is considerable “leakage’ of failures through existing PM defenses, a few additional failure mechanisms may not create a very significant change in failure rate even if the new mechanisms of failure are poorly protected by existing PM tasks. This situation is more likely to be encountered when the equipment is already subject to a large number of randomly timed degradation mechanisms, and is not well protected by extensive condition monitoring activities performed continuously, or at least very frequently.

First ensure that the database does not contain the new degradation mechanism(s). Look carefully in the table after pressing the Degradation button on the Vulnerability form. To add new entries, call or e-mail one of the two database administrators with your request. For each you will need to know the following information:

1. The hardware which is affected
2. The degradation mechanism, and related stressor
3. Whether the degradation exhibits wear out behavior or is quite random
4. For wear out, the expected failure free time before the degradation reaches an advanced stage
5. The actions which provide opportunities to discover or prevent the condition
6. Finally, the effectiveness of the PM tasks in the database Template in addressing the condition, if they were performed at the right time for that specific degradation mechanism.

This information is easily obtained from experienced maintenance personnel if you ask the right questions, and it may therefore be a good idea to include such persons in communications with the database administrators. In practice, information on long-term degradation mechanisms can be discovered during interviews with experienced maintenance personnel in older plants, or in fossil power plants. Once you find the right person, it only takes an hour or two to elicit this information.

Example 2: In a continuation of example 1, assume that three new degradation mechanisms come to your attention, all of which are either natural aging processes or are processes that will occur because of specific conditions at your plant. Assume one of them is expected to be driven by two different stressors, which lead to wear-out after 12 and 15 years respectively, and the two others are wear-out processes at approximately 15 years and 20 years. Because there are 4 ways in which degradation can occur, there will be 4 new records added to the database. Let us further assume that the existing overhaul task addresses all four of the new mechanisms at a high level of effectiveness. Conducting a 'sweep' of the overhaul task interval, as in example 1, we obtain the results in Table 5-2.

Table 5-2
Failure Rate Increases as a Function of Overhaul Task Interval for a Centrifugal Compressor with Added Possibilities for Long Term Degradation

Time	g (t)	λ(t)
5	1	0.062
6	1.32	0.078
7	1.32	0.078
8	1.52	0.078
9	1.71	0.087
10	1.71	0.087
11	2.35	0.119
15	2.36	0.119
20	2.66	0.137
25	2.85	0.141
30	2.85	0.141
35	2.94	0.146
40	2.94	0.148
45	2.97	0.153
50	2.97	0.153
80	3.10	0.154

The failure rate as a function of time, also shown in Table 5-2, was obtained by multiplying these results by λ_0, (= 0.05) as before.

The results of Example 2 are displayed in Figure 5-1, in which the results of Example 1 are shown for comparison. The solid curves are approximate smooth fits.

Adding the new failure mechanisms makes no difference to the failure rate, providing the task interval is kept below 20 years, because the increase in the failure rate with interval dominates the effect of the new mechanisms in this time period.

Let us summarize the interpretation of these curves:

1. A single curve gives the factor by which the failure rate changes in going from one task interval to a different interval. The curve is therefore specific to the PM task whose interval is being varied.

2. For such interval changes, the factor by which the failure rate changes applies at a time given by the new interval *counting from the last time the degraded condition was restored to an as-new condition*. For example, the change in failure rate in going from a 5 year interval to a 10 year interval, is what would be experienced 10 years after the last time the specific condition is known to have been good as new (GAN).

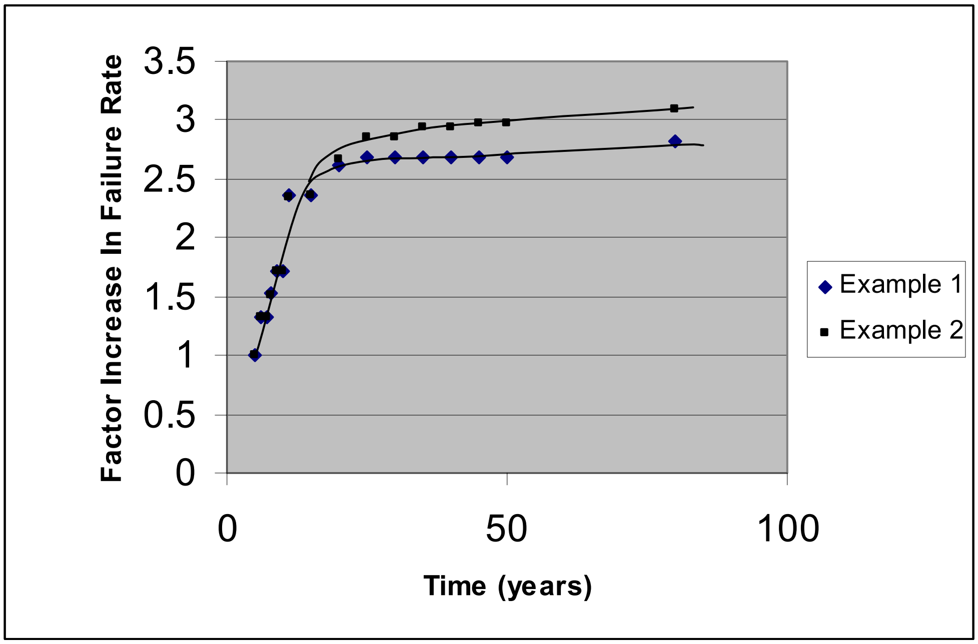


Figure 5-2
Failure Rate Increases as a Function of Overhaul Task Interval for a Centrifugal Compressor with Added Possibilities for Long Term Degradation

In principle, the user has to decide on the time origin, using maintenance history as a guide. However, for the long term degradation mechanisms of interest to Life Cycle Management, the time origin will usually be the time when the equipment was new, or the last time a major refurbishment was performed, whichever is later. A conservative default would be from the time the equipment was originally installed.

3. The time at which a new failure rate applies after 'new' failure modes are added to the database (as in the upper curve in Figure 5-1) will again depend upon the GAN assumption. Assuming the 'new' processes are new only to our state of knowledge, and have been potential wear-out processes from the time the equipment was installed, the new failure rate will apply at the time shown on the chart, counting from the time of installation or from the last time the degraded condition was restored to an as-new condition, whichever is later.

4. What is the time scale that applies if a task is deleted? In this case the increase in failure rate is given by the asymptotic value reached at the right side of the chart, equivalent to task performance at an infinitely long task interval. The time origin for LCM applications should again be the time of installation or the last time the degraded condition was restored to an as-new condition, whichever is later.

How do you calculate results if there is no current PM task that addresses the degraded condition? In this case there is no available 'probe' for the time dependence. You have to add a new task to the database to address the degradation mechanism, which can only be done by the database administrators. However, the database administrators can add a new task quite easily, providing the following information is at hand:

a. Task name

b. Recommended task intervals for relevant combinations of criticality, duty cycle, and service conditions

c. Task effectiveness (high, medium, low) for every degradation mechanism in the component data table, including the original mechanisms as well as the new ones. The new task can be added to the database with little effort, providing, of course, that such a task can be devised to address the new failure mechanisms.

How do you calculate the effect on the future failure rate if no new task(s) can be found to address the new failure mechanisms, and no existing tasks address them either? In this case add a dummy task to the database, which only addresses the new mechanisms, and assume it has a high effectiveness against the new mechanisms. This will enable a sweep of the time dependence to be made as before, using the interval of the dummy task. The high effectiveness will ensure that the protective action of the task essentially 'turns off' failures from the degradation mechanism for task intervals less than the expected failure-free wear-out period, and 'turns it on' as the effectiveness deteriorates during progressive increases of the dummy task interval.

Figure 5-2 shows the results of introducing the same four degradation mechanisms as in Example 2, but with no PM task to attenuate their effects. In this case there is no large competing increase in failure rate due to the overhaul task having its interval extended beyond 5 years. The effect is purely due to the added degradation mechanisms that exert most of their effect in the 20 to 40 year time frame. The total effect is about a 30% increase, due to the fact that there are many other degradation mechanisms, also able to cause failures. Although additional PM tasks might be added to mitigate failures, no PM program can provide perfect protection from all failure causes.

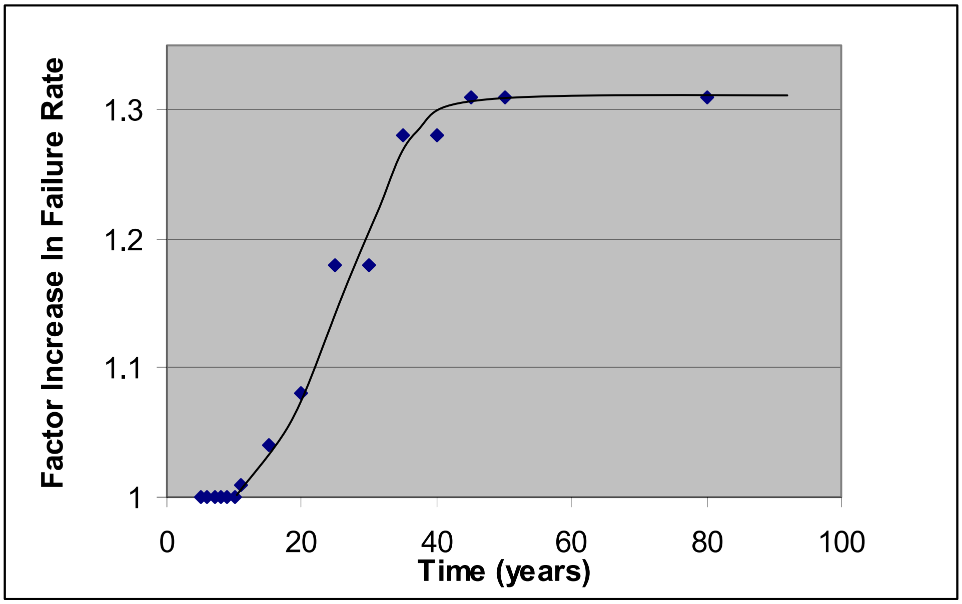


Figure 5-3
Time Dependence of Failure Rate When Added Degradation Mechanisms Have No PM Protection

6
PHYSICAL MODELING WHEN FAILURE RATES ARE NOT AVAILABLE (PASSIVE COMPONENTS)

Physical modeling is most useful when failure is governed by a single (or a very few) degradation processes. This is especially likely to be true for passive components. A general outline of how a physical model for key parameters of the degradation process can be used to determine a time-dependent failure rate is described in this section. Several examples are provided later to illustrate the approach.

A physical model permits a specific degradation or aging effect, x, such as crack length or corrosion depth, to be determined as a function of time, t, and other independent variables that influence the degradation process. Generally, failure is predicted when x reaches a threshold value (such as a critical crack size or the wall thickness of the component) . This kind of a model would only provide a unique and deterministic value of the failure time.

If the threshold value and one or more of the key parameters that influence the degradation process are assigned uncertainty distributions, the model will provide a distribution of failure times. The failure time distribution, f(t), thus generated, may be converted to a time dependent failure rate by using the following relationship:

$$\lambda(t) = f(t) / [1 - \int_0^t f(t')\, dt']$$

The analysis process described above lends itself to an analytical technique known as Monte Carlo simulation, which is described in detail in Appendix D. In the Monte Carlo technique, the deterministic fundamental equation (or equations) governing the failure process is set up in a computer code or spreadsheet. The equation is then solved repeatedly (called trials or simulations) for failure time, sampling from the statistical distributions for the key variables in each simulation. Each simulation thus yields a failure time, and the statistical distribution of failure times for all simulations provides an estimate of the past/future failure time distribution f(t), which can be converted to failure rate as described above. Finally, if actual failure rate data are available, either from plant specific records, or from industry failure data, the past/future failure rate may be updated using the Bayesian process described in Section 4.3 and Appendix A.

The recommended steps for physical modeling of the degradation and failure processes are described in this section.

6.1 Identify Potential Degradation Mechanisms

A number of documents provide guidance on identifying degradation mechanisms that are potentially applicable to various passive component types [1, 2, 3, 5]. The general approach is to develop an Aging Evaluation Matrix for the component, as illustrated in Table 6-1. In addition to identifying potentially active degradation mechanisms, the table also lists preventive maintenance or mitigating measures, which may be in place at the plant to address the specific degradation mechanisms. This table is intended to be a comprehensive list of all degradation mechanisms generally known to affect the category of SSC under consideration.

6.2 Screening Degradation Mechanisms for Applicability to Specific SSC

Before proceeding with physical modeling of the potential degradation mechanisms identified in Section 6.1, it is recommended that the mechanisms be screened for applicability to the specific SSC being evaluated. Although the degradation mechanisms identified in accordance with Section 6.1 are all potentially applicable, there are component specific operating factors (stressors) that influence the degree to which the degradation mechanisms will affect a particular SSC, or whether they will be a serious concern at all.

For example, all metal components are potentially susceptible to the phenomenon of metal fatigue. However, for fatigue to affect a specific SSC, it must be subjected to cyclical stresses, typically caused by thermal cycling or vibration. Thus, if a component is in a system in which operating temperature is constant and relatively low (less than ~150°F), and is not located near potential sources of vibration, such as rotating or reciprocating equipment, then fatigue can generally be ruled out as a concern for that SSC. Similar screening parameters can be established for other degradation mechanisms such as corrosion, stress corrosion, pitting, flow assisted corrosion, etc.

EPRI has compiled an extensive list of screening criteria for the degradation mechanisms that affect passive, pressure retaining components such as piping systems, pressure vessels, pump and valve casings and heat exchangers [10]. These screening criteria are presented in Table 6-2.

Table 6-1
Typical Aging Evaluation Matrix (Ref. 1)

Components	Component Criticality	Aging Mechanisms for Metallic Parts										Aging Mechanisms for Non-Metallic Parts				
		Ductile or Brittle Overload	Fatigue	Wear	Erosion	Wastage/General Corrosion	ID Wastage/General Corrosion	OD Pitting	ID Pitting	Creep or Distorion	Settling	Gasket Aging	Seal Aging	Packing Wear/Aging	OD Coating Degradation (2)	ID Coating Degradation
Intake Piping																
- Large diameter piping	A1	---	---	---	---	CM	CM	CM	CM	---	---	---	---	---	CM	CM
- Vent/vacuum priming manifolds	A3	---	---	---	---	CM	CM	CM	CM	---	---	---	---	---	PM	---
- Repaired areas	A3	---	---	---	---	---	---	CM	---	---	---	---	---	---	CM	---
Discharge Piping																
- Large diameter piping	C2(1)	---	---	---	---	CM	CM	CM	CM	---	---	---	---	---	CM	CM
- Vent/vacuum priming manifolds	C2(1)	---	---	---	---	CM	CM	CM	CM	---	---	---	---	---	CM	---
- Repaired areas	C2(1)	---	---	---	---	---	---	CM	---	---	---	---	---	---	CM	---
Emergency Discharge Piping																
- 24 - 48 inch diameter piping	C2(1)	---	---	---	---	CM	CM	CM	CM	---	---	---	---	---	CM	CM
- Repaired area	C2(1)	---	---	---	---	---	---	---	CM	---	---	---	---	---	---	CM
		---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

(1) Plant shutdown might be required if the leak caused flooding of critical equipment in the turbine basement or soil erosion threatened critical equipment or structures, e.g., in the transformer yard.
(2) Possibly aggravated by soil induced stresses.

PM = preventive maintenance, PdM = predictive maintenance, SR = scheduled replacement, CM = corrective maintenance (run-to-failure)
FNC = failure not credible, FT = functional test, "---" = no active aging mechanism identified

Table 6-2
Screening Criteria for Passive, Pressure Retaining Components (Ref. 10)

Degradation Mechanism		Criteria	Susceptible Regions
Thermal Fatigue	Thermal Stratification and Cycling	–NPS > 1 inch, and –pipe segment has a slope < 45° from horizontal (includes elbow or tee into a vertical pipe), and –potential exists for low flow in a pipe section connected to a component allowing mixing of hot and cold fluids, or potential exists for leakage flow past a valve (i.e., in-leakage, out-leakage, cross-leakage) allowing mixing of hot and cold fluids, or potential exists for convection heating in dead-ended pipe sections connected to a source of hot fluid, or potential exists for two phase (steam/water) flow, or potential exists for turbulent penetration into a relatively colder branch pipe connected to header piping containing hot fluid with turbulent flow, and –calculated or measured ΔT > 50°F, and –Richardson number > 4.0	Nozzles, branch pipe connections, safe ends, welds, heat affected zones (HAZs), base metal, and regions of stress concentration
	Thermal Transients	–operating temperature > 270°F for stainless steel, or operating temperature > 220°F for carbon steel, and –potential for relatively rapid temperature changes including cold fluid injection into hot pipe segment, or hot fluid injection into cold pipe segment, and – $\lvert \Delta T \rvert$ > 200°F for stainless steel, or $\lvert \Delta T \rvert$ > 150°F for carbon steel, or $\lvert \Delta T \rvert$ > ΔT allowable (applicable to both stainless and carbon)	
Stress Corrosion Cracking	IGSCC (BWR)	–evaluated in accordance with existing plant IGSCC program per NRC Generic Letter 88-01	Welds and HAZs

Degradation Mechanism		Criteria	Susceptible Regions
	IGSCC (PWR)	-austenitic stainless steel (carbon content ≥ 0.035%), and –operating temperature > 200°F, and –tensile stress (including residual stress) is present, and –oxygen or oxidizing species are present OR –operating temperature < 200°F, the attributes above apply, and –initiating contaminants (e.g., thiosulfate, fluoride or chloride) are also required to be present	
	TGSCC	– austenitic stainless steel, and –operating temperature > 150°F, and –tensile stress (including residual stress) is present, and –halides (e.g., fluoride or chloride) are present, and –oxygen or oxidizing species are present	Base metal, welds, and HAZs
	ECSCC	– austenitic stainless steel, and –operating temperature > 150°F, and –tensile stress is present, and –an outside piping surface is within five diameters of a probable leak path (e.g., valve stems) and is covered with non-metallic insulation that is not in compliance with Reg. Guide 1.36, OR -austenitic stainless steel, and -tensile stress is present, and an outside piping surface is exposed to wetting from concentrated chloride-bearing environments (i.e., sea water, brackish water, or brine)	Base metal, welds, and HAZs
	PWSCC	–piping material is Inconel (Alloy 600), and –exposed to primary water at T > 570°F, and –the material is mill-annealed and cold worked, or cold worked and welded without stress relief	Nozzles, welds, and HAZs without stress relief

Degradation Mechanism		Criteria	Susceptible Regions
Localized Corrosion	MIC	–operating temperature < 150°F, and –low or intermittent flow, and –pH < 10, and –presence/intrusion of organic material (e.g., Raw Water System), or –water source is not treated with biocides, or	Fittings, welds, HAZs, base metal, dissimilar metal joints (for example, welds and flanges), and regions containing crevices
	PIT	–potential exists for low flow, and –oxygen or oxidizing species are present, and –initiating contaminants (e.g., fluoride or chloride) are present	
	CC	–crevice condition exists (i.e., thermal sleeves), and –operating temperature > 150°F, and –oxygen or oxidizing species are present	
Flow Sensitive	E-C	–cavitation source, and –operating temperature < 250°F, and –flow present > 100 hrs./yr., and –velocity > 30 ft./sec., and –$(P_d - P_v) / \Delta P < 5$	Fittings, welds, HAZs, and base metal
	FAC	–evaluated In accordance with existing plant FAC program	per plant FAC program

1. Key to Acronyms:

IGSCC = Intergranular Stress Corrosion Cracking
TGSCC = Transgranular Stress Corrosion Cracking
ECSCC = External Chloride Stress Corrosion Cracking
PWSCC = Primary Water Stress Corrosion Cracking
MIC = Microbially Influenced Corrosion
PIT= Pitting
CC = Crevice Corrosion
E-C = Erosion-Cavitation
FAC = Flow Assisted Corrosion

6.3 Physical Modeling

For degradation mechanisms that are still applicable after applying the above screening criteria, detailed physical modeling may be performed. This process requires the governing equations for each specific mechanism to be defined. Some examples of fundamental equations for various degradation mechanisms are tabulated below:

Metal Fatigue:

Crack Initiation Life:

$$U = \Sigma\ (n_i / N_i)$$

where: U = Fatigue Usage Factor

n_i = Number of cycles at various applied stress levels

N_i = Number of cycles to failure at the various applied stress levels

Fatigue Crack Growth:

$$da/dN = C\ \Delta K^n$$

where: da/dN = crack propagation rate (e.g. inches/cycle)

ΔK = cyclic stress intensity factor range at crack tip

C, n = Constants that depend on material and environment

Failure Criterion:

Fatigue crack initiates and grows to a critical size (a_{crit})

Stress Corrosion Cracking:

Crack Initiation Life:

$$t_{init} = f\ \text{(applied stress)}$$

where: t_{init} = time to initiate a stress corrosion crack

f = empirical function for specific material and environment

Stress Corrosion Crack Growth:

$$da/dt = C\,K^n$$

where: da/dt = crack propagation rate (e.g. inches/hour)

ΔK = sustained stress intensity factor at crack tip

C, n = Constants that depend on material and environment

Failure Criterion:

Stress corrosion crack initiates and grows to a critical size (a_{crit})

General Corrosion:

Wastage Rate:

$$d = C\,(time)^n$$

where:
d = general corrosion depth at any point in time (in.)
time = time since start of corrosion process (years)
C = effective corrosion rate, in the absence of coating, and considering the effects of Cathodic Protection (CP)
n = power law exponent for non-linear behavior (where applicable)

Pitting Rate:

$$d = C\,(time)^n$$

where:
d = total pit depth at any point in time (in.)
time = time since start of corrosion process (years)
C = effective corrosion rate, in the absence of coating, and considering the effects of Cathodic Protection (CP)
n = power law exponent (generally less than 1)

Coating Degradation:

$$F(CD) = C_0 + C_1 \text{ x time}$$

Where: F(CD) = Cumulative probability of coating degradation per unit length of piping as a function of time.

C_0 = Initial coating damage frequency (per unit length)

C_1 = Rate of occurrence of new coating damage (per unit length per unit time)

Cathodic Protection:

$$C(CP) = C * (1 - CP_{effectiveness})$$

where: C(CP) = Corrosion rate considering CP

C = Corrosion rate with no CP

$CP_{effectiveness}$ = estimate of effectiveness of cathodic protection system as function of system design, measured potential, etc.

Failure Criterion:

Corrosion depth proceeds to some critical depth (either leakage, or a depth that reduces structural margin under applied loads to zero).

If the parameters influencing time to failure in these equations are identified for the SSC being evaluated, and the equations are solved, they will yield a predicted time to failure for each degradation mechanism (a deterministic result). However, in order to evaluate failure rates for use in LCM evaluations, it is more useful to assign statistical uncertainty distributions to the key parameters influencing the failure rates, and to solve the equations in a probabilistic fashion. This process will yield a statistical distribution of time to failure, which can be converted into a failure rate distribution.

The recommended approach to solving the equations probabilistically is Monte Carlo analysis. The Monte Carlo analysis method is described in detail, including an example problem, in Appendix D.

6.4 Bayesian Updating

Once a probabilistic estimate of failure rate is determined using the methods of Section 6.3 above, the estimate can be updated to reflect failure experience using the Bayesian process. The Bayesian updating process is described in detail in Appendix A (Section A3). It refers to a method of estimation that combines prior knowledge or expectations regarding behavior of a statistical problem with actual physical observations of the behavior. By combining the two, we can generally come to a better estimate of expected behavior than with either of the approaches taken individually.

For example, the prior knowledge of expected behavior might result from using a physical model of the type described in 6.3 above. This will predict a certain failure rate or probability of failure versus time. This estimate can be combined (or adjusted) to agree with actual physical observations of failure in the system, either at the plant, or at other plants with similar systems (provided of course that there are no substantive differences in the stressors, operating conditions or other factors affecting the degradation mechanism among the plants). By updating the theoretical failure rate estimate (known as the "prior") in this fashion, we obtain a more accurate failure rate prediction (the "posterior") than either the theoretical prediction or a purely empirical prediction based on failure observations.

7
ILLUSTRATIVE APPLICATIONS

The illustrative applications selected for this guide were the Instrument Air System for active components, and buried Service Water Piping for passive components. Both systems are at the Wolf Creek plant operated by the Wolf Creek Nuclear Operating Corporation. These illustrations serve only as examples focusing on use of the innovative methods described in this guide to understand possible long-term effects on the failure rate of key equipment.

7.1 Instrument Air System

The Instrument Air System at Wolf Creek consists of motors, rotary screw compressors, air receivers, the unheated type of air dryers, and a significant amount of instrumentation and control equipment, normally considered to be part of the larger components. Table C-1 reveals that low voltage motors and dryers do not normally experience a refurbishment as a part of regularly scheduled preventive maintenance. Instrumentation causes a large fraction of failures on all compressors, as is revealed by searching EPIX for compressor failures. However, Table C-1 and the EPRI PM Basis database show that I&C components are replaced on fairly short time scales, making them uninteresting for LCM consideration. This information means that the motors and dryers should be examined for long term PM effects on failure rates. The rotary screw compressors are likely to have less impact on long-term air system reliability because overhaul is a key part of the standard PM program under all combinations of criticality, duty cycle, and service conditions. Nevertheless, this example will focus on the compressors, because they are a relatively new type of component, for which no generic failure data is available, and they also represent a good example of how to use the PM Basis database to examine assumptions about the overhaul and its interaction with other PM tasks.

7.1.1 Rotary Screw Compressors – PM Tasks and Time Dependence

Before looking in detail at individual PM tasks and potential time dependence of the failure rate, it is worth noting that the Wolf Creek compressors cycle between the loaded and unloaded state roughly every minute, suggesting that they are high duty cycle machines, but they are situated in a mild environment. Guidance on what constitutes high duty cycle, and severe service conditions for any given component can be found in the Definitions form of the PM Basis database. In any case, the recommended PM program for rotary screw compressors is insensitive to these conditions, as can be seen in the Template form.

Rotary screw compressors are nominally subject to an internal inspection at 4000 hours, and an annual overhaul which has the main objective of replacing elastomers in the inlet throttle valve, and unloader valve, and replacing the balance piston. The EPRI PM Basis database shows that there is little justification for performing the Internal Inspection at 4000 hours, but it notes:

"The key items of the balance piston, the unloader valve, and the inlet throttle valve suggest a minimum overhaul interval of 8000 run hours. If experience is favorable this might be extended. Performing an overhaul at approximately 1-year intervals does not appear to be cost-effective and may not be necessary. Although utility maintenance experience with these compressors is not extensive, the lack of rationale for the Internal Inspection at 6 months suggests that the Internal Inspection could be moved to a 9 month or 1 year interval and the tasks addressing the balance piston, the unloader valve, and the inlet throttle valve could be performed at the Internal Inspection. This would enable the Overhaul to be performed at a longer interval than 8000 run hours".

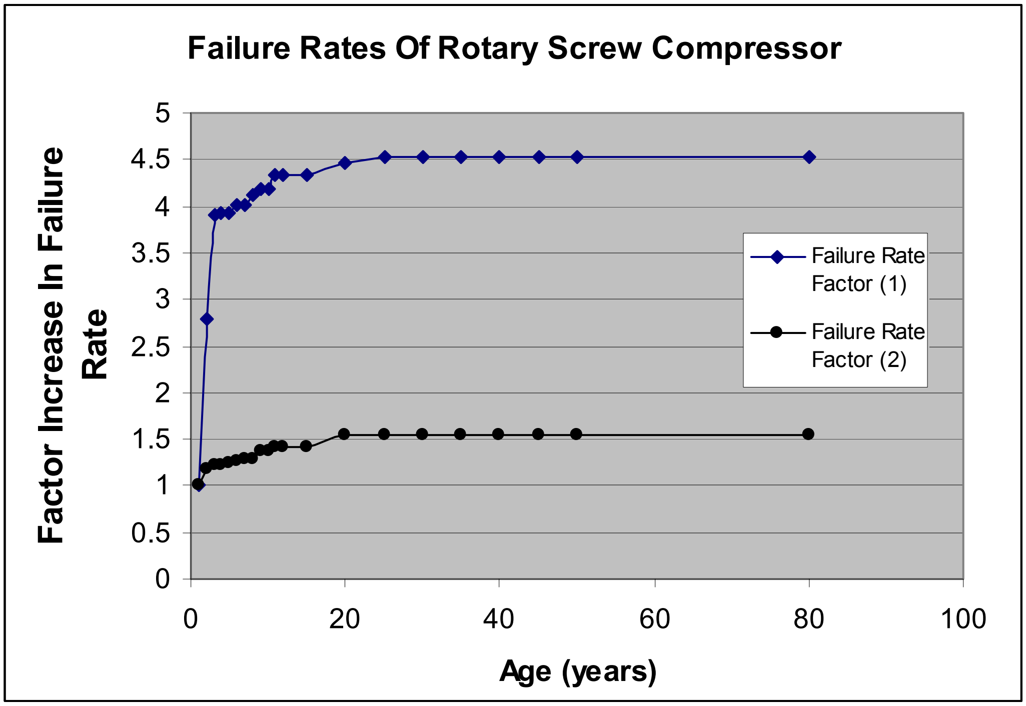


Figure 7-1
Failure Rates of a Rotary Screw Compressor, Depending on Assumptions about the Overhaul Scope and Interval

Currently, at Wolf Creek, this seems to be the case, since the overhaul has not yet been performed on any of the three rotary screw compressors, and will be done only on condition that it is needed, as indicated by conditions observed in more frequent tasks. It therefore seems that the short term wear-out failure mechanisms are probably being adequately addressed by regularly scheduled mechanical PMs at 2000, 4000, and 8000 hours. These activities should provide an opportunity to observe the condition of the major mechanical parts at an adequate interval. Figure 7-1, constructed following the procedure described in Section 5.3, demonstrates that this is indeed the case. However, the scope of these inspections should still be checked against the recommended task content in the PM Basis database to assure adequate coverage.

The first curve shows the time dependence of the failure rate assuming all tasks except the overhaul are performed. The steep rise in the range 1 to 3 years is the consequence of not attending to the short term wear-out modes affecting the balance piston, unloader valve, and the inlet throttle valve. The second curve shows the effect of removing the three key items from the overhaul and taking care of them in the Internal Inspection, equivalent to current practice at Wolf Creek. Even deleting the overhaul does not then have too serious an effect (~50% increase in failure rate), even after 20 years or more, because there are very few items that can only be addressed by the overhaul independently of other tasks. Even then, these do not necessarily cause failure at a specific time as many have to be triggered by other events or failures.

The current Wolf Creek PM program for these compressors does not include Oil Analysis, and the Vibration Analysis task is performed at a 6-month interval, instead of the 3-month interval recommended in the PM Basis. However, making these changes only increased the failure rate by 7%, in line with the information in the Task Ranking form of the database which states that any combination of Internal Inspection, Vibration Analysis, and Oil Analysis may be deleted without too serious an effect on compressor reliability – *providing the overhaul is performed.* If the overhaul is not performed, however, the lack of Oil Analysis raises the increase in failure rate from the ~50% shown in Figure 7-1 to about 66%. The extent to which the existing inspections can determine the wear on the bull gear and the condition of the oil – such as determining whether the oil is of the correct type, has not been determined by the analysis reported here. As for long term trends in the failure rate, these can be seen to vanish as the curves become horizontal at times longer than 20 years.

Table 7-1
Long Term Wear-out Mechanisms for Rotary Screw Compressors.

Failure Location	Degradation Mechanism	Degradation Influence (i.e. Stressor)	Wear-out Time Years
Bearings	Wear	Run time	10-15
Inlet Throttle Valve	Spring failure	Fatigue	10
LP & HP Elements	Wear or damage to screw elements	Inlet air quality, contamination	10-15
Lubrication	Low oil flow	Aging of pump	10-15
Lubrication	Low oil flow	Weak relief spring	10-15
Shaft seal	Cracking	Run time, i.e. heat / friction	5-10
Shaft seal	Wear	Run time, i.e. heat / friction	5-10

The reasons can be found by inspecting the records in the Degradation table of the database, where it is found that there are only a few aging mechanisms with wear-out times as long even as 10 to 15 years, and these are all protected by other tasks in addition to the overhaul. Table 7-1 lists the mechanisms of wear-out, which have minimum life times longer than 10 years, drawn from the PM Basis database.

The database reveals that when the overhaul is shifted to a nine year interval, three degradation mechanisms become essentially unprotected (shown by the number of 'Red' failure mechanisms in the Statistics form). All three concern loss of integrity of tube sheets and baffles in the inter- and after-coolers, either through failure to maintain cathodic protection, corrosion, or vibration. Despite the time frame, these are not necessarily long term mechanisms because they can also occur at times as short as 6 months under the right conditions. The only failure experienced so far on the Wolf Creek compressors involved a similar cooler failure on the C-machine in which the baffle plates in the bleed-off cooler were affected by fretting. If the Overhaul at Wolf Creek stays on an on-condition basis, it is important to determine the extent to which the lesser but more frequent inspections can evaluate the condition of the inter- and after-coolers, tube sheets and baffles.

The above analysis demonstrates that there may be some exposure to increasing failure rates because the overhaul is not performed on a regular basis and the Oil Analysis has been deleted. The magnitude and approximate time scales of the potential changes in failure rate has been estimated. Although more detailed analysis is clearly possible, the main features of the vulnerability to PM changes and long term wear-out failure mechanisms have been illuminated. Obviously, the reader's lack of familiarity with the PM Basis Database may render part of this analysis somewhat obscure, but the purpose of the example is to demonstrate what can be done when the user is experienced with the capabilities and features of the PM Basis database.

7.1.2 Baseline for the Compressor Failure Rate

The above analysis does not provide a scale for the failure rate charts. At Wolf Creek, one failure has occurred in 25 compressor years. A search of the EPIX database yielded 0 failures when the search was confined to Atlas Copco, water-cooled, rotary screw compressors in the ZR series, excluding the rotary lobe and rotary vane type. We therefore seek generic data for all compressors, equate the generic failure rate distribution to a gamma distribution by matching moments (using Section A12), and update it using the plant-specific experience of a single failure in 25 compressor years using the self-conjugate method of Section A10. Finally, we quote single point values as described in Section A13.

The Life Cycle Management Planning Sourcebooks – Volume 1: Instrument Air System [3] reports that failures reported to EPIX for all compressors, unloader valves and the inter-coolers and after-coolers numbered 148 in the 4 years 1997 through 2000. These numbers exclude failures of instrumentation and control components, and of piping, safety relief valves etc, and focus on components that represent the basic compressor – very similar to the way the component is defined in the PM Basis Database. The report also states that there were 142 compressor trains in existence during this time. This gives a mean value estimate of:

$$\lambda_{mean} = 148/(142x4) = 0.26 \text{ failures per compressor year}$$

Although the number of failures was almost certainly an over-estimate because of the inclusion of failures for which no cause was stated (therefore including some failures of instrumentation and other subcomponents), these statistics can provide a generic failure rate. We expect this generic estimate to be higher than it would be if we had generic experience for rotary screw compressors alone, because of the reputed good reliability of this design. However, experience with rotary screw compressors is very limited, leading us to be cautious in extrapolating the generic experience.

The plant specific experience has been good, with only one failure reported for the three compressors in 25 compressor years. The plant-specific statistics alone provide the following estimates using equations 1, 2, and 3 from Section A1:

$$\lambda_{mean} = 1/25 = 0.04$$

The upper 90% confidence bound, $\lambda_{90u} = \chi^2_{0.95}(4) / 50 = 9.488/50$

$= 0.190$

the lower 90% confidence bound, $\lambda_{90l} = \chi^2_{0.05}(2) / 50 = 0.103/50$

$= 0.0021.$

However, only one failure contributes to these results, and the uncertainty is therefore large – a ratio of 0.19/0.002 = 92 between the two confidence limits. We expect to improve this result significantly by incorporating the generic results. However, we do not have an uncertainty distribution for the EPIX results, and using equations 1 through 3 to create one on the basis of statistics alone would be very unwise because the large number of failures would create a small variance, quite out of step with the fact that we know very little about how homogeneous and representative the data sample is.

In these circumstances we have three choices for the generic failure rate distribution:

1. Use a two-step Bayes-Empirical-Bayes procedure to combine a uniform distribution (representing ignorance of the real distribution) with the generic EPIX data.

2. Seek a generic distribution for other rotating machinery, which might resemble compressors.

3. Assume a lognormal distribution for the generic information with a reasonably wide uncertainty distribution.

None of the three methods is very appealing, but the last is certainly the simplest, and probably at least as good as the others. Furthermore, experience has shown that a wide variety of generic data can be adequately represented by a lognormal distribution with an error factor of 5 or 10, but not so small as 3. The first method, using a uniform distribution in a BEB process, is not only more lengthy, but is open to the objection that a uniform distribution may be subject to theoretical concerns, and also does not do justice to our expectation that rotary screw compressors should indeed somewhat resemble other rotating machinery. The second choice is little different from the third, because we would be faced with a variety of generic distributions, and would have no way to choose between them that is clearly superior to using a lognormal distribution with a reasonable error factor.

To use a lognormal prior distribution use equations 20 through 24 of Section A9 to evaluate the parameters of the lognormal from two pieces of information, 1) the mean value is 0.26 failures per year, and 2) we assume an error factor of 10:

By equation 24: $10 = \exp(1.645\sigma)$: whence: $\sigma = (\log_e 10)/1.645 = 2.302/1.645 = 1.40$

The mean, 0.26, is given by $\lambda_m.\exp(\sigma^2/2)$, which gives the median, $\lambda_m = 0.26/\exp(1.4\text{x}1.4/2)$

or, $\lambda_m = 0.26/2.664 = 0.0976.$

The variance is $\lambda_m^2 . \exp(\sigma^2) . (\exp(\sigma^2) - 1) = 0.0976^2 . \exp(1.96)(\exp(1.96)-1) = 0.413$

The parameters of our lognormal generic distribution are thus:

Mean = 0.26, Median = 0.0976, $\sigma = 1.40$, Variance = 0.413 (σ is the standard deviation of $\log_e\lambda$, which is normally distributed, so it does not equal the square root of the variance of λ)

Using the error factor of 10, the upper and lower 90% confidence bounds are given by equation 31:

$\lambda_{90u} =$ 0.976, and $\lambda_{90l} =$ 0.00976

To perform a Bayesian update on this generic distribution, match the mean and variance to the mean and variance of a gamma distribution, as explained in Section A10.

Prior mean = bc = 0.26. Prior variance = $b^2c = 0.413$, whence b = 0.413/0.26 = 1.586.

The c parameter is therefore: 0.26/1.586 = 0.164.

Using equation 26, and our 1 plant specific failure in 25 compressor years, the posterior values of b and c are:

$c_{post} = 1 + 0.164 = 1.164$, and $b_{post} = 1.586/(1 + 25 . 1.586) = 1.586/40.65 = 0.039$

The posterior mean is thus $b_{post} . c_{post} = 0.039 . 1.164 = 0.0454$.

The posterior variance is thus $0.0454 . b_{post} = 0.0454 . 0.039 = 0.00178$

To make it more straightforward to plot the distributions, it is convenient to translate this posterior gamma distribution back into a lognormal, again by matching the mean and variance.

Lognormal variance = $\lambda_m^2 . \exp(\sigma^2) . (\exp(\sigma^2) - 1) = 0.00178$

Lognormal mean = $\lambda_m . \exp(\sigma^2/2) = 0.0454$; thus, squaring it gives $\lambda_m^2 . \exp(\sigma^2) = (0.0454)^2$

Substituting this into the variance gives: $(0.0454)^2 (\exp(\sigma^2) - 1) = 0.00178$,

or $\exp(\sigma^2) = 0.00178/(0.0454)^2 + 1 = 1.863$. So $\sigma = \sqrt{(\log_e 1.863)} = 0.789$.

Therefore, from the mean value expression:

The median, $\lambda_m = 0.0454/ \exp(\sigma^2/2) = 0.0454/\sqrt{1.863} = 0.0454/1.365 = 0.0332$

And error factor = $\exp(1.645\sigma) = \exp(1.645 . 0.789) = 3.66$, which is now <<10

The posterior parameters for the lognormal representation are therefore:

Mean = 0.0454, Median, λ_m = 0.0332, Error Factor = 3.66, λ_{90u} = 0.121, λ_{90l} = 0.00907.

Recall that the confidence limits for the prior distribution were λ_{90u} = 0.976, and λ_{90l} = 0.00976, and the prior mean was 0.26. It is clear that the generic data has been improved by the plant specific update, since the ratio between the upper and lower 90% confidence limits is now only a factor of 13.3, compared to 92 for the plant specific data alone, and 100 for the prior. The mean value has not changed by much as a result of the updating process, and is almost equal to the plant specific value.

The prior and posterior lognormal distributions are plotted on Figure 7-2

Either the mean or the median value can be used to multiply the failure rate factor, g(t), obtained from the Vulnerability evaluation in the PM Basis Database, with the meaning that it is the mean or the median respectively, which is varying in time.

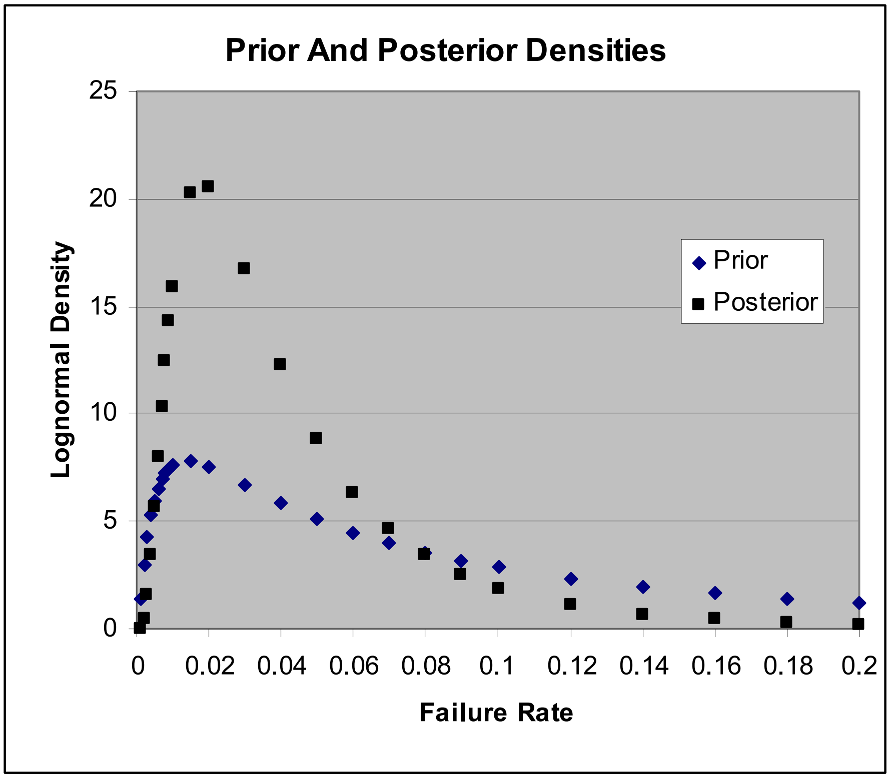


Figure 7-2
The Prior And Posterior Failure Rate Distributions

7.2 Buried Service Water Piping

7.2.1 Damage Mechanisms

Buried pipe will be subject to degradation from both the outside and inside surfaces. Buried pipeline failure can be defined as a through-wall penetration. Such failures can occur by numerous different mechanisms as listed below in approximate order of their importance in the gas pipeline industry :

- Third-Party Interference (Although by far the leading cause of failure in buried gas pipelines, third party damage is significantly less likely to occur within the boundaries of a reactor site)..
- External Corrosion
  - General Corrosion
  - Localized Corrosion – Pitting Corrosion, Crevice Corrosion and Intergranular Attack
  - Microbiological Influence Corrosion (MIC)
  - Galvanic Corrosion

  - Environmentally Assisted Cracking (EAC)- Stress Corrosion Cracking (SCC) and Corrosion Fatigue
  - Corrosion due to Stray Currents
- Internal Corrosion
  - General Corrosion
  - Localized Corrosion
  - MIC
  - EAC
- Fabrication Defects
- Operator Errors (e.g., over-pressurization)
- Fatigue
  - Pressure Cycling
  - Thermal Cycling
- Mechanical Overload
- Secondary Damage (e.g., overload due to loss of support as undetected small leaks produce erosion of backfill)
- Heavy fouling/clogging

Some of the above potential failure mechanisms, especially when related to corrosion mechanisms, warrant some explanation as discussed in Sections 7.2.1.1 through 7.2.1.6.

7.2.1.1 General Corrosion

This form of corrosion is by far the most common of the various forms of corrosion. It is typically characterized by an electrochemical reaction that occurs uniformly over an entire surface area where there is continuous movement of (micro) anodes and cathodes on the metal surface. The metal thins down and eventually fails, either by through-wall penetration or a lack of cross sectional area to support a load. Although general corrosion represents the greatest loss of material on a tonnage basis, general corrosion is usually not a significant concern from a purely engineering viewpoint since the life of equipment as limited by general corrosion can be accurately predicted from the results of comparatively simple corrosion tests.

When a bright fresh metal surface is first exposed to a corrosive environment, an electrochemical reaction between the metal surface and the environment will initiate at some rate. As time passes, the rate of general corrosion typically changes. It can increase, decrease or remain relatively constant. The way in which the general corrosion rate changes with time for a particular system is controlled by a number of factors. The two most important of these factors are the nature of the oxide film formed on the metal surface and the time-dependent characteristics of the environment to which the metal is exposed.

For example, when an iron specimen is exposed to an oxygenated acidic solution, the weight change of the specimen per unit time is nearly constant. A plot of the weight change (loss) versus time is linear. This constant corrosion rate is attributed to the non-protective nature of the oxide film that forms when iron is exposed to an environment that has ready access to the metal surface.

When a specimen of corrosion-resistant stainless steel is exposed to water, the weight change per unit time, i.e., corrosion rate, of the specimen is observed to decrease with increasing time. A plot of the weight change as a function of time has a parabolic shape. The decreasing corrosion rate is attributed to a thickening of the protective passive oxide film that forms on the stainless steel surface. Metals that form protective oxide films exhibit this type of general corrosion behavior. Diffusion of ions or the migration of electrons controls the rate of corrosion. As the oxide thickens, diffusion and migration become more difficult.

7.2.1.2 Localized Corrosion

Localized corrosion involves stationary electrodes, i.e., one area of the metal surface is the anode and another area is the cathode. There are many forms of localized corrosion including crevice corrosion, pitting corrosion and intergranular attack. The nature of the localized corrosion tends to produce metal loss at ever increasing rates as the environment within the pit or electrochemical crevice is isolated from the bulk environment and that localized environment becomes acidified and enriched in damaging ions such as chlorides and sulfates.

Pitting is one of the most destructive and insidious forms of corrosion since it can cause equipment failures due to perforation with essentially no weight loss of the component. It is often difficult to detect pits due to their small size and because they are often covered by corrosion product. Like crevice corrosion, pitting occurs in stagnant environments. Pits usually growth in the direction of gravity due to the creation of a dense concentrated solution in the pit. Pitting is typically characterized by an extended initiation period followed by an auto catalytic (snowballing) propagation. The deepest pit as opposed to the average pit depth is the key concern since it is the deepest pit that will cause perforation. Finally, the relative probability of identifying a pit of a given depth is a function of the area, i.e., the larger the surface area, the deeper the pits. Therefore, laboratory tests cannot be readily used to predict the pitting depths on an actual component.

Crevice corrosion is characterized by a geometrical configuration in which the cathodic reactant, such as dissolved oxygen, can readily gain access by natural or forced convection and diffusion to the metal surface outside the crevice, whereas access to the layer of stagnant solution within the crevice is far more difficult and can be achieved only by diffusion through the narrow mouth of the crevice. However, the presence of a geometrical crevice does not equate to the creation of an electrochemical crevice. If the flow in the geometrical crevice is sufficient to restore the dissolved oxygen content and, thus, eliminate the electrochemical crevice, crevice corrosion will not occur.

Intergranular attack (IGA) is the preferential corrosion of the grain boundary region due to impurity segregation, enrichment or depletion of alloying elements (e.g., chromium depletion) and/or heat treatment induced solid-state reactions at the grain boundary. The more active grain boundary regions act as small anodes galvanically coupled to larger more cathodic grains.

7.2.1.3 Microbiologically Influenced Corrosion (MIC)

Bacteria are responsible for a significant amount of degradation in service water systems. Unfortunately, bacterial interactions with service water systems materials also represent a very complex combination of environmental and biological conditions, which can change and/or be extremely localized. While MIC has been known to exist since the early 1900s, the various mechanisms and interactions are still being discovered and studied.

One MIC mechanism occurs in oxygenated environments where the organism can promote the growth of other organisms. An example of this set of conditions is when slime forming bacteria create a sticky coating on the inside diameter of pipes or tubes. This slimy coating not only entrains other organisms that are being carried in the bulk water, but also provides a potential nutrient source for these other bacteria. *Bacillus* bacteria are just one of the groups that create the extra-polymeric slime being discussed. These organisms are not causing corrosion themselves but they may be influencing the growth of other corrosion causing organisms in this oxygen rich environment. Certain organisms can directly attack the base material in the presence of oxygen. An example is the *Thiobacillus* bacteria that oxidize sulfur and contribute to the creation of sulfuric acid, which in turn corrodes the base metal.

Anaerobic organisms thrive only in the absence or near absence of oxygen. Deposits of aerobic bacteria form tight adhering nodules that create anaerobic under-deposit conditions that are ideal for the anaerobic bacteria. The result can be a separate colony of organisms thriving below the original bacteria that created the nodule.

7.2.1.4 Galvanic Corrosion

Two dissimilar metals in contact with each other, in the presence of an electrolytic solution, can result in galvanic corrosion. The vulnerability of various metals to galvanic corrosion is a function of their position in a galvanic series. This series is commonly defined for materials in seawater, but has also been defined in a variety of other environments. Metals higher in the series (more negative) tend to become the anode and therefore lose material during the corrosion process.

Table 7-2 shows the galvanic series order of some commonly used piping materials. Those metals at the top of the series have a tendency to be anodic and therefore will be degraded when coupled with a metal that is lower in the series. Basically the further apart they are, the stronger the potential for a reaction between the two materials. The spaces between some of the metals are to indicate the basic groupings of materials with similar or closely related galvanic properties. As an example, it would not be wise to couple a mild steel component to a copper component without some form of insulation between them. A second approach, one that is commonly used in home plumbing, is to insert a third material, one that is intermediate between steel and copper (e.g., a brass) to produce two smaller galvanic couples.

Table 7-2
Simplified Galvanic Series for Common Buried Piping Materials (in Seawater)

Magnesium
Magnesium alloys
Zinc
Aluminum
Mild Steel
Wrought Iron
Cast Iron
Stainless Steel(304 active)
Tin Muntz Metals
Naval Brass
Yellow Brass
Red Brass
Copper
Inconel (passive)
Monel
Titanium
Stainless Steel (304 passive)
Stainless Steel (316 passive)

Another key design consideration for galvanically coupled metals is the relative sizes of the cathodic and anodic areas. If there is a large cathodic area, and a smaller anodic area, then the total corrosion current produced will be greater.. Hence, the corrosion of the more active metal will be accelerated. The results can be a rapid corrosion that could result in through-wall penetrations at the site of the anode in fairly short time.

7.2.1.5 Environmentally Assisted Cracking

Most alloys when subjected to an external or residual tensile stress and contact with certain environments develop cracks. Stress corrosion cracking (SCC) is the term given to this sub-critical crack growth of susceptible alloys under the influence of a tensile stress of sufficient magnitude while exposed to a "corrosive" environment. SCC is a very complex phenomenon that has interrelated mechanical, electrochemical and metallurgical factors.

The most critical factor concerning SCC is that SCC is a "conjoint" phenomenon where the three conditions necessary for producing SCC must be simultaneously present. The elimination of any one of these three factors or the reduction of one of these three factors below some threshold level eliminates SCC. The three **necessary** conditions for SCC are:

1. A susceptible material

2. A tensile stress (applied and/or residual)

3. A corrosive environment (an environment that can provide the electrochemical driving force for the corrosion reaction)

SCC can proceed through a material in two modes, intergranular (through the grain boundaries) and transgranular (through the grains). Sometimes the modes are mixed or the mode switches from one mode to the other. Intergranular stress corrosion cracking (IGSCC) and transgranular stress corrosion cracking (TGSCC) often occur in the same alloy depending on the environment, the microstructure or the stress/strain state. SCC usually occurs perpendicular to the tensile stress.

Fatigue, the number one cause of materials failures, is the tendency of a metal to fracture under repeated cyclic stressing. Corrosion fatigue is fatigue aggravated by corrosion reactions. Since fatigue failures usually occur at stress levels below the yield stress after numerous cycles, the presence of a corrosive environment reduces the number of cycles to failure and reduces the stress level at which failure occurs. The nominal fatigue limit, if any, is eliminated. Thus, corrosion fatigue is the reduction of the fatigue resistance of a material due to the presence of a corrosive environment. Although corrosion fatigue is characterized by cracking like SCC, corrosion fatigue is not environmentally specific, i.e., all environments will reduce the fatigue life of a component. Also, almost all corrosion fatigue cracking is transgranular.

7.2.1.6 Corrosion due to Stray Currents

Stray currents from a piping cathodic protection system (see Section 7.3 3), railway systems, mining operations, welding operations, etc. can detrimentally affect buried structures. For example, the stray currents from a cathodic protection system can convert a nearby separate piping system into a sacrificial anode for the other piping system. This phenomenon often occurs in marinas where adjacent docked ship's cathodic protection systems compete with each other for corrosion control dominance.

7.2.2 Buried Piping Failure Mitigation

Most of the approaches for pipeline failure mitigation involve corrosion mitigation on the exterior surface. The dominant mitigation techniques include coatings, cathodic protection, a combination of coatings and cathodic protection, chemical treatment (ID) and cleaning (ID).

7.2.2.1 Coatings

Coatings create a physical protective barrier between the soil electrolyte and the metal pipe. There are three types of coatings: inert or essentially inert, inhibitive and sacrificial. Various combinations of these three types of coatings are found in many coating systems. However, no coating is "perfect." Asphalts and bitumen asphalts derived from petroleum and coal, respectively, are widely used by themselves and in combination with other materials such as epoxies to form useful coatings for buried piping.

7.2.2.2 Cathodic Protection

Cathodic protection is a process to reduce corrosion of a structure by changing it from an anode to a cathode by an impressed current or connecting it to a more active metal, i.e., a sacrificial anode such as magnesium, aluminum or zinc, Figure 7-3.

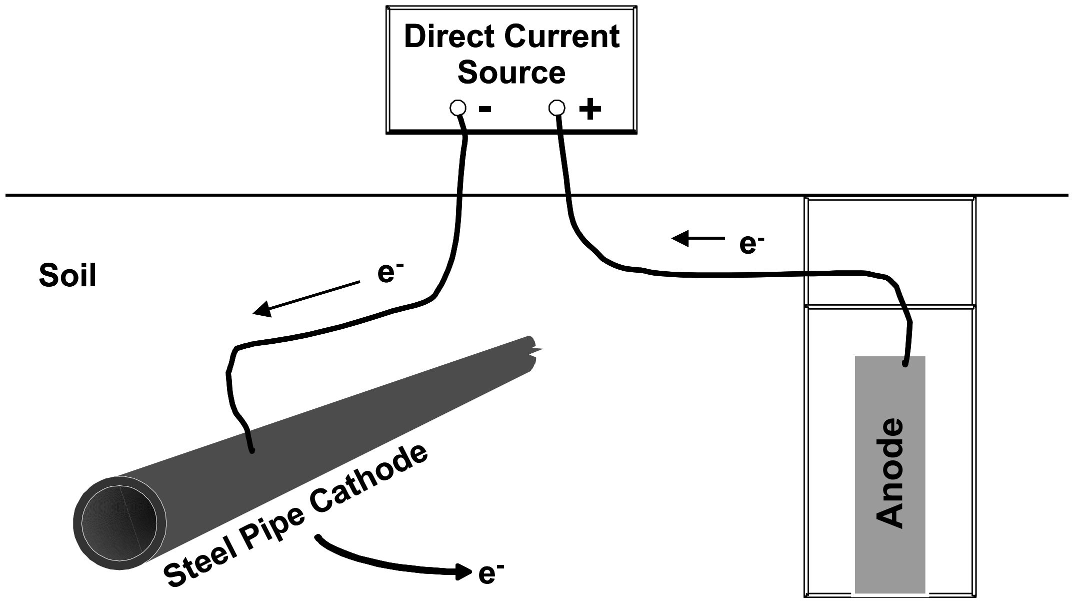


Figure 7-3
Cathodic Protection of a Buried Pipe

Buried piping, because it is surrounded by an electrolyte, is where cathodic protection is most often used. Since most metal surfaces form natural anode/cathode areas, the key is to stop or redirect the formation of the anode. Impressing a direct current to the surface to be protected and providing a sacrificial anode that can be replaced, protects the piping base material. When cathodic protection is successfully applied, the entire surface of the pipe to be protected becomes a cathode and is highly resistant to corrosion.

7.2.2.3 Chemical Treatment

Appropriate water chemical treatment programs are as varied as the types of plants, water qualities and service conditions that make each plant (unit) unique. Inhibitors are added to some service water systems for corrosion control. Inhibitors typically produce a more protective corrosion product film so that general and localized corrosion are mitigated.

Deposit control agents are used to eliminate or minimize deposition and accumulation of minerals deposited from solution or from suspension. Effective control of deposits maintains heat transfer through heat exchangers, eliminates clogging of piping or heat exchanger tubes, and avoids sites where localized corrosion can occur beneath deposits.

The two basic strategies for controlling microorganisms are the use of biocides and biostats. A biocide is a chemical agent that kills bacteria, while a biostat is a chemical that inhibits the growth of bacteria.

The most common biocide is chlorine. It is a very effective oxidizing agent that can kill most bacteria under the proper conditions. Chlorine is, however, sensitive to pH and when the pH exceeds (approximately) 8.0 the ability of chlorine to destroy bacteria decreases rapidly. Bromine has been used as an effective biocide in situations where the normal pH exceeds 8.0. Chlorine can also potentially degrade certain materials.

Other drawbacks to using these oxidizing biocides must also be recognized. One drawback is that oxidizing biocides can shift the corrosion potential to the point that it can increase the general corrosion rates in carbon steel and pitting in stainless steels and copper alloys. A second is the fact that when these chemicals produce oxygen they can create problems such as water hammer.

EPA discharge limits have also become a factor in the use of these chemicals and some plants have sought alternatives such as hydrogen peroxide and ozone. These are more environmentally friendly, but have other problems such as cost and viability. They can also exhibit the same drawbacks as the other oxidizing biocides.

Other non-oxidizing biocides are available such as the quaternary amines, gluteraldehyde and isothiazolin. A significant advantage they have over the oxidizing biocides is that in the same concentrations they are much less corrosive. They are much more expensive and must be used in higher concentration and their experience base is limited.

7.2.2.4 Cleaning

Cleaning is an advisable policy for any system but it is especially valid for minimizing corrosion problems. Two categories of cleaning strategies can be defined: chemical and mechanical. These can be mutually exclusive or they may be used together in one cleaning program.

7.2.2.4.1 Mechanical Cleaning

Making the assumption that corrosion deposits are established on the surface of the pipe, an initially aggressive cleaning strategy can be evaluated. Several different mechanical techniques are available. Scrapers with various abrasive qualities can be inserted into the pipe. The degree of abrasion should be chosen based on the material to be removed and the type of base metal being cleaned. Pushing these devices through the pipe can be accomplished by hydraulic pressure by using either water or air. These are effective and provide the least problem when they are used in straight runs, although many can negotiate some elbows.

Other mechanical processes include water jets (hydro lasing), sand jetting, air bumping and even dry ice pellets. One of the problems associated with the cleaning process is disposal of the residue when the cleaning process is completed. Air bumping has a limited impact on tightly adhering deposits.

7.2.2.4.2 Chemical Cleaning

In a chemical cleaning process several things must be considered including the deposit characteristics (such as quantity of material and chemical constituents), the base metal composition, whether the chemical cleaning will be performed on-line or off-line, the compatibility with on-going water treatment programs, the quantity and disposal of hazardous wastes, etc.

The type of deposit to be removed typically governs the choice of the various cleaning agents. Two standard categories include (1) scale and metal oxides (e.g., ammoniated citric acid, ethylenediamine tetra acetic acid [EDTA], phosphonates/phosphorous acid, sulfuric acid, 1-hydroxy-ethylidine-1,1-diphosphonic acid [HEDP], etc.) and (2) organic deposits (oxidizing agents, polymeric ionic dispersants non-oxidizing biocides, alkaline surfactant detergents, nonionic penetrant/dispersants, nonionic alkyl surfactants, etc.)

7.2.3 Important Buried Piping Characteristics

Based on the results of a Dutch buried gas pipeline failure frequency study [11], the following pipe and environmental characteristic appear to be important to failure frequency modeling of buried piping:

- Pipe Characteristics
  - Alloy
  - Pipe wall thickness
  - Pipe diameter
  - Ground cover
  - Coating
  - Age of pipe (since last inspection)
- Environmental Characteristics
  - Frequency of construction activity
  - Frequency of drainage, pile driving, deep plowing, placing dam walls
  - Percent of pipe under water table
  - Percent of pipe exposed to fluctuating water table
  - Percent of pipe exposed to heavy root growth
  - Percent of pipe exposed to chemical contamination
  - Soil type (sand, clay, peat, etc.)
  - Soil pH
  - Soil resistivity
  - Cathodic protection

– Number of rectifiers
– Frequency of rectifier inspections
– Presence of stray currents
– Number of bond sites

The model yielded an uncertainty distribution over the failure frequency per kilometer when values for the above parameters were specified in the Dutch study. Although some failure data was available, the data was not sufficient to quantify all the parameters of the model. In fact, the data provide significant estimates only when it was aggregated over large populations. However, maintenance decisions involve specific pipe segments not large populations.

The overall lack of data resulted in significant uncertainties. It was determined that the effects of pipe or environmental characteristics were best understood in terms of their effects on the uncertainty of failure frequency. The model addressed such examples as:

1. Given a 9 inch diameter pipe with a 0.28 inch wall located in sandy soil since 1960 with a bitumen coating, etc. what is the probability that the failure frequency per year due to corrosion will exceed the yearly failure frequency due to third-party interference?

2. Given a 9-inch diameter pipe with a 0.28-inch wall located in sandy soil since 1970 with heavy root growth, chemical contamination and fluctuating water table, how is the uncertainty in failure frequency affected by the type of coating?

3. Given a clay soil with a pH of 4.3, resistivity of 4,000 ohm-cm and a pipe exposed to fluctuating water table, which factors or combinations of factors are associated with high corrosion rate?

To solve these quandaries, the investigators had to resolve the following three problems:

1. How should the failure frequency be modeled as a function of the above listed pipe and environmental parameters so as to optimize the existing data?

2. How should existing data be supplemented with structured expert judgment?

3. How can information involving complex interdependencies be communicated easily to management?

The distinctive feature of this study was that the investigators modeled not only the failure frequency, but also the uncertainty in the failure frequency. It is therefore useful to summarize the Dutch approach to modeling uncertainty.

7.2.4 Modeling Uncertainty

The failure of buried piping is a complex phenomenon that depends on physical and electrochemical processes, piping characteristics, inspection and preventive maintenance policies, and third party interactions. Although a significant amount of buried pipeline information is available, this information is not sufficient to predict failure frequency under all relevant conditions. Therefore, predictions of failure frequencies involve significant uncertainties and utility management requires a defensible and traceable assessment of these uncertainties [11].

For example, a one-mile length of buried pipe is observed for one year and the number of failures is recorded. The number of failures may be zero, one, two, etc., most probably zero. The failure frequency for this one mile-year will be zero. If a large number of one mile sections of buried pipe with common physical characteristics (e.g., all 9 inch diameter coated piping in sand) are monitored for a number of years, a failure frequency can be calculated by dividing the total number of failures by the number of mile-years.

Both of the above example failure frequencies are empirical failure frequencies that can be readily measured. If the failure frequency per mile-year as a function of certain specified characteristics is desired, then the population of mile-years is no longer an empirical population. It is a virtual population consisting of all potential specified characteristics. The virtual population is not precisely defined since the specified characteristics cannot specify all the parameters of the pipeline. They can only specify the characteristics that are chosen. Specifying the intended virtual population would require specifying the distributions of all relevant parameters over that population, which is virtually impossible.

The Dutch study addressed this concern by indirectly specifying the virtual population, regarding the observed mile-years as a random sample of the virtual population [11]. This means that the distribution of unspecified variables is that which would be approximated in a large number of mile-years by the empirical population of pipelines. The investigators indicated that the virtual population specified by this approach need not be statistically homogeneous, i.e., it may contain statistically distinct sub-populations. Basically, the empirical population of mile-years is regarded as a random sample from the virtual population.

Hence, the failure frequency per mile-year of buried pipe as a function of specified characteristics is a physically measurable quantity that can be measured by observing large empirical populations. The uncertainty in these measurements is statistical, i.e., it is due to sampling fluctuations. This type of uncertainty can be quantified by statistical techniques.

Since there are too many characteristics that must be specified and the empirical populations may be too small to support statistical estimates, expert engineering judgment must often be applied to assess the failure frequencies [11]. Experts quantify their uncertainty relative to the physically measurable quantities (failure frequency per mile-year under given conditions) by stating their subjective probability distributions for the quantities in question. When these distributions are appropriately combined, the result is a “combined expert” subjective probability distribution over a physically measurable quantity. More precisely, this method provides a combined expert uncertainty distribution as a function of the values of the various physical variables, and conditional on the probabilities of certain events from historical data. The uncertainty over these parameters and event probabilities can be factored at a latter stage to produce overall uncertainty distributions.

7.2.5 Wolf Creek Buried Piping Evaluation

7.2.5.1 Wolf Creek Buried Piping General Description

The Wolf Creek buried piping system selected for this illustrative application is outlined in Table 7-3 [12].

Table 7-3
Wolf Creek Buried Piping System

Item	Description			
	Alloy	Diameter, in.	Length, ft.	Thickness, in.
Piping 1	Carbon steel (ASTM A283)	42	2,950	0.375
Piping 2	Carbon steel (ANSI B31.1) Class 150	30	375	0.365
Piping 3	Carbon steel (ANSI B31.1), Class 150	24	62	0.365
Joints	Welded			
OD Coating	Coal-tar enamel protective coating for steel water pipe, American Water Work Association (AWWA) Standards C-203-73			
Coating degradation	Yes			
Pressure, psig	80-140			
Temperature, ºF	32 - 90			
Flow rate, gpm	25,000 - 45,000			
Water source	Lake			
Corrosion mitigation system	Cathodic protection monitored monthly for potential			
MIC experience	No			
Biofouling experience	No			
Leakage	Three external originated leaks			

7.2.5.2 Wolf Creek Buried Piping Cathodic Protection System History

The original Wolf Creek cathodic protection system (April 1984) consisted of approximately 288 close proximity pre-packaged anodes in 10 foot deep holes, 14 inches in diameter with coke breeze backfill [12]. Two 120-ampere/50 volt rectifiers and two 60-ampere/50 volt rectifiers powered the anodes. However, it was determined that this system did not provide sufficient protection to several areas of the plant, so a series of upgrades were implemented, as described below .

Based on industry information concerning cathodic protection of nuclear power plant, the plant staff decided that a remote bed should be installed. A survey was conducted to identify the areas where shielding was a problem so that close proximity anodes could be installed. In 1990, a remote anode bed was installed that provided protection to most of the piping away from the power block . The system consisted of 100 Durichlor™ 51 TA5A anodes in 14 inch by 15 feet deep holes. This bed is located approximately 1200 feet southwest from the plant fence near the plant lakeshore line. These anodes are powered by two 450-ampere/120 volt rectifiers.

On September 23, 1999, approximately 25 new close proximity anodes were energized on the west side of the power block.. A 300-ampere/60 volt rectifier powers this system. The anode holes are 20 inches in diameter by 25 feet deep. Each hole contains two 175 pound, Durichlor™ 51, TA5A anodes and approximately 3500 pounds of coke breeze. They are spaced approximately 50 feet apart. A similar system on the east side of the power block was energized on January 8, 2002.

In summary, the plant site incorporates approximately 70 large, double stacked, vertical, two horizontal double and one 6 horizontal close proximity anodes. Two 300-ampere/60 volt rectifiers, two old 120 ampere/50 volt rectifiers and one old 60-ampere/50 volt rectifier power the system. There are three large non-stacked close proximity anodes at the circulating water screen house powered by the other old 60-ampere/50 volt rectifier. The remote bed is in operation. There is small system at the potable water pump house consisting of six TA3 anodes powered by a 12-ampere/24 volt rectifier. The engineering staff at Wolf Creek is replacing consumed anodes at the wastewater treatment facility. A 120-ampere/50 volt rectifier powers this system.

All piping is connected to the plant ground mat. The negative sides of all rectifiers are connected to the plant ground mat. All building steel is connected to the plant ground mat. The plant ground mat was tested on January 7, 1985. It was measured to be 0.060 to 0.061 Ohms to remote earth.

7.2.5.3 Wolf Creek Buried Piping Cathodic Protection Monitoring

The cathodic protection system is checked on a monthly basis for rectifier output, permanent test station potentials and surface potentials with a portable half-cell [12]. Typically, the potentials are in the range of -1.000 Volt to -2.000 Volts. Measurements close to the anodes are more negative. Permanent half-cell test stations with an isolatable test coupon to measure the polarization potential without the effect of IR drop are being installed. The system is draining approximately 1156 amperes (total). It is believed that all piping system areas are currently receiving sufficient protection.

7.2.5.4 Wolf Creek Buried Piping Soil Characteristics

The metal to soil potential values vary from -0.961 volts at TS11 to -3.084 Volts at TS23. TS23 is the northern most test station [12]. It is connected to the lime sludge discharge line on the opposite end of the plant from the remote anode bed. The remote anode bed is causing the -3.084-volt shift from ¾ of a mile away. Most test station values are between -1.000 volts to -2.000 volts.

On September 4, 1974 soil resistance measurements were made. The four-pin method provided values that ranged from 7.66 ohmmeters to 59.37 ohmmeters. The “Vibroground” instrument provided a value of 27.29 ohmmeters and 38.30 ohmmeters. A report by a vendor indicated a soil resistivity of approximately 33 ohmmeters. Much of the plant site was excavated and has a gravel and gravel-clay back fill.

Construction photographs indicate that the back fill on much of the piping was power tamped gravel or a power tamped gravel-clay mixture. This operation may have damaged some of the pipe coatings.

7.2.5.5 Wolf Creek Buried Piping Failure History and Repair

The first leak was identified during the summer of 1992 [12]. In April of 1993, an inspection of the pipe’s interior identified a leak (hole) in Service Water supply line EA-029-HBD-20”. This leak was caused by localized corrosion from the exterior surface due to exterior coating failure. The failure was promoted by inadequate cathodic protection. To stop this leak, a 0.375-inch x 6 inch x 9-inch patch fabricated of A106 Gr. B carbon steel was welded over the leak region. Two subsequent leaks were repaired using the same method.

7.2.6 Physical Modeling of Wolf Creek Buried Piping

Closer review of the general damage mechanisms for buried piping identified in 7.2.1 allows a number of them to be screened out as non-applicable to the Wolf Creek buried service water piping. Although third party damage is the leading cause of failure of buried pipelines in general, it is considered that sufficient controls will be enforced within a nuclear plant protected area such as Wolf Creek that the likelihood of inadvertent damage to important buried piping systems is virtually nil. Fabrication defects, while likely to be present, have not led to any problems during the long period of plant operation until present, and therefore are unlikely to lead to problems in the future unless they are acted upon by some other service related degradation mechanism that causes them to grow (such as those evaluated below). Therefore, the evaluations of active service degradation conditions should include any potential effects of preexisting fabrication defects, and they are considered sufficient to address this concern. Operator errors of sufficient magnitude to cause a rupture or significant damage are also unlikely in the service water system. Fatigue damage is screened out as not applicable because the operating temperature and pressure of the system are both small, and there are no significant vibration sources near the buried portion of the system. Per Table 7-3 the current study addresses only large diameter piping, such that heavy fouling or clogging are not serious concerns.

That leaves external and internal corrosion as the only degradation mechanisms that need to be evaluated as part of a long-term reliability assessment.

7.2.6.1 External Corrosion

External corrosion is a common failure mechanism in buried piping in nuclear plants, as it is for buried piping in general. In fact, the subject piping at Wolf Creek has experienced some failures (leakage) due to this cause. For the buried piping to fail due to external corrosion, two lines of defense must be breached, however. [11] First, the protective coating must be damaged, and second, depending on the location of the coating damage, the cathodic or stray current protection system must not be functioning as intended. Coating damage may be present from initial construction, or may occur in service due to third party damage or environmental factors.

Assuming that the coating has been breached, general corrosion and pit corrosion will reduce the wall thickness until a critical value is reached, at which point the pipe fails. There are numerous references that provide methodology for critical flaw or corrosion cavity depths as a function of the size of the degradation [13, 14]. However, for a low-pressure system such as the service water system, it is conservative to assume that the critical form of external corrosion is a pit (since pitting corrosion rates are much faster than the general corrosion rate) and that failure will occur when the pit depth reaches the wall thickness (i.e. leakage). Thus:

$$d = C\,(\text{time})^{n} \qquad \textbf{Eq. 7-1}$$

$$\text{time} = (d/C)^{1/n} \qquad \textbf{Eq. 7-2}$$

$$EL = (th/C)^{1/n} \qquad \textbf{Eq. 7-3}$$

where: d = total pit depth at any point in time (in.)

time = time since start of corrosion process (years)

EL= Effective Life of the piping (time to failure)

th = original piping wall thickness, and

C = effective corrosion rate, in the absence of coating, and considering the effects of Cathodic Protection (CP)

n = an exponent (generally less than 1)

Note that the parameters controlling the effective life in the above equation (th and C) are uncertain, and likely to be statistically distributed. (In a perfectly general formulation, n would also be uncertain, but for purposes of this analysis, it is assumed to be a known, deterministic parameter.) Piping is generally procured to a wall thickness tolerance of ±12.5%. The corrosion rate (C) is a function of a number of factors, including piping material, soil type and acidity (ph), stray currents and status of the cathodic protection system. Furthermore, equation (3) only applies at locations where the protective coating has been breached, and coating damage is also likely to be statistically distributed over the piping surface. The following paragraphs describe a statistical treatment of these uncertainties, which has been adapted from [11].

As defined in Section 6.3, Coating Damage (CD) is commonly characterized by a frequency of occurrence per unit length and time (e.g. N occurrences per year per mile of buried piping). The characterization may have a time-independent term, to account for construction coating defects, and an environmental term that would be expected to increase with time.

$$F(CD) = C_0 + C_1 \text{ x time} \qquad \textbf{Eq. 7-4}$$

Where: F(CD) = Cumulative probability of coating degradation per unit length of piping as a function of time.

C_0 = Initial coating damage frequency (per unit length)

C_1 = Rate of occurrence of new coating damage (per unit length per unit time)

In a perfectly general sense, the time-dependent term might also include the potential for coating damage due to third party interference, but once again, in a carefully controlled nuclear plant environment, the potential for third party damage is considered nil. Thus the C_1 term in equation (4) is solely a function of the type of coating and environmental factors such as soil type, water table, tree roots, and potential chemical contamination. Data exists on these sources of coating damage from oil and gas pipelines [14, 15].

Note that equation (4) gives an observable frequency, not a probability, since it has physical dimensions, and can assume any non-negative value (e.g. 10 damage zones per year per mile of piping. Probabilities are dimensionless, and must be between zero and one. Under suitable assumptions, however, frequencies can be transformed into probabilities to permit their use in failure rate computations. If we assume, for example, that the average number of construction coating defects is N per mile, and that the occurrences follow a Poisson distribution with respect to distance along the pipe length, then we can divide the pipe into a number of smaller segments, for which the probability of degradation occurring in one segment is much less than unity, such that the probability of two events occurring in one segment is very small. In this case, N / (# of segments) is approximately the probability of one event occurring in a segment.

Finally, the Cathodic Protection (CP) system is generally made up of a series of sacrificial anodes, powered by a series of rectifiers, and spaced periodically along the length of the buried piping. Depending on the details of the CP system, it generally can be assumed that the system is fully effective near the anodes. However, if the spacing between the anodes is too large, or the imposed potential is insufficient for the specific soil conditions and piping, then the CP system will have reduced effectiveness at points between the anodes. The effectiveness of the CP system might thus be visualized as the saw-tooth function illustrated in Figure 7-4, in which the effectiveness varies linearly between a maximum and minimum value over the length of the pipe (i.e. the maximum and minimums of the saw-tooth function in Fig. 7-4). Specific values of the maximum and minimum effectiveness will depend upon the specifics of the CP system for the piping being evaluated [13, 14].

Finally, per Ref. [11], the corrosion rate may be adjusted for cathodic protection effectiveness in the following manner:

$$C(CP) = C * (1 - CP_{effectiveness})$$ **Eq. 7-5**

where: $C(CP)$ = Corrosion rate considering CP

C = Corrosion rate with no CP

$CP_{effectiveness}$ = estimate of effectiveness of cathodic protection system as function of system design, measured potential, etc.

Thus if the $CP_{effectiveness}$ is 1 (100% effective) the corrosion rate is zero. If the $CP_{effectiveness}$ is 0.6 (60% effective), the corrosion rate is 40% of the base rate, and so on, with decreasing CP effectiveness resulting in linearly increasing corrosion rates, up to the base rate, for totally ineffective CP.

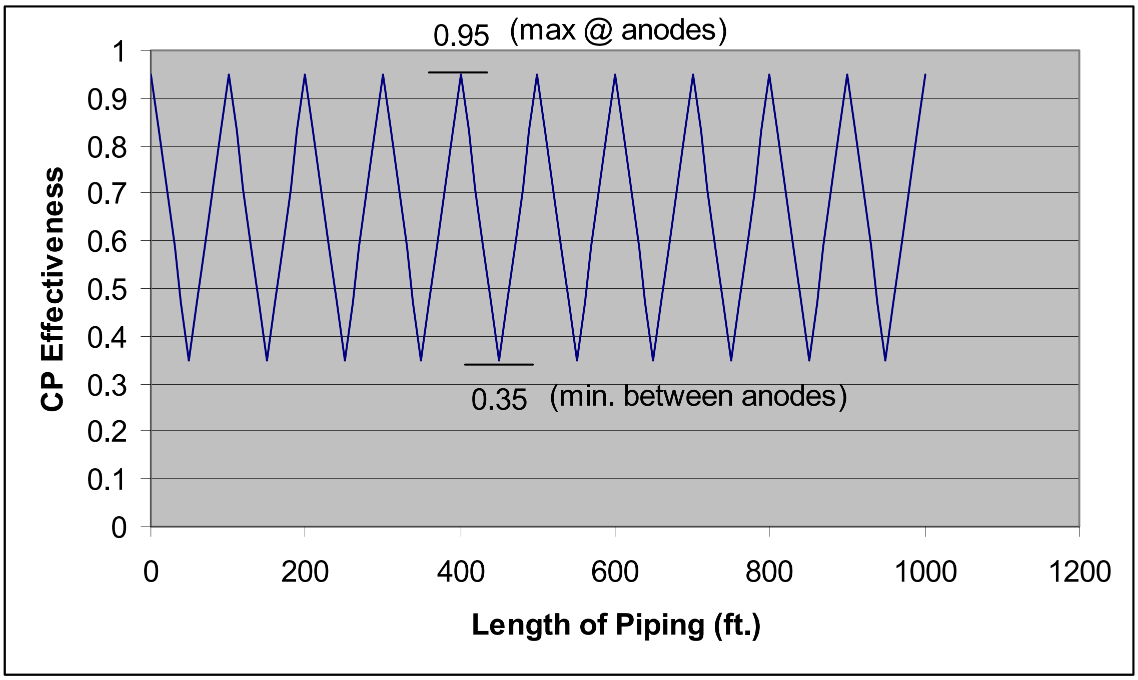


Figure 7-4
Schematic Illustration of Cathodic Protection Effectiveness Model

The above equations have been implemented in the form of an Excel Spreadsheet (Appendix E), which contains a Monte Carlo algorithm to predict the probability of buried piping failure (leakage) versus years of operation, for various values governing variables input by the user. Four random variables are included in the algorithm:

- RN1 = a random number used to determine the time to Protective Coating Damage
- RN2 = a random number used to index the base corrosion rate C
- RN3 = a random number used to index the level of corrosion protection (between max & min)
- RN4 = a random number used to index the piping thickness within the tolerance distribution

The following table gives a set of typical values of the input parameters recommended by corrosion experts at Structural Integrity Associates for the specific piping configuration of the Wolf Creek buried service water piping.

Table 7-4
Parameters used in Monte Carlo Analysis for External Corrosion of Wolf Creek Buried Piping

Corrosion Rate (in/yr)	Const. "C" Mean = 0.0084 STD = 0.545 (log-normal)	Exponent "n" 1.06
Wall Thickness (in)	Mean = 0.375 STD = 0.023 (normal)	
Coating Damage Frequency (per mile)	Construction 500 [15]	Environmental (add'l per yr.) 100
CP Effectiveness Pre-1992 Post-1999	Max. 0.3 0.8	Min. 0.0 0.5
Length of Piping Analyzed (ft)	Total Length 3000	Segment Length 1 (3000 Segments)

The resulting Wolf Creek failure predictions are presented in Figure 7-5 and Appendix E. For the time period prior to 1990, during which the CP system was relatively ineffective, the results indicate a failure probability of 0.001 (3 failures in 3000 segments) in approximately 10 years. This is roughly consistent with the operating experience at the plant, in which three failures were observed in the early 1990s, prior to upgrading the CP system (Section 7.2.5.5). Subsequent to improvements in the CP system, the probability of failure is not predicted to reach this level (0.001) until approximately 24 years, indicating a much longer expected lifetime of the piping.

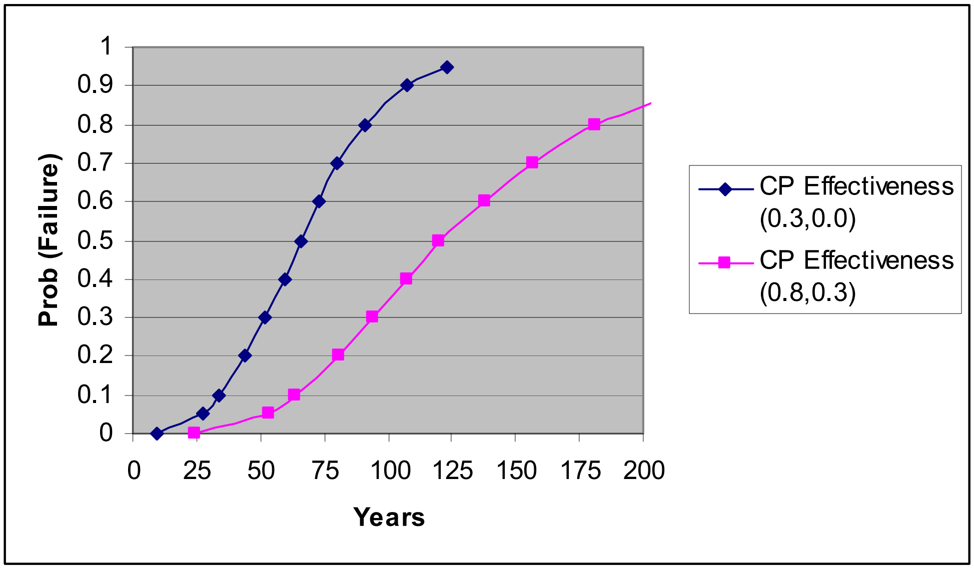


Figure 7-5
Results of External Corrosion Assessment of Wolf Creek Buried Service Water Piping

7.2.6.2 Internal Corrosion

The base level of internal corrosion will be a function of the material of construction, the fluid, temperature, and fluid chemistry.

For fresh waters, general corrosion of carbon steel will be based upon the correlations developed by Pisigan and Singley [28]. Key parameters in their model are the hardness of the water (which also incorporates the actual pH), chlorides, sulfates, conductivity, and dissolved oxygen. The time element in Pisigan & Singley's expression was normalized to 1 year. The nominal value will be determined at the system's nominal temperature. At other temperatures, the value will be corrected for temperature using

$$CR = CR_0 * \exp(0.0462*(T-T_0))$$

Effects of flow will impact general corrosion (corrosion rates will increase linearly with flow rate), pitting and MIC (in both cases, slow flows will produce more severe localized corrosion due to microbiological or non-biological sources).

Several approaches to the distribution of corrosion rate were evaluated. These included estimates based upon the best fit prediction, using the nominal values for water chemistry, and the maximum and minimum predicted values from the extremes of the water chemistry; with and without an additional factor to account for inaccuracies inherent in the model.

The above theoretical distribution on corrosion rate was compared to a set of more than 600 individual thickness measurements made at a Hydro-Power plant 1997. The key assumption involved is that a large number of metal loss measurements from carbon steel exposed to water should define the distribution of metal loss (and metal loss rate) for other environments, even those where the absolute value of the rate may differ from that in which the measurements were taken. The distribution from plant measurements is shown in Figure 7-6.

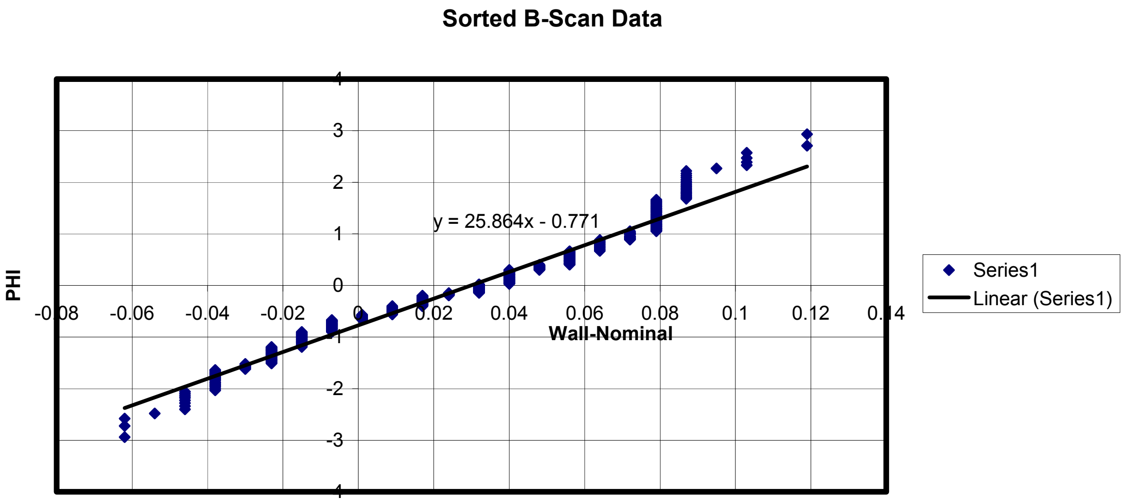


Figure 7-6
Distribution of Corrosion Measurements in a Hydro-Plant Penstock

Converting these data to an average corrosion rate (by dividing by the exposure time of about 14 years) gives a range of 0.183 ipy over a range of PHI of 5.87. The resulting standard deviation (i.e., PHI = 1.0) is 0.0022 ipy.

A Pitting Factor (1 = Very low susceptibility; to 5 = very high susceptibility) was applied. For each system, this number will be based upon flow, extremes in water chemistry, etc. plus history from inspections or failures or problems with mud or silt. The pitting rate for each Pitting Factor is determined by multiplying a random number times the base general corrosion rate. This creates a localized corrosion matrix. For each segment, the pitting rate is defined by a random number for pitting that “looks up” the pitting rate for that segment in the localized corrosion matrix.

A similar approach was used for MIC. It has its own tabulation with slightly different values. The MIC Factor (1 to 5) is also adjusted for prior problems with MIC or corrosion.

Total corrosion (within each segment) is the sum of the general corrosion, pitting, and MIC. Internal corrosion results are also benchmarked to failure history or corrosion determinations from inspection or monitoring activities where applicable.

Corrosion Mitigation

Internal corrosion will be mitigated by the presence of a coating (assumed to be 100% effective where it is in place). All coatings will be assumed to have some number of initial flaws per lineal dimension with the number of those flaws increasing (linearly) with time. That expression for the time dependence of the coating will be based upon the coating being only 25% effective when the coating reaches its stated design life (e.g., 15 years for rubber lined carbon steel pipe).

Internal corrosion will also be mitigated by the addition of corrosion inhibitors. Inhibitor type and concentration will be compared to the recommended concentration for that inhibitor in the water of interest in order to define the maximum level of inhibitor effectiveness. Using an approach similar to that for CP effectiveness, an inhibitor effectiveness factor will be applied based upon inhibitor addition schedule and the inhibitor addition history. That factor may also be modified if inhibitor was added after surfaces had already corroded (i.e., inhibitor effectiveness on fouled or corroded surfaces is much less than for clean surfaces). The inhibiting factor is applied to the sum of general and pitting corrosion.

MIC will be mitigated by the addition of biocides. Biocide type, concentration, and addition schedule will be compared to the recommended concentration and addition schedule for that biocide in the water of interest in order to define the maximum level of biocide effectiveness. The MIC mitigation factor is applied by decreasing the MIC Factor in the MIX matrix. For example, a system that is considered highly susceptible to MIC (MIC Factor = 5) with no treatment but that has a fairly good biocide treatment (e.g., MIC mitigation index = 2) would have its MIC Factor adjusted from a 5 to a 3. For the lower MIC Factor, maximum rates are less and the probability of MIC is also less.

The following values of these parameters were selected for analysis of the Wolf Creek service water system. (Table 7-5). The resulting probability of failure versus time is illustrated in Figure 7-6, for both normal and log-normal distributions of corrosion rate.. The results indicate that, with the input data assumed, no failures due to internal corrosion would be expected until approximately 25 years of plant operation. This is consistent with plant experience in this piping to date. Because of the good operating experience to date, no alternative mitigation or maintenance scenarios were investigated.

Table 7-5
Parameters used in Monte Carlo Analysis for Internal Corrosion of Wolf Creek Buried Piping

Corrosion Rate (in/yr)	Mean = 0.0024 (Normal) Mean = -6.0524 (Log Normal)	STD = 0.0022 (Normal) STD = 0.12174 (Log Normal)
Wall Thickness (in)	Mean = 0.375	STD = 0.023 (normal)
Inside Coating	None	
Pitting Susceptibility MIC Susceptibility	2 2	Scale of 1 to 5; 1= Very low susceptibility; 5= Very high susceptibility
Inhibitor Effectiveness	0.5	Scale of 0 to 1; Max. Effectiveness = 1
Biocide Effectiveness	0.0	Scale of 0 to 4; 4 = Fully Effective
Length of Piping Analyzed (ft)	Total Length 3000	Segment Length = 1 (3000 Segments)

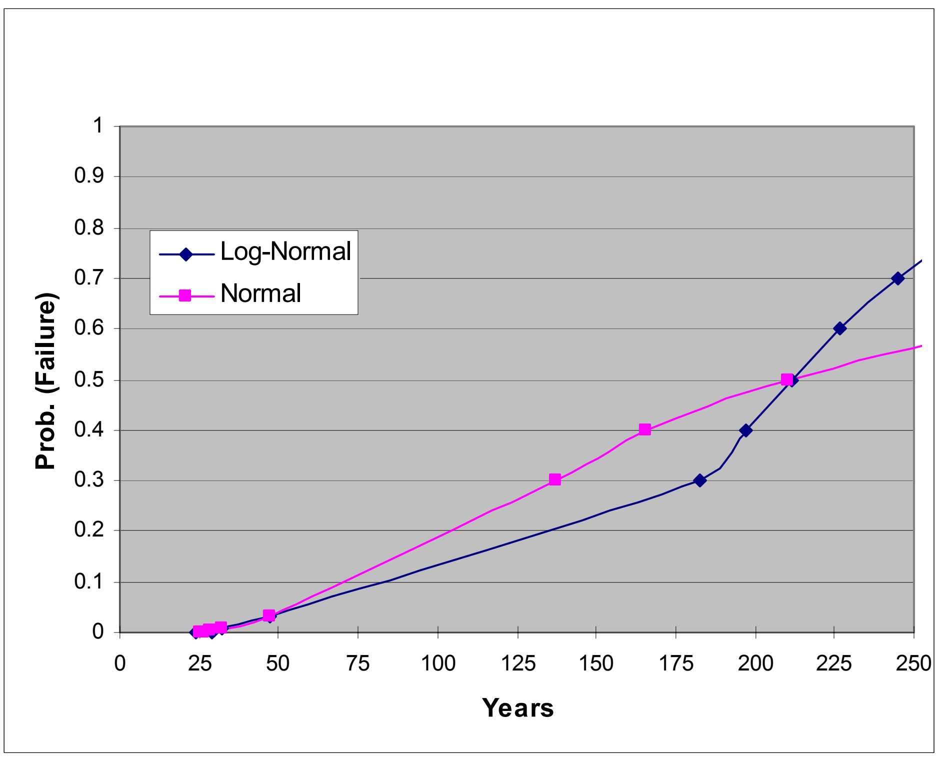


Figure 7-7
Results of Internal Corrosion Assessment of Wolf Creek Buried Service Water Piping

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A
METHODS FOR MANIPULATING DATA ON FAILURE RATES AND PROBABILITIES OF FAILURE ON DEMAND

This Appendix contains sufficient technical information and examples for the user to make the best use of all the quantitative failure data likely to be encountered, with a view to obtaining the best possible values of the current failure rate, and the best predictions of the future failure rate. The 16 sections of Appendix A provide a fairly comprehensive set of tools usable by those who are not expert in the field of reliability. For the first-time reader, there is a benefit in reading through these sections in numerical order, before attempting to use them individually.

Although the mathematics may appear quite complex in some parts, the equations provide all the essentials necessary to manipulate failure data for application to Life Cycle Management. The accompanying text explains the equations to the extent that non-mathematicians and non-statisticians should have little difficulty in using the methods without further guidance. Wherever further development may be necessary to take advantage of more advanced methods, the text provides a note to that effect.

Statistical tables needed to evaluate any of the equations are presented in Tables A-1 through A-7, in notation consistent with that used in the equations. When other compilations of statistical tables might differ in definition, a note is provided in the text.

A1 Constant Failure Rate Over Time

A failure rate over time summarizes the number of failures experienced over a period of time. The actual number of failures obviously can vary from one occasion to another even when the same time period is involved, and is distributed according to a Poisson distribution, to be described in Section A6. The usual measure, λ, for the failure rate, does not require knowledge of the individual times to failure, but only the total number of failures, N_f, in the cumulative number of component years, T, in the operating environment:

$$\lambda = N_f / T \qquad \textbf{Eq. A-1}$$

The upper (two-sided) confidence bound on λ, λ_{upper}, at a confidence level of $(1-\alpha)$, is:

$$\lambda_{upper} = \chi^2_{1-\alpha/2}(2N_f + 2) / 2T \qquad \textbf{Eq. A-2}$$

The lower (two-sided) confidence bound on λ, λ_{lower}, at a confidence level of $(1-\alpha)$, is:

$$\lambda_{lower} = \chi^2_{\alpha/2}(2N_f) / 2T \qquad \textbf{Eq. A-3}$$

A confidence level of (1-α) means that the probability is (1-α) that the true failure rate is between λ_{upper} to λ_{lower}. So, if the confidence level is 90%, $\alpha/2 = 0.05$. The notation used here corresponds to that used in most tabulations of the χ^2 (chi-squared) distribution, in which α is the area under the distribution of χ^2 from 0 to χ^2. The χ^2 distribution can be found in Table A-1, and in most statistical texts or compilations, but be aware that some statistical tables tabulate the complement of this quantity, i.e. the area from χ^2 to 1, so check the definition. In Table A-1, select the column with value ε equal to $\alpha/2$ or $1-\alpha/2$, and read the confidence limit using the row labeled with $\nu = 2N_f$ or $2N_f + 2$.

Example: Two failures are observed in a group of pumps over a cumulative operating period of 3 pump years (suppose 2 pumps over 1.5 calendar years). The estimate for λ is 2/3 = 0.67 failures/year. For the confidence bounds look up the value of $\chi^2_{0.95}$ (6) (=12.6) for the upper bound, and $\chi^2_{0.05}$ (4) (=0.711) for the lower bound. Then:

$$\lambda_{upper} = 12.6/6 = 2.1 \text{ per year}$$

$$\lambda_{lower} = 0.711/6 = 0.12 \text{ per year}$$

Notice that the ratio $\lambda_{upper} / \lambda_{lower} = 17.5$, which is a very wide range of uncertainty.

If the statistics were improved by making observations over a much longer time, so that 14 failures were observed in 21 pump years, $\chi^2_{0.95}$ (2x14+2) becomes 43.8 for the upper bound, and $\chi^2_{0.05}$ (28) becomes 16.9 for the lower bound. Then the estimate for the failure rate remains the same at 0.67, but:

$$\lambda_{upper} = 43.8/42 = 1.04 \text{ per year}$$

$$\lambda_{lower} = 16.9/42 = 0.40 \text{ per year}$$

Notice that now the ratio $\lambda_{upper} / \lambda_{lower} = 2.6$, so the uncertainty is much less than before.

Equation 2 for the upper confidence limit can be used even when there have been no failures at all ($N_f = 0$). The lower limit is then zero.

A different prescription for the upper limit is often used when there have been no failures, by quoting the upper *one-sided* confidence limit which has the value:

$$\lambda_{upper,\ one\ sided} = -\left(\log_e (1-\alpha)\right)/ T \qquad \textbf{Eq. A-3a}$$

In nuclear plant practice, as discussed in (Ref 6 Villemeur), this estimate is usually calculated for a 50% confidence level, so that the actual value has a 50% chance of being both above and below this level. Equation 3a then becomes $\lambda_{upper,\ one\ sided} = 0.693/T$. It is clearly equivalent to assuming that about 0.7 failures have occurred, even though the actual value is zero. See also Ref 17, Mann, Schafer, and Singpurwalla.

A2 Constant Failure Probability on Demand

The number of failures on demand, follows a binomial distribution, described in Section A7. The estimate for the probability of failure on demand, P_f, is simply:

$$P_f = n / N_d \qquad \textbf{Eq. A-4}$$

where n is the number of failures upon demand, and N_d is the cumulative number of demands on the group of components.

The confidence limits for this distribution are given by solutions to the following equations:

$P_{f\,lower}$ is the p value which satisfies: $\sum_{i=n}^{N_d} C^i_{Nd}\, p^i (1-p)^{Nd-i} = \alpha / 2$ **Eq. A-5**

$P_{f\,upper}$ is the p value which satisfies: $\sum_{i=0}^{n} C^i_{Nd}\, p^i (1-p)^{Nd-i} = \alpha / 2$ **Eq. A-6**

where $C^i_{Nd} = N_d! / [i!(N_d - i)!]$ **Eq. A-7**

with $x! = x(x-1)(x-2)\ldots..3.2.1$, and $0! = 1$.

You do not need to use equations 5 and 6 directly because solutions can be found in Table A-2, and in statistical tabulations covering the binomial distribution. In Table A-2, select the table for the confidence level required, and read the confidence limits from the body of the table. The tables, unfortunately, have a range of application restricted to 48 demands or less. To work with larger numbers of demands use the fact that at these larger numbers the number of demands can be treated as a continuum, like time, and there is a close analogy between the failure rate of the Poisson model and the probability of failure on demand. The third example below explains the procedure.

Caution, - in some texts, the binomial distribution is described for p equal to the probability of success, rather than the probability of failure. In that case, the above statements are still all true, except that n becomes the number of successes.

Once again, a confidence level of $(1-\alpha)$ means that the probability is $(1-\alpha)$ that the true failure rate lies between λ_{upper} to λ_{lower}. So, if the confidence level is 90%, $\alpha/2 = 0.05$. The ratio between the upper and lower confidence bounds is just as sensitive to the number of failures as were the bounds for the Poisson distribution.

When no failures occur in N_d demands, the two-sided confidence bounds on p become

$P_{flower} = 0$ and $P_{fupper} = 1 - (\alpha/2)^{1/n}$ **Eq. A-7a**

Nuclear plant practice favors the use of a *one-sided* upper confidence bound in this situation, given simply by $1 - \alpha^{1/n}$, stated at a 50% confidence level. Thus:

$$P_{fupper} = 1 - 0.5^{1/n} \qquad \textbf{Eq. A-7b}$$

Example 1: Find the 90% confidence limits on the probability of failure on demand if there are 2 failures in 15 demands. The estimated probability of failure on demand is 2/15 = 0.13. In Table A-2.2, labeled "Two-Sided Confidence Limits For Binomial Distribution, Confidence Level: 1-α = 0.9", use the column headed 13 because 15 – 2 = 13. The confidence limits for 2 failures can be read as 0.024 to 0.363.

Example 2: State the one-sided upper 50% confidence limit when there are no failures in 15 demands. Equation 7b gives $1 - 0.5^{1/15} = 1 - 0.5^{0.0666} = 1 - 0.955 = 0.045$.

Example 2: 2 failures have occurred in 100 demands. What are the two-sided 95% confidence limits on the probability of failure on demand? The estimate of probability of failure on demand is 2/100 = 0.02. 100-2 =98 is outside the range of the column headings of table A-2. However, when the number of demands exceeds the range of the tables, equations 2 and 3 can be used as a rather accurate analogue, equating N_d with T, and n with N_f, and using Table A-1:

$$P_{upper} = \chi^2_{1-\alpha/2}(2x2 + 2) / 2x100 = \chi^2_{.975}(6) / 200 = 14.449 / 200 = 0.072$$

$$P_{lower} = \chi^2_{\alpha/2}(2x2) / 2x100 = \chi^2_{.025}(4) / 200 = 0.484 / 200 = 0.0024$$

A3 Updating Knowledge of Failure Rates with New Data

Sections A3 to A13 deal with the common situation where new data has come to hand. To make the best use of it requires some kind of combination of the new data with the estimates available before the new data was obtained. A trivial case is where values already exist for the failure rate or probability of failure on demand, *and the numbers of failures etc which gave rise to these values is known*. This might arise when plant specific data is being updated with additional plant specific data, and the details of the earlier calculations are still available. Combined values can then be computed from equations (1) to (7), after the new experience (number of failures, number of component years of exposure, number of demands) is simply added to the old.

More often the situation is not as trivial. The more normal situation has the following characteristics, 1) you have some kind of knowledge of the failure rate (the 'prior' knowledge), 2) the prior failure history is not known in terms of the numbers of failures and component years of exposure, and 3) new estimates must be made for the failure rate and its confidence bounds.

In this case, the prior knowledge is represented by a probability distribution for the failure rate. The failure rate is thus treated as a random variable, with an uncertainty expressed by the prior distribution. The prior may be a very crude discrete representation, such as 'there is a 75% chance that the failure rate is 0.1/year, and a 25% chance that it is 0.01/year, or it may be a completely specified probability distribution such as a lognormal. The prior distribution specifies what you know of the possible values of the failure rate, without any reference to an underlying statistical model of the failure processes, and with no access to the raw statistics which gave rise to it. Bayes formula provides the link between the prior distribution, the new data (e.g. 1 additional failure in 28 demands), and the final distribution, which is called the posterior distribution:

Bayes Formula:

$$\text{Posterior}(\lambda) = K \times \text{Prior}(\lambda) \times \text{Likelihood Of The Data Given } \lambda \qquad \textbf{Eq. A-8}$$

K is a constant explained below. The prior distribution of λ is given. It is the distribution you obtain from an industry database expressing prior knowledge about λ. The Likelihood expresses the probability of getting exactly the results which were obtained for the new data, if the failure rate had had the value λ. This value is treated as a variable, so you need a statistical model of the underlying failure process, such as the Poisson, or the Binomial to find the Likelihood for a general value of λ.

There is usually no difficulty at all in writing down the Likelihood. For the normal case where the data contains multiple values (e.g. a set of failure times), the likelihood will be the repeated product of the probability distributions for the type of data involved, because it expresses the probability of getting the first value, *and* the second *and* so on.

The constant, K, is obtained by normalizing the right hand side of equation (8) to unity by integrating over the full range of possible λ values. The posterior is then a properly normalized probability density when K is calculated as:

$$1/K = \int_0^\infty \text{Prior}(\lambda') \,.\text{Likelihood Of The Data Given } \lambda' \,.d\lambda' \qquad \textbf{Eq. A-9}$$

Although equations (8) and (9) may require numerical methods to evaluate, confidence bounds on λ are conceptually easy to understand and to evaluate directly. In the general case, you have to integrate the posterior to find K from equation 9, and to calculate confidence limits, but there are some ways to avoid the integration. These are described below.

If the new data is a large data set from a homogeneous population of components (in terms of PM, duty cycle etc), combining it with the prior will have a dominating effect, with the posterior resembling the new data more than the prior. The more usual situation is for the prior to be a rather wide distribution, representing significant uncertainty about λ, as discussed before, and the new data is of meager statistical weight, possibly differing markedly from the prior in terms of mean value, and even in terms of its confidence limits. The Bayesian updating process of equations 8 and 9 take precise account of these disparities, and automatically results in a posterior distribution with appropriate weight given to the location and variance of both sources of the data.

There are many variations of the Bayesian approach. New data may take the form of 1) a set of n times to failure, t_1, t_2, t_3, …….t_n, or more simply, 2) n additional failures which occurred in a total operational time of T component years, or 3) additional estimates of λ, its confidence bounds, or its probability distribution from other sources. Similar considerations apply to the probability of failure-on-demand. In the remaining sections of Appendix A, we consider each in turn. All the methods described fall in the general class known as Parametric Empirical Bayes (PEB).

A4 Likelihood for New Times to Failure (Constant Failure Rate)

The most detailed level at which new data may become available is as a set of times to failure. In the power industry, it will be unusual to obtain data on failure times, but if you do obtain data in this form, use the following procedure to embody the assumption that the failure rate does *not* change in time. If we believe that the failure rate is constant in time with value λ, then the times to failure are distributed according to an <u>exponential</u> distribution, E(t, λ):

$$E(t,\lambda) = \lambda e^{-\lambda t} \qquad \textbf{Eq. A-10}$$

The likelihood for a data sample of n new failure times is then the repeated product:

$$L(t_1,t_2,t_3, \ldots\ldots t_n,\lambda) = \lambda e^{-\lambda t_1} . \lambda e^{-\lambda t_2} . \lambda e^{-\lambda t_3} \ldots\ldots \lambda e^{-\lambda t_n}$$

$$L(t_1,t_2,t_3, \ldots\ldots t_n,\lambda) = \lambda^n . \exp(-\lambda \sum_{i=1}^{n} t_i) \qquad \textbf{Eq. A-11}$$

Because: e^a times e^b times e^c times……. = $e^{(a+b+c+\ldots\ldots)}$. Equation 11 gives one important part of equation 8.

A5 Likelihood for New Times to Failure (Time Dependent Failure Rate)

If, on the other hand, we believe that the underlying statistical process leads to a time dependent failure rate, λ(t), the most general power law statistical model to use for the underlying times to failure is not an exponential distribution but a <u>Weibull</u>:

$$W(\eta,\gamma,\beta,t) = (\beta/\eta) . [(t-\gamma)/\eta]^{(\beta-1)} . \exp\text{-}[(t\text{-}\gamma)/\eta]^{\beta} \qquad \textbf{Eq. A-12}$$

With

$$\lambda(\eta,\gamma,\beta,t) = (\beta/\eta) . [(t-\gamma)/\eta]^{(\beta-1)} \qquad \textbf{Eq. A-12a}$$

See Appendix A14 for further discussion of the meaning of the Weibull parameters, η,γ, and β.

Using equation 12, the likelihood is then:

$L(t_1,t_2,t_3, \ldots\ldots t_n, \eta,\gamma,\beta) =$

n n

$$(\beta/\eta)^n \,.\, \exp\left(-\sum_{i=1} [(t_i-\gamma)/\eta]^\beta\right) \,.\, \prod_{i=1} [(t_i - \gamma)/\eta]^{(\beta-1)}$$ **Eq. A-13**

Where π just means take the product of all the terms for the n values of t_i.

Notice that λ no longer appears explicitly in the likelihood, but is replaced by the three Weibull parameters.

If the prior information depended on the hypothesis that the failure rate was a constant in time, then the prior value of the shape parameter is β=1, which reduces equation 12 to an exponential distribution of failure times (i.e. to equation 10, apart from a shift in the time origin, and reduces equation 12a to the single value $\lambda = \beta/\eta$. However, employing a Bayesian updating process for β is then self defeating, because the prior would be an infinitely narrow distribution centered on the one value β=1. This overwhelms the likelihood of equation 8 and results in retaining the exponential distribution for the posterior on β, regardless of assumptions about η, and regardless of the new data. Of course, we may reflect that our prior assumption about the constancy of λ was not based on information but on convenience, and was just an assumption which does not merit the assignment of such a strong prior distribution. The time-independent assumption for the prior is therefore not a useful approach when updating a Weibull.

The other extreme to adopt would be a so-called non-informative prior on β, provided it could include practical bounds on the possible values of β, perhaps from 1 to 5 for failure rates which are not decreasing with time. Unfortunately, the choice of such a prior is a mine field of conceptual problems which this guide has no space to pursue, except to recommend that it is probably wiser not to proceed in this direction, at least not without expert statistical assistance.

An alternative is to adopt the value of β obtained purely from the new sample of failure times, and to condition only the η parameter on the prior scale information available from λ, under the assumption that λ was constant in time. The prior distribution of η is the prior distribution of λ (for example, a lognormal), transformed so that it expresses a distribution of $1/\lambda$. Use the transformed distribution, $h(\eta)$, as the prior in equation 8, with equation 13 as the likelihood, and with β fixed at the value found from the Weibull analysis. The transformation to be used is

$$h(\eta) = -(1/\eta)^2 \,.\, \text{Prior}(1/\eta)$$

Prior($1/\eta$) is identical to Prior(λ) with λ physically replaced by $1/\eta$. The integration in equation 9 is then over all possible values of η from zero to infinity. The posterior distribution for η can then be used to express selected point values of η (e.g. the mean, or median) which could be used in equation 12a to develop the failure rate as a function of time. This procedure is similar to the Weibayes procedure outlined below, but has the advantage that the prior information on the time scale incorporated in the distribution over λ, is updated using the new data in a true Bayesian manner.

Because of the difficulties expressed above, some Weibull analysts adopt an approach which has been called Weibayes (Ref 9, Abernethy). The method consists of adopting a value for β from historical analyses (i.e. a generic value), or from engineering knowledge of the physics of failure, and then using that value in a maximum likelihood estimate of η using the new data. The new value of η results only from the time scale of the new data and does not incorporate any scale information from the prior data. β does not change during the updating procedure, and is not derived from the new data. In the author's view this procedure is a significant departure from Bayesian updating and should be treated with caution.

Needless to say, the complexity of these procedures would not be justified if the new sample data and the Weibull parameters derived from it could be relied on to be a distinctly superior representation of reality than the prior failure rate distribution.

There are methods to decide if the data is better represented by one distribution rather than another (perhaps the best and simplest is the Method of Support which directly compares the log-likelihoods for two alternative hypotheses on the same data (Ref h 18 Edwards). The problem with applying these methods is that the prior and likelihood information will most likely have very different statistical weights. Furthermore, comparisons between a time dependent and a time independent failure rate necessarily compare a three parameter fit (Weibull) to the data with a one parameter fit (Exponential). Unless the sample of data is extensive, which means it must include a significant fraction of the component life, the three parameter fit is always liable to perform better than a single parameter fit, for reasons which have nothing to do with the validity of the case.

Unfortunately, none of these procedures for updating Weibull parameters is on very solid ground. Considering the fact that in nuclear power environments, available prior information is even less likely to involve Weibull parameters than will the new data, we will do best to use only new data to define the Weibull parameters, and refrain from updating it with prior information.

A6 Likelihood for Number of New Failures (Failure Rate)

When new data is simply of the form that n failures have occurred in a time T, we use the Poisson distribution of the number of failures to create the likelihood function. The Poisson distribution also contains the assumption that the rate, λ, is a constant over time. $P(x,\lambda T)$ is the probability of observing exactly x failures when the expected (i.e. the mean) value is λT failures:

$$P(x,\lambda T) = e^{-\lambda T} (\lambda T)^x / x! \qquad x = 1, 2, 3\ldots \qquad \textbf{Eq. A-14}$$

The likelihood of observing exactly n failures is thus:

$$L(n,\lambda T) = P(n,\lambda T) \qquad \textbf{Eq. A-15}$$

This likelihood does not involve a repeated product of the Poisson distribution, because there is only one result, n, in exposure T.

Notice that the Poisson distribution is actually a single parameter distribution which depends only on the product λT, rather than λ and T independently of each other. However, to use it to break out the failure rate obviously requires us to also know the value of T. The mean number of failures is λT for this distribution, with variance also equal to λT.

A7 Likelihood for Number of New Failures (Failure on Demand)

When new data is of the form that n failures have occurred in a number of demands, N_d, we use the Binomial distribution of the number of failures to create the likelihood function. The Binomial distribution also contains the assumption that the probability of failure-on-demand, p, is a constant over time. $B(i,p,N_d)$ is the probability of observing exactly i failures when the expected (i.e. the mean) value is pN_d failures:

$$B(i,p,N_d) = N_d! / [i!(N_d-i)!] \,.\, p^i(1-p)^{Nd-i} \qquad i = 1, 2, 3 \ldots N_d \qquad \textbf{Eq. A-16}$$

The likelihood of observing exactly n failures is thus:

$$L(n,p,N_d) = B(n,p,N_d) \qquad \textbf{Eq. A-17}$$

The mean value of the number of failures for this distribution is pN_d, with variance $p(1-p)N_d$. Caution, - in some texts, the method is described for p equal to the probability of success, rather than the probability of failure. In that case, the above statements are still all true, except that i and n become the number of successes.

A8 Likelihood for a New Distribution

When new data is in the form of a probability density, $g(\lambda)$, from a different source, the likelihood is simply the new data, since by definition, $g(\lambda)$ represents the appropriate relative probabilities, i.e. the likelihood, of getting various values of λ. In this case equations (8) and (9) become the overlap probability, between the prior and the new distributions.

$$\text{Posterior}(\lambda) = \frac{\text{Prior}(\lambda) \,.\, g(\lambda)}{\int_0^\infty \text{Prior}(\lambda') \,.\, g(\lambda')d\lambda'} \qquad \textbf{Eq. A-18}$$

This is therefore the approach to use to combine different generic sources of data on the same parameter.

A9 Lognormal Prior Distribution of Failure Rate

This section simply introduces the lognormal distribution and the relations between its parameters. A common choice for the prior distribution of λ, or for the probability of failure-on-demand, is the lognormal. The reason is that lognormal distributions are favored by PSA practitioners, and so a large amount of existing failure rate knowledge, whether plant-specific or from generic industry sources, will be found in this form. The lognormal is perfectly serviceable but usually requires numerical methods to perform Bayesian calculations. The usual assumption is that the lognormal expresses uncertainty in λ, which is, however, a constant in time. The lognormal probability density, LN(λ), is given by:

$$LN(\lambda) = [1/\sqrt{(2\pi)}] . [1/\lambda\sigma] . \exp [-\{\ln(\lambda/ \lambda_m)\}^2 / (2\sigma^2)] \quad \textbf{Eq. A-19}$$

Where σ is the standard deviation of lnλ, and ln(x) is the logarithm of x to base e. The mean and variance are:

$$\text{Mean} = \lambda_m . \exp(\sigma^2/2) \quad \textbf{Eq. A-20}$$

$$\text{Variance} = \lambda_m^2 . \exp(\sigma^2) . (\exp(\sigma^2) - 1) \quad \textbf{Eq. A-21}$$

Other useful values are:

$$\text{Median} = \lambda_m \quad \textbf{Eq. A-22}$$

$$\text{Mode} = \lambda_m / \exp(\sigma^2) \quad \textbf{Eq. A-23}$$

$$\text{Error Factor} = \exp(1.645\ \sigma) \quad \textbf{Eq. A-24}$$

The Error Factor provides a way to calculate the symmetric lower and upper confidence bounds at a 90% confidence level. See equation 31 of A13, and also A12 for examples of using the error factor.

A10 Self-Conjugate Prior: Constant Failure Rate

It should be obvious that use of a general prior distribution, along with the likelihoods which stem from the statistical failure models described in A4 to A8, will require numerical computation to evaluate the posterior from equations (8) and (9). There are two extremely useful situations where use of likelihoods of the standard forms already described, leads to the posterior distribution being of the same functional form as the prior, hence the term self-conjugate. All that needs to be done to perform a Bayesian update for these cases is to modify the parameters of the prior distribution in trivial ways to immediately arrive at the posterior, without going through the rigors of solving equations 8 and 9.

These two methods are of great utility because, 1) they are suited to likelihoods based on Poisson and Binomial failure models, which we have seen above are the most frequently needed cases, and 2) the prior distributions have very general forms which can be made to approximate almost any form of knowledge about the failure rate and the probability of failure-on-demand, including lognormal distributions.

There has been some criticism of self-conjugate priors on the grounds that they may be a little too resistant to modification by the new data, because they tend to under-emphasize the uncertainty in the tail regions of the distributions. However, for the purposes of LCM applications they are a very convenient starting point. The tail region issue can be resolved by incorporating a non-informative prior into the parametric prior in a first Bayes updating step before the new data is introduced. The improved prior is then used in the way described in the sections of this Appendix. This two-stage Bayes-Empirical Bayes approach (BEB) seems to be a robust improvement to the single stage Parametric-Empirical Bayes procedures described here, but it is more complex, and users are advised to seek expert statistical input to select an appropriate non-informative prior.

The first case is presented for a constant failure rate, λ, which uses a Poisson-based likelihood as described in A6. The prior distribution is chosen to be the gamma distribution, $G(\lambda,b,c)$:

$$G(\lambda,b,c) = (\lambda/b)^{(c-1)} . \exp[-(\lambda/b)] / [b\Gamma(c)]$$ **Eq. A-25**

$\Gamma(c)$ is the gamma function which can be found in most statistical tabulations. The mean failure rate = bc, and the variance = b^2c. You can choose to restrict c to take only integer values, in which case, $\Gamma(c) = (c - 1)!$ Restricting c in this way has the justification that c is closely associated with the number of failures, at least when c is not too small, and it makes it easy to plot the distribution without using tabulations of the gamma function. However, it introduces extra error when using the method of matching moments (see A12) to determine equivalent distributions. LCM users should restrict the c parameter to integer values.

Suppose the parameters of the prior are b_0,c_0. When the new data consists of n failures in an exposure time of T years, the posterior distribution will still be of the gamma form, but with parameters, b_1,c_1, where:

$$b_1 = b_0/(1 + T\,b_0) \; ; \quad \text{and} \quad c_1 = c_0 + n$$ **Eq. A-26**

The updated mean failure rate is b_1c_1 instead of b_0c_0 for the prior. This is a very easy way to avoid the complexities of equations 8 and 9.

Example: Prior information for the failure rate is a gamma distribution, with parameters $b_0 = 1$, $c_0 = 0.05$, so that the mean value (bc) of the failure rate is 0.05/year, with a standard deviation (square root of the variance, b^2c) = 0.22. If more recent data consists of just 2 failures in 100 component years of operation what is the new mean and standard deviation? $b_1 = 1/(1+100x1) = 0.01$, and $c_1 = 2.05$. The new mean is thus 0.0205/year, and the new standard deviation is 0.0143. If we had elected to restrict c_1 to an integer value ($c_1 = 2$) it would not have significantly influenced the result in this case, but there is usually no need to do this.

In this example, the new data dominates the mean because the prior distribution had a standard deviation about 4.4 times the mean, and the new data had more statistical weight. To see this consider that the new data on its own would have given a mean value of $\lambda = 0.02$ with a 2-sided upper 90% confidence limit (equation 2) of $\chi^2_{0.95}(6)/200 = 0.053$. Although this is still 2.5 times the mean, the difference between the upper 90% limit and the mean is roughly 2 times the standard deviation, suggesting a standard deviation in the range 0.01 to 0.02. We can estimate the standard deviation exactly by stating that the standard deviation on the *number of failures* is the square root of the variance ($=\surd(\lambda T) = \surd(N_f/T \times T)$), and is thus $\surd N_f$, equal to 1.414, giving the standard deviation on the estimate of λ of 1.414/100 = 0.014. Therefore the new data alone would give $\lambda = 0.02$ with a standard deviation of ±0.014. It clearly is more significant than the prior information which stated $\lambda = 0.05$ with a standard deviation of ±0.22.

It is worth remembering that the standard deviation of the number of failures in a Poisson rate process is the square root of the number of failures, as this gives the analyst an immediate sense of the uncertainty in this number.

A11 Self-Conjugate Prior: Constant Probability of Failure-on-Demand

This case uses a Binomial-based likelihood as described in A7. The prior distribution is chosen to be the beta distribution, BETA(p,V,W), with p the probability of failure-on-demand. For this application, the parameters, V and W, must be integers:

$$\mathrm{BETA}(p,V,W) = \{(V+W-1)! / [(V-1)!(W-1)!]\}.\ p^{(V-1)}.(1-p)^{(W-1)} \qquad \textbf{Eq. A-27}$$

The mean probability of failure-on-demand is given by V/(V+W), and the variance is VW / $[(V+W)^2(V+W+1)]$.

Suppose the parameters of the prior are V_0,W_0. When the new data consists of n failures in N_d additional demands, the posterior distribution will still be of the beta form, with parameters, V_1,W_1, where:

$$V_1 = V_0 + n \quad ; \quad \text{and} \quad W_1 = W_0 + N_d - n \qquad \textbf{Eq. A-28}$$

The parameter V_0 is thus modified by adding the number of additional failures, whereas W_0 is modified by adding the number of additional successes. The posterior mean probability of failure-on-demand is $V_1/(V_1+W_1)$ instead of $V_0/(V_0+W_0)$ for the prior. This method for the binomial distribution is just as straightforward as the previous use of the gamma prior for the Poisson distribution.

Caution, - in some texts, the method is described for p equal to the probability of success, rather than the probability of failure. In that case, the above statements are still all true, except that n becomes the number of new successes, V is associated with the number of successes rather than failures, and W is associated with the number of failures.

A12 Parameters for the Prior – Method of Moments

When the prior distribution which is available to you is of the appropriate self-conjugate form you use it directly with the parameters provided, following the procedures of A10 and A11. However, it may happen that your prior is not in this form. For example, it will often be a lognormal prior distribution, and you then wish to convert it to an equivalent gamma or beta distribution so you can more conveniently use the conjugate prior methods of A10, and A11. A good way to match two distributions of any kind is to equate their means and variances. This is the method of matching moments for any one or two parameter distributions. Obviously, if there are more than two parameters to be specified, more than two moments must be matched, but we do not need to go beyond matching the mean and variance to address all the distributions mentioned in previous sections. The mean and variance of the lognormal, gamma and beta distributions were given in sections A9, A10, and A11, respectively.

For example, if a prior lognormal distribution had a mean of 0.01 failures per year and an error factor of 18, the standard deviation of $\ln\lambda$ must be $\sigma = \ln(18)/1.645 = 1.757$, by equation 24. In that case the variance is $\lambda_m^2 . \exp(1.757^2) . (\exp(1.757^2) - 1)$ by equation 21. So:

$$\text{Variance} = \lambda_m^2 . 21.91 . 20.91 = 458.19\, \lambda_m^2$$

$$\text{Mean} = \lambda_m . \exp(1.757^2/2) = 10.956\, \lambda_m \quad \text{by equation 20}$$

$$= 0.01 \quad \text{(given)}$$

Therefore, $\lambda_m = 0.00091$, and the variance is 0.000382. Note the median, λ_m, is 10 times smaller than the mean, not an unusual situation for failure rate distributions which tend to have long tails in the upper part of the range. If we need to match the lognormal prior to a gamma distribution, we put:

Mean: $bc = 0.01$

Variance: $b^2c = 0.000382$, equivalent to a standard deviation of 0.02.

Whence: $b = 0.0382$, and $c = 0.262$. These two values would then be used as prior values, b_0 and c_0, before modifying them with new data. Suppose the new data were 1 failure (n) in 10 additional years (T) of component experience. Equation 26 gives

$b_1 = b_0/(1 + b_0T)$ i.e. $b_1 = 0.0382/(1 + 0.382)$ i.e. $b_1 = 0.0276$

$c_1 = c_0 + n$ i.e. $c_1 = 1.262$

The new mean value of λ is thus 0.0276 x 1.262 = 0.034, and the new variance is 0.00096, whereas the new data alone would have given $\lambda_{mean} = 0.1$ failures per year, and the prior information had $\lambda_{mean} = 0.01$ failures per year. The new data does not completely dominate the prior, but it changes it significantly. This is because the standard deviation on just 1 failure is $\sqrt{1}=1$ failure, giving a standard deviation for λ based on the new data alone of 1/10, i.e. $\lambda_{mean} = 0.1 \pm 0.1$, whereas the prior had $\lambda_{mean} = 0.01 \pm 0.02$.

The posterior distribution over λ is still of the gamma form:

$$\text{Posterior}(\lambda) = [(2/\,0.0276^2) . (\lambda/0.0276)^{(1.262-1)} . \exp[-(\lambda/0.0276)] / \chi^2_{2.524}]$$

Of course, the example could be worked by numerically evaluating the posterior directly using equations (8) and (9), using the likelihood, $\lambda 10e^{-10\lambda}$, from equation 10:

$$\text{Posterior}(\lambda) = \frac{[1/\lambda] . \exp[-\{\ln(\lambda/\,0.00091)\}^2 / (2\text{x}1.757^2)] . \lambda e^{-10\lambda}}{\int_0^\infty [1/\lambda'] . \exp[-\{\ln(\lambda'/\,0.00091)\}^2 / (2\text{x}1.757^2)] . \lambda' e^{-10\lambda'} . d\lambda'}$$

The numerical constants which cancel out between the numerator and denominator, have been omitted. This result would be somewhat more accurate than matching the moments, but it involves a lot more work, and the difference would only be seen by plotting the distributions.

When matching mean and variance for a beta distribution in the case of a probability of failure on-demand, recall that the beta distribution parameters, V and W, are restricted to integer values. This means that you have to round off the values to the nearest integer. For example, if you find that the matching equations give you V = 24.31, and W = 1.66, then you select V = 24, and W = 2.

A13 Point Estimates and Confidence Bounds

When you end up with a posterior distribution for the failure rate, but need to quote or use a single value for λ, point estimates of failure rate or probability of failure-on-demand can be chosen which correspond to the mean, median, or mode of the prior or posterior distributions.

In general, Bayesian confidence bounds are obtained by numerically integrating over the posterior distributions, although in special cases there exist closed forms for these integrals. If the distribution for the failure rate is $P(\lambda)$, the confidence bounds at a $(1-\alpha)$ confidence level are the solutions of:

$$\alpha/2 = \int_0^{\lambda_{lower}} P(\lambda')\, d\lambda' \qquad \textbf{Eq. A-29}$$

and

$$1 - \alpha/2 = \int_0^{\lambda_{upper}} P(\lambda')\, d\lambda' \qquad \textbf{Eq. A-30}$$

In the case of a lognormal distribution, the 90% confidence bounds can be expressed very simply in terms of the Error Factor, EF, which was defined by equation 24, such that:

$$\lambda_{lower} = \lambda_m / EF \quad \text{and} \quad \lambda_{upper} = \lambda_m \cdot EF \qquad \textbf{Eq. A-31}$$

Bounds for other confidence levels for a lognormal distribution can be determined from tabulations of integrals of the normal distribution function ($\ln\lambda$ is normally distributed), as an alternative to using a numerical procedure to evaluate equations 29 and 30. In general, bounds on a lognormal distribution are not very important in updating failure rate data, because even if you begin with a lognormal prior, the posterior distribution will not usually be lognormal.

In the case of a gamma posterior distribution, the chi-squared distribution gives the two-sided confidence bounds at the $(1-\alpha)$ level. Use Table A-1, as shown previously, to evaluate:

$$\lambda_{lower} = (b_1/2) \cdot \chi^2_{\alpha/2}(2c_1) \qquad \textbf{Eq. A-32}$$

and

$$\lambda_{upper} = (b_1/2) \cdot \chi^2_{(1-\alpha/2)}(2c_1) \qquad \textbf{Eq. A-33}$$

For a beta distribution, use the tabulated values of percentage points of a beta distribution given in Tables A-3, or perform a numerical procedure based on equations 29 and 30 in order to determine the confidence limits. The three Tables A-3.1 to A-3.3 give the lower confidence limit for $\alpha/2$ = 2.5%, 5%, and 10%, i.e. for confidence levels of 95%, 90%, and 80%, respectively. To find the upper limits, interchange the values of V and W when using the tables, and then subtract the value obtained from the table from unity.

For example, if V=20, and W =10, Table A-3.2 shows the lower 90% limit to be $P_{lower} = 0.52$. Lookup the table again with V=10 and W=20 to get $P_{upper} = 1 - 0.20 = 0.80$. You may need to interpolate for intermediate values of V and W.

A14 Weibull Analysis of Times to Failure

In the case where a set of times to failure is available, preferably for a single failure mechanism, the assumption of a Weibull distribution is the standard procedure. This is a general three parameter power law model for the failure times. The Weibull failure time distribution, repeated here, has been stated previously in A5, equation 12.

$$W(\eta,\gamma,\beta,t) = (\beta/\eta) \cdot [(t-\gamma)/\eta]^{(\beta-1)} \cdot \exp\text{-}[(t\text{-}\gamma)/\eta]^{\beta} \qquad \textbf{Eq. A-12}$$

Which gives the time dependent failure rate as

$$\lambda(\eta,\gamma,\beta,t) = (\beta/\eta) \cdot [(t-\gamma)/\eta]^{(\beta-1)} \qquad \textbf{Eq. A-12a}$$

This distribution is of wide generality, capable of representing accurately the exponential distribution when the shape parameter, $\beta = 1$, and even of approximating a normal distribution when $\beta = 3.44$.

The location parameter, γ, the useful life or minimum life, can be removed by making a shift of the time axis, because it only indicates that the time dependent behavior begins at time, $t= \gamma$. Therefore, the standard analysis procedure assumes one does not know the value of γ, until you begin plotting the times to failure on Weibull paper. This is equivalent to initially assuming that the times to failure are distributed according to the two parameter Weibull distribution (i.e. equation (12) with $\gamma = 0$). Unfortunately, the value of γ is not determined directly, even by later plots.

The parameter η is called the scale parameter or the characteristic life. This is the age at which 63.2% of the sample will have failed (when $\gamma = 0$, otherwise you need to add the value of γ to the characteristic life). Clearly, η provides some indication of the width of the distribution. The parameter, β, is a shape parameter, capable, as shown above, of making the distribution approximate the shape of many other distributions. When $\beta>1$, the failure rate is increasing with time.

The Weibull plot requires the times to failure to be ordered from the smallest to the largest. It also requires the total population of components subject to the sample conditions to be known. For example, if 20 components are to participate in the data sample, the failure of the first (shortest time to failure), represents a failure of 5% of the total. Failure of the second represents cumulative failure of 10% of the total, and so on. The Weibull plot consists of plotting the cumulative failure percentage on the y-axis, and the failure time on the x-axis (time is most common, but it could be cycles, revolutions, etc).

Draw a straight line through the points, usually by eye, but conceivable using linear regression. If this can not be done because the line needs to curve, the points must be replotted using the set $(t_i - \gamma)$ rather than t_i. Estimate the value of γ as follows:

Draw a curved line through the data points, select an arbitrary point (y_2, t_2) approximately in the center of the line.

Choose two other points, one above and one below the center point, and both exactly equidistant from it in the vertical direction. Label the points 1, 2, and 3 with 1 for the shortest time.

Use: $\gamma = t_2 - (t_3 - t_2) . (t_2 - t_1) / [(t_3 - t_2) - (t_2 - t_1)]$ as an estimate for γ.

If the replotted points are still not linear, the data can not be represented by a Weibull distribution.

The estimate for η is found by reading the t value at which the straight line through the points intersects the dashed 'η estimate' line on the paper.

The estimate for β is found by drawing a line perpendicular to the plotted line through the estimation point marked on the top left corner of the graph paper. The estimate for β is read where the perpendicular crosses the β-scale along the top of the paper.

It is important that the group of components which provided the n times to failure must be defined before the failure times are observed. This means you can not allow a small number of failures which occur in a large population to define the sample, because you do not know beforehand which components will fail. Thus, in the normal power plant situation where there is a large population of components, N, and you find that n of them fail, you must use N as the sample size, not n. The cumulative failure percentage at the nth failure time is 100n/N. In power plants this will almost always be a small percentage, with the result that the Weibull plot will be confined close to the bottom of the Weibull chart. Either the result will be that estimates of η and β are impossible to make, or they will have uncertainties so large that they do not provide useable information.

This 'no information' scenario is simply a statement that when only a small fraction of a population of components has failed, you can not say anything about the time dependence of the failures of the other components at more distant times.

A15 Linear Regression Applied to Estimates of Failure Rate

In the case where you may acquire multiple values for the failure rate which purport to address the same equipment at a variety of ages, it may be possible to determine an age dependence of the failure rate simply by analyzing the values using regression, i.e. by drawing a line through them on a chart of failure rate versus age. The simplest lines would be straight lines, hence, the name linear regression. The main problem with this approach is that such data samples will most likely be in the form of probability distributions which individually display a wide dispersion of possible values of λ, a dispersion which can not be represented easily in the regression approach. The following sections outline the use of point values (mean, median, mode) from such distributions, as well as upper and lower confidence bounds.

The assumption here is that a set of point estimates, λ_i, are correlated with the age of the equipment in each sample. Generally, only a linear time dependence is sought. The values of λ_i would be plotted as y values and the age of each sample, t_i, as x values. Linear regression can improve upon drawing a straight line through the points by eye, because it is a formal process capable of estimating the parameters a, and b of the relation, $\lambda(t) = at + b$, and also of estimating confidence intervals for the parameters. However, the procedure will not take account of the prior uncertainty in each data point, other than by the degree of scatter displayed by all the points about the regression line.

To perform the analysis, use one of many standard software packages which perform a variety of least squares fitting procedures. In this guide we restrict the treatment to the cautions which were stated in section 2.1.3 about the widening of confidence intervals at each end of the data range, and the related inability to extrapolate outside the range of the data.

A16 Use of the EPRI PM Basis Database to Compare the Reliability of Different Component Types

If you can not find any data to represent the failure rate of a component type, neither generic, plant specific, time dependent nor time independent, you will have to use a different component type as a surrogate. This is not so unreasonable as it may seem. It is reasonable to expect that a DC motor will have a failure rate more similar to that of an AC motor than to a printed circuit board. Many different kinds of high speed rotating machinery will share may failure mechanisms, but these could not be expected to resemble the failure mechanisms of a high voltage breaker. It is clear that an appreciation of general design features will suggest which equipment may have failure rates which resemble each other. Of course, it is also common experience to find that two different models or manufacturers of the same basic component may nevertheless differ markedly in reliability. In these cases, experience usually points to specific design elements as the reasons for the differences.

Start with equipment in the same broad category. Eliminate any which are known to have operating experience markedly different from the component of interest. Focus on one or two potential surrogate component types and verify that failure rate information is available for them. Use the EPRI PM Basis database to compare the expected unreliability of the component types of interest under equivalent assumptions about duty cycle, service conditions, and comprehensiveness of PM program. The Statistics summary of the Default Vulnerability calculation will provide the necessary measure of unreliability. In the database, select the component type, then the Vulnerability button, then the Statistics button.

The Statistics form provides numerical results in terms of the numbers and percentages of opportunities for failures represented by subsets of the data. The number in the top right box is proportional to the number of failures which are *not* prevented by the PM program. These are the failures which are responsible for the residual unreliability which is experienced when using the PM program which has been analyzed. Compare this result between a potential surrogate component type and the component of interest. If they do not differ by more than a factor of 2 or 3 in this measure of unreliability, consider that the failure rate of the surrogate will form a satisfactory replacement.

In fact it is quite reasonable to use the ratio of the two results as an adjustment factor on the failure rate. This comparison can be carried much further using the database, with consequent refinements of the results at each stage. For example, an examination of the 'Red' records will reveal the reason why they are not well protected by the PM tasks. In some cases the reason will lie in a paucity of tasks, in others in the fact that the tasks are not done frequently enough, in yet others in a larger proportion of randomly occurring failure mechanisms. If degradation mechanisms which are thought to not apply to the component of interest are removed (only with administrative access to the data tables), and others added which are thought to be valid additions for the component of interest, the result can be made more realistic. Furthermore, adjustments can be made to the PM tasks, using the statistics results for Custom Vulnerability calculations, in which the user is free to make the PM coverage for the two components as comparable as possible.

The fact that these estimates can be made rather easily, should not encourage any user to believe the results to better than a factor of 3. However, since the normal margins of uncertainty on equipment failure rates are of this magnitude anyway, the method may have some utility. Its main disadvantage, of course, is that both the component of interest and potential surrogates must be present in the database.

Statistical Tables

Table A-1
Percentage Points Of The Chi-Squared Distribution With ν Degrees Of Freedom, $\chi^2_\varepsilon(\nu)$

	Values Of••									
ν	0.005	0.025	0.05	0.10	0.20	0.80	0.90	0.95	0.975	0.995
1	0.0000393	0.000982	0.00393	0.0158	0.0642	1.642	2.706	3.841	5.024	7.879
2	0.0100	0.0506	0.103	0.211	0.446	3.219	4.605	5.991	7.378	I0.597
3	0.0717	0.216	0.352	0.584	1.005	4.642	6.251	7.815	9.348	12.838
4	0.207	0.484	0.711	1.064	1.649	5.989	7.779	9.488	11.143	14.860
5	0.412	0.831	1.145	1.610	2.343	7.289	9.236	11.070	12.832	16.750
6	0.676	1.237	1.635	2.204	3.070	8.558	10.645	12.592	14.449	18.548
7	0.989	1.690	2.167	2.833	3.822	9.803	12.017	14.067	16.013	20.278
8	1.344	2.180	2.733	3.490	4.594	11.030	13.362	15.507	17.535	21.955
9	1.735	2.700	3.325	4.168	5.380	12.242	14.684	16.919	19.023	23.589
10	2.156	3.247	3.940	4.865	6.179	13.442	15.987	18.307	20.483	25.186
11	2.603	3.816	4.575	5.578	6.989	14.631	17.275	19.675	21.920	26.757
12	3.074	4.404	5.226	6.304	7.807	15.812	18.549	21.920	23.337	28.300
13	3.565	5.009	5.892	7.042	8.634	16.985	19.812	22.362	24.736	29.819
14	4.075	5.629	6.571	7.790	9.467	18.151	21.064	23.685	26.119	31.319
15	4.601	6.262	7.261	8.574	10.307	19.311	22.307	24.996	27.488	32.801
16	5.142	6.908	7.962	9.312	11.152	20.465	23.542	26.296	28.845	34.267
17	5.697	7.564	8.672	10.085	12.002	21.615	24.769	27.587	30.191	35.718
18	6.265	8.231	9.390	I0.865	12.857	22.760	25.989	28.869	31.526	37.156
19	6.844	8.907	10.117	11.651	13.716	23.900	27.204	30.144	32.852	38.582
20	7.434	9.591	I0.851	12.443	14.578	25.038	28.412	31.410	34.170	39.997
21	8.034	10.283	11.591	13.240	15.445	26.171	29.615	32.671	35.479	41.401
22	8.643	10.982	12.338	14.041	16.314	27.301	30.813	33.924	36.781	42.796
23	9.260	11.688	13.091	14.848	17.187	28.429	32.007	35.172	38.076	44.181
24	9.886	12.401	13.848	15.659	18.062	29.553	33.196	36.415	39.364	4S.558
25	10.520	13.120	14.611	16.473	18.940	30.675	34.382	37.652	40.646	46.928
26	11.160	13.844	15.379	17.292	19.820	31.795	35.563	3S.885	41.923	48.290
27	11.808	14.573	16.151	18.114	20.703	32.912	36.741	40.113	43.194	49.645
28	12.461	15.308	16.928	18.939	21.588	34.027	37.916	41.337	44.461	50.993
29	13.121	16.047	17.708	19.768	22.475	35.139	39.087	42.557	45.722	52.336
30	13.787	16.791	18.493	20.599	23.364	36.250	40.256	43.773	46.979	53.672
35	17.156	20.558	22.462	24.812	27.820	41.802	46.034	49.798	53.207	60.304
40	20.674	24.423	26.507	29.067	32.326	47.295	51.780	55.755	59.345	66.792
45	24.281	28.356	30.610	33.367	36.863	52.757	57.480	61.653	65.414	73.190
50	27.962	32.348	34.762	37.706	41.426	58.194	63.141	67.502	71.424	79.512
55	31.708	36.390	38.956	42.078	46.011	63.610	68.770	73.309	77.384	85.769
60	35.510	40.474	43.186	46.478	50.614	69.006	74.370	79.080	83.301	91.970
65	39.360	44.595	47.448	50.902	55.233	74.367	79.946	84.819	89.181	93.122
70	43.253	48.750	51.737	55.349	59.868	79.752	85.500	90.530	95.027	104.230
75	47.186	52.935	56.052	59.815	64.515	85.105	91.034	96.216	100.843	110.300
80	51.153	57.146	60.390	64.299	69.174	90.446	96.550	101.879	106.632	116.334
85	55.151	61.382	64.748	68.799	73.843	95.777	102.050	107.521	112.397	122.337
90	59.179	65.640	69.124	73.313	78.522	I0I.097	107.536	113.145	118.139	128.310
95	63.963	69.919	73.518	77.841	83.210	106.409	113.008	118.751	123.861	134.257
100	67.312	74.216	77.928	82.381	87.906	111.713	118.468	124.342	129.565	140.179
105	71.414	78.530	82.352	86.933	92.610	117.009	123.917	129.918	135.250	146.078
110	75.536	82.861	86.790	91.495	97.321	112.299	129.355	135.480	140.920	151.956
115	79.679	87.207	91.240	96.067	102.038	127.581	134.782	141.030	146.574	157.814
120	83.839	91.567	95.703	100.648	106.762	132.858	140.201	146.568	152.215	163.654

Table A-2
Two-Sided Confidence Limits For Binomial Distribution, Confidence Level: 1-α = 0.8

#Fail-ures	Number Of Demands Minus The Number Of Failures																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	.900	.684	.536	.438	.369	.319	.280	.250	.226	.206	.189	.175	.162	.152	.142	.134	.127	.120
	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
1	.949	.804	.680	.584	.510	.453	.406	.368	.337	.310	.288	.268	.251	.236	.222	.210	.199	.190
	.051	035	.026	.021	.017	.015	.013	.012	.010	.010	.609	.006	.007	.007	.007	.006	.006	.006
2	.965	.857	.753	.667	.596	.538	.490	.450	.415	.386	.360	.337	.317	.300	.284	.269	.256	.245
	.196	.143	.112	.093	.079	.069	.061	.055	.049	.045	.042	.039	.036	.034	.032	.030	.028	.027
3	.974	.888	.799	.721	.655	.599	.552	.511	.475	.444	.417	.393	.371	.357	.334	.319	.304	.291
	.320	.247	.201	.170	.147	.130	.116	.105	.096	.088	.08l	.076	.071	.067	.063	.059	.056	.054
4	.979	.907	.830	.760	.699	.646	.599	.559	.523	.492	.464	.439	.416	.396	.378	.361	.345	.331
	.416	.333	.279	.240	.210	.188	.169	.154	.142	.131	.122	.114	.107	.101	.095	.090	.086	082
5	.983	.921	.653	.790	.733	.682	.638	.598	.563	.532	.503	.478	.455	.434	.415	.397	.381	.366
	.490	.404	.345	.301	.267	.240	.219	.201	.185	.172	.161	.151	.142	.134	.127	.121	.115	.110
6	.985	.931	.870	.812	.760	.712	.669	.631	.596	.565	.537	.512	.489	.467	.448	.430	.413	.398
	.547	.462	.401	.354	.318	.288	.264	.243	.226	.210	.197	.185	.175	.165	.158	.150	.143	.137
7	.987	.939	.884	.831	.781	.736	.695	.658	.625	.594	.567	.541	.518	.497	.477	.459	.442	.426
	.594	.510	.448	.401	.362	.331	.305	.282	.263	.246	.231	.218	.207	.196	.187	.178	.170	.163
8	.988	.945	.895	.846	.799	.757	.718	.682	.650	.620	.592	.567	.544	.523	.503	.464	.457	.451
	.632	.550	.489	.441	.402	.369	.342	.318	.297	.279	.263	.249	.236	.225	.214	.205	.196	.188
9	.990	.951	.904	.858	.815	.774	.737	.703	.671	.642	.615	.590	.568	.546	.526	.508	.491	.475
	.663	.585	.525	.477	.437	.404	.375	.350	.329	.310	.293	.278	.264	.252	.241	.230	.221	.212
10	.990	.955	.912	.869	.828	.790	.754	.721	.690	.662	.636	.611	.589	.567	.548	.529	.512	.496
	.690	.614	.556	.508	.468	.435	.406	.380	.356	.338	.321	.305	.290	.277	.265	.254	.244	.235
11	.991	.958	.919	.878	.839	.803	.769	.737	.707	.679	.654	.630	.608	.587	.567	.549	.532	.515
	.712	.640	.583	.536	.497	.463	.433	.408	.365	.364	.346	.330	.315	.301	.289	.277	.267	.257
12	.992	.961	.924	.886	.849	.815	.762	.751	.722	.695	.670	.647	.525	.604	.585	.567	.550	.533
	.732	.663	.607	.561	.522	.488	.459	.433	.410	.389	.370	.353	.336	.324	.311	.299	.288	.277
13	.993	.964	.929	.893	.858	.825	.793	.764	.736	.710	.685	.662	.641	.620	.601	.583	.556	.550
	.749	.683	.629	.584	.545	.511	.482	.456	.432	.411	.392	.375	.359	.345	.331	.319	.308	.297
14	.993	.966	.933	899	.866	834	.804	.775	.748	.723	.699	.576	.655	.635	.616	.599	.582	.566
	.764	.700	.648	.604	.566	.533	.503	.477	.454	.433	.413	.396	.380	.365	.351	.338	.327	.316
15	.993	.968	.937	.905	.873	.842	.813	.786	.759	.735	.711	.689	.669	.649	.630	.613	.596	.580
	.778	.716	.666	.622	.585	.552	.523	.497	.474	.452	.433	.415	.399	.384	.370	.357	.345	.333
16	.994	.970	.941	.910	.679	.850	.622	.795	.770	.746	.723	.701	.681	.662	.643	.626	.609	.594
	.790	.731	.681	.639	.603	.570	.541	.516	.492	.471	.451	.433	.417	.401	.387	.374	.362	.350
17	.994	.972	.944	.914	.885	.857	.830	.604	.779	.756	.733	.712	.692	.673	.655	.638	.622	.606
	.801	.744	.696	.655	.619	.587	.558	.533	.509	.488	.468	.450	.434	.418	.404	.391	.378	.366
18	.994	.973	.946	.918	.890	.863	.837	.612	.788	.765	.743	.723	.703	.684	.667	.650	.634	.618
	.810	.755	.709	.669	.634	.602	.574	.549	.525	.504	.485	.467	.450	.434	.420	.406	.394	.382
19	.995	.974	.949	.922	.895	.869	.843	.819	.796	.774	.752	.732	.713	.695	.677	.660	.645	.629
	.819	.766	.721	.682	.547	.617	.589	.564	.541	.519	.500	.482	.465	.449	.435	.421	.408	.396
20	.995	.976	.951	.925	.899	.874	.849	.826	.803	.782	.761	.741	.722	.704	.687	.671	.655	.640
	.827	.776	.732	.694	.660	.630	.603	.578	.555	.534	.514	.496	.480	.464	.449	.436	.423	.411
22	.995	.978	.955	.931	.907	.883	.660	.836	.817	.796	.776	.757	.739	.722	.705	.689	.674	.659
	.841	.793	.752	.716	.683	.654	.628	.603	.581	.560	.541	.523	.506	.491	.476	.462	.449	.437
24	.996	.979	.959	.936	.914	.891	.870	.849	.828	.809	.790	.772	.754	.737	.721	.706	.691	.677
	.853	.808	.769	.735	.703	.675	.650	.626	.604	.584	.565	.547	.530	.515	.500	.486	.473	.461
26	.996	.981	.961	.941	.919	.896	.678	.858	.838	.820	.802	.784	.767	.751	.736	.721	.706	.692
	.863	.821	.784	.751	.721	.694	.669	.646	.625	.605	.586	.569	.552	.537	.522	.508	.495	.483
28	.996	.982	.964	.944	.924	.905	.685	.866	.848	.830	.812	.796	.779	.764	.749	.734	.720	.706
	.872	.832	.797	.766	.737	.711	.687	.664	.643	.624	.606	.588	.572	.557	.543	.529	.516	.503
30	.997	.983	.966	.948	.929	.910	.691	.873	.856	.838	.822	.806	.790	.775	.760	.746	.733	.719
	.880	.842	.809	.778	.751	.726	.702	.681	.660	.641	.623	.606	.590	.575	.561	.548	.535	.522

Table A-3
Two-Sided Confidence Limits For Binomial Distribution, Confidence Level: 1-α = 0.9

# Failures	Number Of Demands Minus The Number Of Failures																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	.950	.776	.632	.527	.451	.393	.348	.312	.283	.259	.238	.221	.206	.193	.181	.171	.162	.153
	.000	.000	.000	.000	000	.000	.000	.000	.000	.000	.000	.000	.000	000	.000	.000	.000	.000
1	.975	.865	.751	.657	.582	.521	.471	.429	.394	.364	.339	.316	.297	.279	.264	.250	.238	.226
	.025	.017	.013	.010	.009	.007	.006	.006	.005	.005	.004	.004	.004	.003	.003	.003	.003	.003
2	.983	.902	.811	.729	.659	.600	.550	.507	.470	.438	.410	.385	.363	.344	.326	.310	.296	.283
	.135	.098	.076	.063	.053	.046	.041	.037	.033	.030	.028	.026	.024	.023	.021	.020	.019	.0l8
3	.987	.924	.847	.775	.711	.655	.607	.564	.527	.495	.466	.440	.417	.396	.377	.359	.344	.329
	.249	.169	.153	.129	.111	.098	.087	.079	.072	.066	.061	.057	.053	.050	.047	.044	.042	.040
4	.990	.937	.871	.807	.749	.697	.650	.609	.573	.540	.511	.484	.461	.439	.419	.401	.384	.369
	.343	.271	.225	.193	.169	.150	.135	.123	.113	.104	.097	.090	.085	.080	.075	.071	.068	.065
5	.991	.947	.889	.831	.778	.729	.685	.645	.610	.577	.548	.522	.498	.476	.456	.437	.420	.404
	.418	.341	.289	.251	.222	.200	.18l	.166	.153	.142	.132	.124	.116	.110	.104	.099	.094	.090
6	.993	.954	.902	.050	.800	.755	.713	.675	.640	.609	.580	.554	.530	.508	.487	.469	.451	.435
	.479	.400	.345	.303	.271	.245	.224	.206	.191	.178	.166	.156	.148	.140	.132	.126	.120	.115
7	.994	.959	.913	.865	.819	.776	.736	.700	.667	.636	.608	.582	.558	.536	.516	.496	.479	.462
	.529	.450	.393	.350	.315	.287	.264	.244	.227	.212	.199	.188	.177	.168	.160	.152	.148	.139
8	.994	.963	.921	.877	.834	.794	.756	.721	.689	.659	.632	.606	.583	.561	.540	.521	.504	.487
	.571	.493	.436	.391	.355	.325	.300	.279	.260	.244	.230	.217	.206	.196	.185	.178	.170	.163
9	.995	.967	.928	.867	.847	.809	.773	.740	.709	.680	.653	.628	.605	.583	.563	.544	.526	.509
	.606	.530	.473	.427	.390	.360	.333	.311	.291	.274	.259	.245	.233	.222	.212	.202	.194	.186
10	.995	.970	.934	.896	.658	.822	.788	.756	.726	.698	.672	.647	.525	.603	.583	.564	.547	.530
	.636	.562	.505	.460	.423	.391	.364	.341	.320	.302	.286	.271	.258	.246	.236	.226	.217	.208
11	.996	.972	.939	.903	.868	.834	.801	.770	.741	.714	.689	.665	.642	.621	.602	.583	.565	.549
	.661	.590	.534	.489	.452	.420	.392	.368	.347	.328	.311	.296	.282	.270	.256	.246	.238	.229
12	.996	.974	.943	.910	.876	.844	.812	.783	.755	.729	.704	.681	.659	.638	.618	.600	.583	.566
	.684	.615	.560	.516	.478	.446	.418	.394	.372	.353	.335	.319	.305	.292	.280	.269	.259	.250
13	.996	.976	.947	.915	.884	.852	.823	.794	.767	.742	.718	.695	.673	.653	.634	.616	.598	.582
	.703	.637	.583	.539	.502	.470	.442	.417	.395	.375	.356	.341	.327	.313	.301	.289	.279	.269
14	.997	.977	.950	.920	.890	.860	.832	.804	.778	.754	.730	.708	.687	.667	.648	.630	.613	.597
	.721	.656	.604	.561	.524	.492	.464	.439	.417	.397	.379	.362	.347	.333	.320	.308	.297	.287
15	.997	.979	.953	.925	.896	.868	.840	.814	.788	.764	.742	.720	.699	.680	.661	.643	.627	.611
	.736	.674	.623	.581	.544	.513	.484	.460	.437	.417	.398	.382	.366	.352	.339	.327	.315	.305
16	.997	.980	.956	.929	.901	.874	.848	.822	.798	.774	.752	.731	.711	.692	.673	.656	.639	.623
	.750	.690	.641	.599	.553	.531	.504	.479	.456	.436	.417	.400	.384	.370	.357	.344	.333	.322
17	.997	.981	.958	.932	.906	.880	.854	.830	.806	.783	.762	.741	.721	.703	.685	.667	.651	.635
	.762	.704	.656	.616	.560	.549	.521	.496	.474	.453	.435	.417	.402	.387	.373	.351	.349	.338
18	.997	.982	.960	.935	.910	.885	.86l	.837	.814	.792	.771	.750	.731	.713	.695	.678	.662	.647
	.774	.717	.671	.631	.596	.565	.538	.513	.491	.470	.451	.434	418	.403	.389	.377	.365	.353
19	.997	.983	.962	.938	.914	.890	.866	.843	.821	.800	.779	.759	.740	.722	.705	.688	.672	.657
	.784	.729	.684	.645	.611	.580	.553	.529	.506	.486	.467	.450	.434	.419	.405	.392	.380	.368
20	.998	.984	.963	.941	.918	.894	.871	.849	.828	.807	.787	.767	.749	.731	.714	.698	.682	.667
	.793	.741	.696	.658	.625	.595	.568	.543	.521	.501	.482	.464	.448	.433	.419	.406	.394	.382
22	.998	.985	.967	.946	.924	.902	.881	.860	.839	.820	.801	.782	.764	.747	.731	.715	.700	.685
	.810	.760	.718	.682	.649	.620	.594	.570	.546	.528	.509	.492	.476	.461	.446	.433	.421	.409
24	.998	.986	.969	.950	.930	.909	.889	.869	.850	.831	.813	.795	.778	.762	.746	.731	.716	.702
	.824	.777	.737	.702	.671	.643	.617	.594	.572	.552	.534	.517	.500	.485	.471	.458	.445	.433
26	.998	.987	.971	.953	.934	.915	.896	.877	.859	.841	.823	.807	.790	.775	.759	.744	.730	.716
	.836	.792	.754	.720	.690	.663	.638	.615	.594	.575	.556	.539	.523	.508	.494	.481	.468	.456
28	.998	.988	.973	.956	.938	.920	.902	.884	.867	.850	.833	.817	.801	.785	.771	.757	.743	.730
	.847	.805	.768	.736	.707	.681	.657	.635	.614	.595	.577	.560	.544	.529	.515	.501	.489	.477
30	.998	.989	.975	.959	.942	.925	.908	.891	.874	.858	.842	.826	.811	.796	.782	.768	.755	.742
	.856	.816	.782	.751	.723	.697	.674	.652	.632	.613	.595	.579	.563	.548	.534	.521	.508	.496

Table A-4
Two-Sided Confidence Limits For Binomial Distribution, Confidence Level: 1-α = 0.95

#Fail-ures	Number Of Demands Minus The Number Of Failures																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	.975	.842	.708	.602	.522	.459	.410	.369	.336	.308	.285	.265	.247	.232	.218	.206	.195	.185
	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
1	.987	.906	.806	.716	.641	.579	.527	.483	.445	.413	.385	.360	.339	.319	.302	.287	.273	.260
	.013	.008	.006	.005	.004	.004	.003	.003	.003	.002	.002	.002	.002	.002	.002	.001	.001	.001
2	.992	.932	.853	.777	.710	.651	.600	.556	.518	.484	.454	.478	.405	.383	.364	.347	.331	.317
	.094	.068	.053	.043	.037	.032	.028	.025	.023	.021	.019	.018	.017	.016	.015	.014	.013	.012
3	.994	.947	.882	.816	.755	.701	.652	.610	.572	.538	.508	.481	.456	.434	.414	.396	.379	.363
	.194	.147	.118	.099	.085	.075	.067	.060	.055	.050	.047	.043	.040	.038	.036	.034	.032	.030
4	.995	.957	.901	.843	.788	.738	.692	.651	.614	.581	.551	.524	.499	.476	.456	.437	.419	.403
	.284	.223	.184	.157	.137	.122	.109	.099	.091	.084	.078	.073	.066	.064	.061	.057	.054	.052
5	.996	.963	.915	.863	.813	.766	.723	.684	.649	.616	.587	.560	.535	.512	.491	.471	.453	.436
	.359	.290	.245	.212	.187	.167	.151	.139	.128	.118	.110	.103	.097	.091	.087	.082	.078	.075
6	.996	.968	.925	.878	.833	.789	.749	.711	.677	.646	.617	.590	.565	.543	.522	.502	.484	.467
	.421	.349	.299	.262	.234	.211	.192	.177	.163	.152	.142	.133	.126	.119	.113	.107	.102	.098
7	.997	.972	.933	.891	.849	.808	.770	.734	.701	.671	.643	.616	.592	.570	.549	.529	.512	.494
	.473	.400	.348	.308	.277	.251	.230	.213	.198	.184	.173	.163	.154	.146	.139	.132	.126	.121
8	. 997	.975	.940	.901	.861	.823	.787	.753	.722	.692	.655	.639	.516	.593	.573	.553	.535	.518
	.517	.444	.390	.349	.315	.289	.266	.247	.230	.215	.203	.191	.181	.172	.164	.156	.149	.143
9	.997	.977	.945	.909	.872	.837	.802	.770	.740	.711	.685	.660	.636	.615	.594	.575	.557	.540
	.555	.482	.428	.386	.351	.323	.299	.278	.260	.244	.231	.218	.207	.197	.188	.180	.172	.165
10	.998	.979	.950	.916	.882	.848	.816	.785	.756	.728	.702	.678	.655	.634	.614	.595	.577	.560
	.587	.516	.462	.419	.384	.354	.329	.308	.289	.272	.257	.244	.232	.221	.211	.202	.194	.186
11	.998	.981	.953	.922	.890	.858	.827	.797	.769	.743	.718	.694	.672	.651	.631	.612	.594	.578
	.615	.546	.492	.449	.413	.363	.357	.335	.315	.298	.282	.268	.256	.244	.234	.224	.215	.207
12	.998	.982	.957	.927	.897	.867	.837	.809	.782	.756	.732	.709	.687	.666	.647	.628	.611	.594
	.640	.572	.519	.476	.440	.410	.384	.361	.340	.322	.306	.291	.278	.266	.255	.245	.235	.227
13	.998	.983	.960	.932	.903	.874	.846	.819	.793	.768	.744	.722	.701	.680	.661	.643	.626	.609
	.661	.595	.544	.501	.465	.435	.408	.384	.364	.345	.328	.313	.299	.287	.275	.264	.255	.245
14	.998	.984	.962	.936	.909	.881	.854	.828	.803	.779	.756	.734	.713	.694	.675	.657	.640	.624
	.681	.617	.566	.524	.488	.457	.430	.407	.385	.366	.349	.334	.320	.306	.295)	.283	.273	.264
15	.998	.985	.964	.939	.913	.887	.861	.836	.812	.789	.766	.745	.725	.705	.687	.669	.653	.637
	.698	.636	.586	.544	.509	.478	.451	.427	.406	.386	.369	.353	.339	.325	.313	.302	.291	.281
16	.999	.986	.965	.943	.918	.893	.868	.844	.820	.798	.776	.755	.736	.717	.698	.681	.665	.649
	.713	.653	.604	.563	.529	.498	.471	.447	.425	.405	.388	.372	.357	.343	.331	.319	.308	.298
17	.999	.987	.968	.946	.922	.898	.874	.851	.828	.806	.785	.765	.745	.727	.709	.692	.676	.660
	.727	.669	.621	.58l	.547	.516	.488	.465	.443	.423	.406	.389	.374	.360	.347	.335	.324	.314
18	.999	.988	.970	.948	.925	.902	.879	.857	.835	.814	.793	.773	.755	.736	.719	.702	.686	.671
	.740	.683	.637	.597	.564	.533	.506	.482	.460	.440	.422	.406	.391	.376	.363	.351	.340	.329
19	.999	.988	.971	.950	.929	.906	.884	.862	.841	.821	.801	.782	.763	.745	.728	.712	.696	.681
	.751	.696	.651	.612	.579	.549	.522	.498	.476	.456	.439	.422	.406	.392	.379	.366	.355	.344
20	.999	.989	.977	.953	.932	.910	.889	.868	.847	.827	.808	.789	.771	.753	.737	.720	.705	.690
	.762	.708	.664	.626	.593	.564	.537	.513	.492	.472	.454	.437	.421	.407	.393	.381	.369	.356
22	.999	.990	.975	.956	.937	.917	.897	.877	.858	.839	.820	.803	.785	.768	.752	.737	.722	.707
	.781	.730	.688	.651	.619	.590	.565	.541	.519	.500	.481	.465	.449	.434	.421	.408	.396	.385
24	.999	.991	.976	.960	.942	.923	.904	.885	.867	.849	831	.814	.798	.782	.766	.751	.737	.723
	.797	.749	.708	.673	.642	.614	.589	.566	.545	.525	.507	.490	.475	.460	.446	.433	.421	.410
26	.999	.991	.976	.962	.945	.928	.910	.893	.875	.858	.841	.825	.809	.794	.779	.764	.750	.736
	.810	.765	.726	.693	.663	.636	.611	.588	.567	.548	.530	.513	.497	.483	.469	.456	.444	.432
28	.999	.992	.980	.965	.949	.932	.916	.899	.882	.866	.850	.834	.819	.804	.790	.776	.762	.749
	.822	.779	.743	.710	.681	.655	.631	.609	.588	.569	.551	.535	.519	.504	.491	.478	.465	.453
30	.999	.992	.981	.967	.952	.936	.920	.904	.889	.873	.858	.843	.826	.814	.800	.786	.773	.760
	.833	.792	.757	.725	.697	.672	.649	.627	.607	.588	.571	.554	.539	.524	.510	.498	.485	.473

Table A-5
Values Of P For Which The Cumulative Fraction Of The Area Under The Beta Distribution Equals 2.5%, i.e. For A Confidence Level Of 95%.

Value Of V	Value Of W											
	1	2	3	4	5	6	10	12	15	20	30	60
1	0.02500	0.01258	0.00840	0.00631	0.00505	0.00421	0.00253	0.00211	0.00169	0.00126	0.00084	0.00042
2	0.15811	0.09429	0.06758	0.05274	0.04327	0.03669	0.02283	0.01921	0.0l551	0.01175	0.00791	0.00399
3	0.29240	0.19412	0.14663	0.11812	0.09899	0.08523	0.05486	0.04658	0.03798	0.02906	0.01977	0.01009
4	0.39764	0.28358	0.22278	0.18405	0.15701	0.13700	0.09092	0.07787	0.06409	0.04951	0.03403	0.01757
5	0.47818	0.35877	0.29042	0.24486	0.21201	0.18709	0.12760	0.11017	0.09147	0.07132	0.04953	0.02585
6	0.54074	0.42128	0.34914	0.29930	0.26238	0.23379	0.16336	0.14210	0.11893	0.09356	0.06562	0.03463
7	0.59038	0.47349	0.39991	0.34755	0.30790	0.27667	0.19753	0.17299	0.14588	0.11573	0.08194	0.04372
8	0.63058	0.51750	0.44390	0.39026	0.34888	0.31578	0.22983	0.20252	0.17198	0.13753	0.09827	0.05298
9	0.66373	0.55498	0.48224	0.42814	0.38574	0.35138	0.26019	0.23058	0.19708	0.15878	0.11444	0.06235
10	0.69150	0.58722	0.51586	0.46187	0.41896	0.38380	0.28864	0.25713	0.22110	0.17938	0.13038	0.07175
11	0.71509	0.61520	0.54553	0.49202	0.44900	0.41338	0.31528	0.28221	0.24402	0.19930	0.14601	0.08114
12	0.73535	0.63970	0.57187	0.51911	0.47623	0.44042	0.34021	0.30588	0.26587	0.21850	0.16130	0.09050
13	0.75295	0.66132	0.59540	0.54354	0.50101	0.46520	0.36355	0.32821	0.28667	0.23698	0.17622	0.09979
14	0.76836	0.68052	0.61652	0.56568	0.52363	0.48797	0.38542	0.34928	0.30647	0.25476	0.19076	0.10901
15	0.78198	0.69768	0.63559	0.58582	0.54435	0.50895	0.40594	0.36918	0.32532	0.27185	0.20492	0.11812
20	0.83157	0.76184	0.70839	0.66411	0.62616	0.59296	0.49168	0.45370	0.40697	0.34780	0.26997	0.16201
30	0.88430	0.83298	0.79193	0.75669	0.72550	0.69743	0.60674	0.57056	0.52422	0.46239	0.37498	0.24027
60	0.94037	0.91201	0.88828	0.86708	0.84764	0.82954	0.76678	0.73968	0.70299	0.65017	0.56658	0.41107
∞	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Table A-6
Values Of P For Which The Cumulative Fraction Of The Area Under The Beta Distribution Equals 5.0%, i.e. For A Confidence Level Of 90%.

Value Of V	Value Of W											
	1	2	3	4	5	6	10	12	15	20	30	60
1	0.05000	0.02532	0.01695	0.01274	0.01021	0.00851	0.00512	0.00426	0.00341	0.00256	0.00170	0.00085
2	0.22361	0.13535	0.09761	0.07644	0.06285	0.05337	0.03332	0.02805	0.02268	0.01719	0.01158	0.00585
3	0.36840	0.24860	0.18926	0.15316	0.12876	0.11111	0.07187	0.06110	0.04990	0.03822	0.02604	0.01332
4	0.47287	0.34259	0.27134	0.22532	0.19290	0.16875	0.11267	0.09666	0.07969	0.06167	0.04248	0.02198
5	0.54928	0.41820	0.34126	0.28924	0.25137	0.22244	0.15272	0.13211	0.10991	0.08588	0.05978	0.03129
6	0.60696	0.47930	0.40031	0.34494	0.30354	0.27125	0.19086	0.16636	0.13955	0.11006	0.07739	0.04097
7	0.65184	0.52932	0.45036	0.39338	0.34981	0.31524	0.22669	0.19895	0.16818	0.13377	0.09499	0.05085
8	0.68766	0.57086	0.49310	0.43563	0.39086	0.35480	0.26011	0.22972	0.19556	0.15682	0.11240	0.06082
9	0.71687	0.60584	0.52991	0.47267	0.42738	0.39041	0.29120	0.25865	0.22164	0.17908	0.12950	0.07082
10	0.74113	0.63564	0.56189	0.50535	0.45999	0.42256	0.32009	0.28580	0.24639	0.20050	0.14622	0.08079
11	0.76160	0.66132	0.58990	0.53434	0.48925	0.45165	0.34693	0.31126	0.26985	0.22106	0.16252	0.09070
12	0.77908	0.68366	0.61461	0.56022	0.51560	0.47808	0.37190	0.33515	0.29208	0.24078	0.17838	0.10052
13	0.79418	0.70327	0.63656	0.58343	0.53945	0.50217	0.39516	0.35756	0.31314	0.25966	0.19379	0.11024
14	0.80736	0.72060	0.65617	0.60436	0.56112	0.52420	0.41685	0.37862	0.33309	0.27775	0.20875	0.11983
15	0.81896	0.73604	0.67381	0.62332	0.58088	0.54442	0.43711	0.39842	0.35200	0.29507	0.22326	0.12930
20	0.86089	0.79327	0.74053	0.69636	0.65819	0.62460	0.52099	0.48175	0.43321	0.37136	0.28936	0.17453
30	0.90497	0.85591	0.81606	0.78150	0.75070	0.72282	0.63185	0.59522	0.54807	0.48477	0.39458	0.25416
60	0.95130	0.92458	0.90192	0.88150	0.86266	0.84504	0.78342	0.75661	0.72016	0.66738	0.58326	0.42519
∞	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.0000	1.00000	1.00000

Table A-7
Values Of P For Which The Cumulative Fraction Of The Area Under The Beta Distribution Equals 10.0%, i.e. For A Confidence Level Of 80%.

Value	Value Of W											
Of V	1	2	3	4	5	6	10	12	15	20	30	60
1	0.10000	0.05132	0.03451	0.02599	0.02085	0.01741	0.01048	0.00874	0.00700	0.00525	0.00351	0.00175
2	0.31623	0.19580	0.14256	0.11224	0.09259	0.07882	0.04945	0.04169	0.03375	0.02562	0.01729	0.00875
3	0.46416	0.32046	0.24664	0.20091	0.16964	0.14685	0.09565	0.08148	0.06667	0.05117	0.03494	0.01791
4	0.56234	0.41611	0.33319	0.27860	0.23966	0.21040	0.14161	0.12177	0.10064	0.07808	0.05393	0.02798
5	0.63096	0.48968	0.40382	0.34462	0.30097	0.26732	0.18513	0.16056	0.13394	0.10497	0.07330	0.03847
6	0.68129	0.54744	0.46178	0.40058	0.35422	0.31772	0.22559	0.19716	0.16587	0.13123	0.09260	0.04921
7	0.71969	0.59375	0.50992	0.44827	0.40053	0.36228	0.26292	0.23139	0.19619	0.15659	0.11161	0.05999
8	0.74989	0.63164	0.55040	0.48924	0.44100	0.40176	0.29726	0.26327	0.22483	0.18093	0.13019	0.07077
9	0.77426	0.66315	0.58484	0.52473	0.47657	0.43689	0.32885	0.29293	0.25182	0.20420	0.14828	0.08148
10	0.79433	0.68976	0.61448	0.55574	0.50803	0.46829	0.35793	0.32051	0.27721	0.22642	0.16583	0.09208
11	0.81110	0.71250	0.64022	0.58302	0.53603	0.49649	0.38475	0.34619	0.30111	0.24759	0.18283	0.10257
12	0.82540	0.73216	0.66279	0.60721	0.56108	0.52193	0.40954	0.37012	0.32361	0.26778	0.19928	0.11290
13	0.83768	0.74933	0.68271	0.62878	0.58361	0.54498	0.43248	0.39245	0.34481	0.28701	0.21518	0.12308
14	0.84834	0.76443	0.70044	0.64813	0.60398	0.56595	0.45378	0.41332	0.36479	0.30534	0.23054	0.13310
15	0.85770	0.77783	0.71630	0.66559	0.62247	0.58511	0.47359	0.43286	0.38366	0.32283	0.24539	0.14295
20	0.89125	0.82706	0.77578	0.73219	0.69412	0.66034	0.55476	0.51428	0.46386	0.39910	0.31243	0.18960
30	0.92612	0.88023	0.84212	0.80864	0.77851	0.75104	0.66029	0.62333	0.57545	0.51067	0.41750	0.27063
60	0.96235	0.93773	0.91643	0.89702	0.87897	0.86198	0.80192	0.77553	0.73946	0.68688	0.60235	0.44158
∞	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

B
NERC-GADS CAUSE CODES APPLICABLE TO NUCLEAR PLANT COMPONENTS

INDEX TO SYSTEM/COMPONENT CAUSE CODES FOR NUCLEAR PLANTS

This set of codes contains the following:

- The reactor
- The containment system
- The reactor coolant system including chemical, volume, and pressure control system
- Safety systems, both electrical and mechanical
- Residual heat removal systems
- Closed loop cooling water for reactor systems
- Service water for closed loop cooling and other reactor systems
- Steam generators
- Main steam systems up to the outboard containment isolation valve
- Feedwater systems from the reactor or steam generator up to the outboard containment isolation valve
- Blowdown systems
- Radioactive waste and off-gas systems

Core/Fuel

2010 Fuel failure including high activity in Reactor Coolant System (RCS) or off-gas system

2020 Control rod pattern changes and control rod repatch. (Preconditioning following a pattern change is to be reported using code 2031.)

2021 Power limited by rod pattern. (If rod pattern is limited by fuel limits, use appropriate code below.)

2030 Fuel limits - peaking factors

2031 Fuel preconditioning

2032 Fuel limits - MCPR (Minimum Critical Power Ratio - BWR units only)

2033 Fuel limits - MAPLHGR (Maximum Average Planar Linear Heat Generation Rate - BWR units only)

2034 Core tilt restrictions

2035 Core xenon restrictions

2036 End-of-life scram reactivity/rod worth restrictions

2037 Other fuel limits (use codes 9110 and 9120 for core coastdown, conservation, or stretch)

2040 Core physics tests

2050 Burnable poison problems including poison curtains

2060 Excore nuclear instrumentation

2061 Incore nuclear instrumentation

2062 Other fuel/core related instrumentation problems

2070 Normal refueling

2071 Refueling equipment problems

2072 Fuel storage

2080 Fueling machine and auxiliaries (CANDU)

2082 Fuel transfer problems (CANDU)

2090 Other core/fuel problems

Control Rods and Drives

2110 Control rod drive motors

2111 Control rod magnetic jack drives

2112 Control rod hydraulic drives

2120 Control rod scram mechanisms

2125 Reactivity control units (CANDU)

2130 Control rod assemblies other than drive and scram mechanisms

2140 Control rod drive cooling

2150 Control rod instrumentation

2151 Control rod drive controls

2152 Control rod drive power supplies

2155 Control rod testing

2160 Other control rod drive problems

Reactor Vessel and Internals

2170 Reactor vessel flanges and seals

2171 Reactor vessel nozzles

2172 Feedwater sparges

2173 Jet pumps

2174 Core support

2175 Specimen holders

2176 Control rod guides (not in fuel)

2180 Calandria and Calandria tubes (CANDU)

2185 Coolant assemblies (pressure tubes) (CANDU)

2199 Other reactor vessel problems

Reactor Coolant System

Pumps

2200 Reactor coolant/recirculating pumps

2210 Reactor coolant/recirculating pump motors

2220 Reactor coolant/recirculating pump MG sets

Piping

2230 Reactor coolant system piping

2240 Reactor coolant system pipe supports

2250 Reactor coolant system filters and strainers

2260 Reactor coolant flanges, fittings, and manways

Pressurizer

2265 Pressurizer (also see codes 2290, 2330, and 2340)

Valves

2270 Power operated relief and safety/relief valves

2280 Non-power operated safety valves

2290 Pressurizer spray valves

2300 Recirculation loop flow control valves

2320 Other reactor coolant valves (including RCS boundary valves in connected systems)

Instruments and Controls

2330 Pressurizer level instruments and controls

2340 Pressurizer pressure instruments and controls

2350 BWR feedwater controls

2360 BWR pressure controls

2370 Reactor trip system including sensors, logic, and actuators (includes spurious trips but not valid trips)

2380 Reactor control system/integrated control system problems

2390 Other reactor coolant system instruments and controls

Miscellaneous (Reactor Coolant System)

2399 Other miscellaneous reactor coolant system problems

Steam Generators and Steam System

2400 Steam generator tube leaks

2411 Steam generator tube inspections

2412 Steam generator tube supports

2420 Steam generator moisture separators and dryers

2421 Steam generator feedwater nozzles

2422 Other steam generator internals problems

2430 Steam generator shell

2431 Steam generator flanges, manways, and fittings

2432 Steam generator supports and snubbers

2440 Steam generator chemistry (excluding feedwater chemistry)

2441 Steam generator tube lancing

2442 Steam generator chemical cleaning

2443 Steam generator modifications

2450 Blowdown system piping

2460 Blowdown system valves

2470 Blowdown system instruments and controls

2480 Other blowdown

2500 Steam piping (up to turbine stop valves and bypass valves)

2510 Main steam isolation valves (BWR and PWR)

2515 Main steam isolation valve testing

2520 Main steam safety/relief valves (except BWR)

2521 Main steam safety/relief valve testing

2530 Atmospheric or condenser dump valves (not SRVs)

2540 Other steam valves

2550 Steam generator instruments (including piping and valves) (no RPS or SAS inputs)

2560 Steam generator controls

2599 Other steam generator problems

Core Cooling/Safety Injection (where portions of these systems also serve in the makeup system, report problems as CVCS problems)

2600 High pressure safety injection, core injection, or core spray pumps (including RCIC)

2601 Motors for high-pressure pumps

2602 Steam turbine drives for high-pressure pumps (including RCIC)

2603 High pressure piping

2604 High pressure valves

2609 Other high-pressure injection problems

2620 Low pressure safety injection, core spray, or decay heat pumps

2621 Motors for low-pressure pumps

2622 Low pressure piping

2623 Low pressure valves

2624 Low pressure heat exchangers

2625 Accumulators (up to and including check valves)

2628 Residual heat removal/decay heat removal system

2629 Other low-pressure problems

2630 Safeguard actuation system (including sensors, logic, activators, and sequencers)

2649 Other emergency core cooling/residual heat removal system problems

Electrical Safety Systems

2650 Emergency diesel generators (including actuating systems)

2651 Emergency diesel generator output breakers

2660 Safeguard buses and associated equipment (transformers, breakers, etc.)

2670 DC safety system power supplies

2680 120V AC safety system power supplies (including inverter)

2699 Other electrical safety system power supplies (use codes 3600 to 3659 for nonsafety electrical systems)

Containment System

2700 Containment structure

2701 Containment liner

2702 Containment hatches

2703 Containment penetrations

2720 Containment isolation valves and dampers

2730 Containment isolation actuation

2740 Containment penetration pressurization system

2750 Containment hydrogen control system (vents, recombiners, etc.)

2760 Containment spray system (including actuation)

2770 Containment cooling system - normal

2771 Containment cooling and gas cleanup - post accident

2780 Containment testing

2799 Other containment system problems

Chemical and Volume Control/Reactor Water Cleanup

2805 Moderator systems (CANDU)

2806 Moderator purification (CANDU)

2807 Moderator poison injection (CANDU)

2810 Makeup pumps

2811 Boric acid transfer pumps

2812 Tanks

2813 Demineralizers

2814 Filters

2815 Heat exchangers

2816 Valves and piping

2817 Instruments and controls

2819 Other CVCS and RWC problems

Nuclear Cooling Water Systems

2820 Nuclear closed cooling water pumps

2821 Nuclear closed cooling water piping

2822 Nuclear closed cooling water valves

2823 Nuclear closed cooling heat exchanger

2825 Turbine building closed cooling water system

2829 Other closed cooling water system problems

2830 Nuclear service water pumps

2831 Nuclear service water piping

2832 Nuclear service water valves

2833 Nuclear service water heat exchangers

2839 Other service water problems

Auxiliary Systems (see codes 3110 to 3999 for other auxiliary systems)

2840 Auxiliary feedwater pumps

2841 Auxiliary feedwater pump motors

2842 Auxiliary feedwater pump steam turbines (including steam control valves)

2843 Auxiliary feedwater piping

2844 Auxiliary feedwater valves

2849 Other auxiliary feedwater problems

2870 Radioactive liquid waste system problems

2880 Radioactive gas and waste system problems

2890 Condenser off-gas system problems

Miscellaneous (Reactor)

2900 Reactor overhaul (use for non-specific overhaul only; see page B-1)

2990 Plant radiation levels

2991 Radioactivity discharge levels to the environment

2995 Reactor performance testing (use code 9999 for total unit performance testing)

2999 Other miscellaneous nuclear reactor problems

BALANCE OF PLANT

Condensing System

Condenser Tubes

3110 Condenser tube leaks

3111 Condenser tube fouling shell side

3112 Condenser tube fouling tube side

3113 Condenser tube and water box cleaning (including circulating water flow reversal)

3119 Other condenser tube casing or shell and internal problems

Condenser Casing or Shell and Internals

3120 Tube sheets

3121 Expansion joint

3122 Gaskets and seals

3123 Hot well

3124 Tube sheet fouling

3129 Other condenser casing or shell and internal problems

Vacuum Equipment

3130 Air ejectors

3131 Air ejector piping and valves

3132 Inter and after condensers

3133 Vacuum pumps

3134 Vacuum pump piping and valves

3149 Loss of vacuum not attributable to a particular component such as air ejectors or valves. Also high backpressure not attributable to high circulating water temperature or vacuum losses from a known cause.

Condenser Controls

3150 Hot well level controls

3151 Vacuum pump and air ejector controls

3159 Other condensing system controls and instruments

Miscellaneous (Condensing System)

3170 Condenser inspection (use code 3110 to report looking for tube leaks)

3180 Major condenser overhaul

3185 Water side cathodic protection

3190 Air leakage (for losses not attributable to previously noted equipment related codes)

3199 Other miscellaneous condensing system problems

Circulating Water Systems

3210 Circulating water pumps

3211 Circulating water pump motors

3220 Circulating water piping

3221 Circulating water piping fouling

3230 Circulating water valves

3235 Cooling tower booster pump

3236 Cooling tower booster motor

3238 Cooling tower fan motors

3239 Cooling tower fan motors - variable speed

3240 Cooling tower fans

3241 Cooling tower efficiency below design

3242 Cooling tower fill damage

3243 Cooling tower icing

3244 Cooling tower fires

3245 Other cooling tower problems

3246 Cooling tower fouling

3250 Circulating water system instruments and controls

3260 Traveling screens

3261 Traveling screen fouling

3270 Intake system problems other than traveling screens

3271 Intake grating fouling

3280 High circulating water temperature (not due to season, tower efficiency below design, or other listed equipment problem)

3285 Circulating water chemistry

3299 Other circulating water system problems

Condensate System

Pumps, Piping, and Valves

3310 Condensate/hotwell pumps

3311 Condensate/hotwell pump motor

3312 Condensate booster pump

3313 Condensate booster pump motor

3314 Condensate booster pump motor - variable speed

3315 Condensate booster pump drive (other than 3313 and 3314)

3320 Condensate piping

3330 Condensate valves

Low/Intermediate Pressure Heater and Deaerators

3339 LP heater head leaks

3340 LP heater tube leaks

3341 LP heater other

3342 IP heater tube leaks

3343 IP heater other

3344 Deaerator (including level control)

3345 IP heater head leaks

Polishers/Chemical Addition

3350 Condensate polishing and filtering systems

3351 Chemical addition systems

3352 Feedwater chemistry (not specific to condenser, polishers, or chemical addition)

Miscellaneous (Condensate System)

3360 Condensate makeup and return (including storage tanks)

3370 Condensate system controls and instrumentation (not hotwell level, heater level, or deaerator level controls: see codes 3150-3159, 3344, 3502.

3380 Condensate coolers

3399 Other miscellaneous condensate system problems

Feedwater System (excluding extraction or drain systems)

3401 Startup feedwater pump

3402 Startup feedwater pump drives - all types

3408 Feedwater pump drive - controls

3409 Feedwater pump drive motor - variable speed

3410 Feedwater pump

3411 Feedwater pump drive - motor

3412 Feedwater pump drive - steam turbine

3413 Feedwater pump coupling and drive shaft

3414 Feedwater pump local controls

3415 Feedwater pump/drive lube oil system

3416 Other feedwater pump problems

3417 Feedwater pump drive - main shaft

3418 Feedwater pump drive - other

3419 Feedwater pump drive - gear

3420 Feedwater piping

3430 Feedwater regulating (boiler level control) valve

3431 Other feedwater valves

3439 HP heater head leaks

3440 High pressure heater tube leaks

3441 Other high-pressure heater problems (see condensate system for LP and IP heater codes)

3499 Other feedwater system problems

Heater Drain Systems

3501 Heater drain pumps

3502 Heater level control

3503 Heater drain piping

3504 Heater drain valves

3505 Heater drain pump drive

3509 Other heater drain system problems

Extraction Steam

3520 Extraction steam piping

3521 Extraction steam valves

3522 Extraction steam instruments and controls

3529 Other extraction steam system problems

Electrical (excluding nuclear safety (Class 1E) systems)

3600 Switchyard transformers and associated cooling systems

3611 Switchyard circuit breakers

3612 Switchyard system protection devices

3619 Other switchyard equipment

3620 Main transformer

3621 Unit auxiliaries transformer

3622 Station service startup transformer

3623 Auxiliary generators (except nuclear emergency generators)

3629 Other switchyard or high voltage system problems

3630 480-volt transformers

3631 480-volt circuit breakers

3632 480-volt conductors and buses

3633 480-volt insulators

3634 480-volt protection devices

3639 Other 480-volt problems

Note: for other voltages, see codes 3660-3689.

3640 AC instrument power transformers

3641 Circuit breakers

3642 Conductors and buses

3643 Inverters

3644 Protection devices

3649 Other AC instrument power problems

3650 DC instrument power battery chargers

3651 DC circuit breakers

3652 DC conductors and buses

3653 DC protection devices

3659 Other DC power problems

3660 4160-volt transformers

3661 4160-volt circuit breakers

3662 4160-volt conductors and buses

3663 4160-volt insulators

3664 4160-volt protection devices

3669 Other 4160-volt problems

3670 12kV-volt transformers

3671 12kV-volt circuit breakers

3672 12kV-volt conductors and buses

3673 12kV-volt insulators

3674 12kV-volt protection devices

3679 Other 12kV-volt problems

3680 other voltage transformers

3681 other voltage circuit breakers

3682 other voltage conductors and buses

3683 other voltage insulators

3684 other voltage protection devices

3689 other voltage problems

Auxiliary Systems

Service Water (Open System)

3810 Service water pumps and motors

3811 Service water piping

3812 Service water valves

3813 Service water heat exchangers

3814 Service water system fouling

3819 Other service water problems

Closed Cooling Water Systems

3821 Closed cooling water piping

3822 Closed cooling water valves

3823 Closed cooling water heat exchangers

3824 Closed cooling water system fouling

Other closed cooling water system problems

Auxiliary Steam

3830 Auxiliary boiler

3831 Auxiliary steam piping

3832 Auxiliary steam valves

3833 Auxiliary steam controls and instruments

3834 Auxiliary boiler tube leaks

3839 Other auxiliary steam problems (also see extraction steam codes 3520 to 3529; startup bypass codes 0630 to 0660; and soot blower steam code 0870)

Service Air

3840 Service air compressors

3841 Service air piping

3842 Service air valves

3843 Service air dryers

3849 Other service air problems

Instrument Air

3850 Instrument air compressors

3851 Instrument air piping

3852 Instrument air valves

3853 Instrument air dryers

3854 N_2 backup to instrument air

3859 Other instrument air problems

Fire Protection System

3860 Fire protection system pumps

3861 Fire protection system piping

3862 Fire protection system valves

3863 Fire protection system fouling

3869 Other fire protection system problems

Miscellaneous (Auxiliary Systems)

3899 Other miscellaneous auxiliary system problems

Miscellaneous (Balance of Plant)

3950 Process computer

3960 Thermal derating (thermal efficiency losses in balance of plant when specific cause(s) unknown)

3999 Other miscellaneous balance of plant problems

STEAM TURBINE

Besides the turbine, this set includes the steam stop/control valves, turbine control system, and the turbine auxiliaries. The extraction steam codes are contained in the Balance of Plant set.

High Pressure Turbine

4000 Outer casing

4001 Inner casing

4009 Nozzle bolting

4010 Nozzles and nozzle blocks

4011 Diaphragms

4012 Buckets or blades

4013 Diaphragms unit and shroud type

4014 Bucket or blade fouling

4015 Wheels or spindles

4020 Shaft seals

4021 Dummy rings

4022 Gland rings

4030 Rotor shaft

4040 Bearings

4099 Other high-pressure turbine problems

Intermediate Pressure Turbine

4100 Outer casing

4101 Inner casing

4109 Nozzle bolting

4110 Nozzles and nozzle blocks

4111 Diaphragms

4112 Buckets or blades

4113 Bucket or blade fouling

4115 Wheels or spindles

4120 Shaft seals

4121 Dummy rings

4122 Gland rings

4130 Rotor shaft

4140 Bearings

4199 Other intermediate pressure turbine problems

Low Pressure Turbine

4200 Outer casing

4201 Inner casing

4209 Nozzle bolting

4210 Nozzles and nozzle blocks

4211 Diaphragms

4212 Buckets or blades

4213 Bucket or blade fouling

4215 Wheels or spindles

4220 Shaft seals

4221 Dummy rings

4222 Gland rings

4230 Rotor shaft

4240 Bearings

4250 Other low-pressure turbine problems

Valves

4260 Main stop valves

4261 Control valves

4262 Intercept valves

4263 Reheat stop valves

4264 Combined intercept valves

4265 Miscellaneous drain and vent valves

4266 Main stop valve testing

4267 Control valve testing

4268 Reheat/intercept valve testing

4269 Other turbine valves

Piping

4270 Crossover or under piping

4279 Miscellaneous turbine piping

<u>Lube Oil</u> (do not include bearing failures due to lube oil)

4280 Lube oil pumps

4281 Lube oil coolers

4282 Lube oil conditioners

4283 Lube oil system valves and piping

4284 Lube oil pump drive

4289 Other lube oil system problems

Controls

4290 Hydraulic system pumps

4291 Hydraulic system coolers

4292 Hydraulic system filters

4293 Hydraulic system pipes and valves

4299 Other hydraulic system problems

4300 Turbine supervisory system (use codes 4290 to 4299 for hydraulic oil)

4301 Turbine governing system

4302 Turbine trip devices (including instruments)

4303 Exhaust hood and spray controls

4304 Automatic turbine control systems - mechanical

4305 Automatic turbine control systems - mechanical – hydraulic

4306 Automatic turbine control systems - electro-hydraulic - analog

4307 Automatic turbine control systems - electro-hydraulic - digital

4308 Automatic turbine control systems - digital control and monitoring

4309 Other turbine instrument and control problems

Miscellaneous (Steam Turbine)

4400 Major turbine overhaul (use for non-specific overhaul only; see page B-1)

4401 Inspection

4410 Turning gear and motor

4420 Vibration of the turbine generator unit that cannot be attributed to a specific cause such as bearings or blades (use this code for balance moves)

4430 Gland seal system

4440 Moisture separator/reheater (nuclear including MSR drains, controls, etc.)

4445 Steam reheater

4450 Water induction

4460 Turbine overspeed trip test

4470 Differential expansion

4490 Turbine performance testing (use code 9999 for total unit performance testing)

4499 Other miscellaneous steam turbine problems

GENERATOR

This set of codes contains the generator, exciter, generator cooling systems, and generator controls. Note the main leads up to and including the generator output breaker are included in this set of codes.

Generator

4500 Rotor windings

4510 Rotor collector rings

4520 Stator windings, bushings, and terminals

4530 Stator core iron

4540 Brushes and brush rigging

4550 Generator bearings and lube oil system

4555 Bearing cooling system

4560 Generator vibration (excluding vibration due to failed bearing and other components)

4570 Generator casing

4580 Generator end bells and bolting

Exciter

4600 Exciter drive - motor

4601 Exciter field rheostat

4602 Exciter commutator and brushes

4603 Solid state exciter element

4604 Exciter drive - shaft

4609 Other exciter problems

Cooling System (report failures caused by water leaks into generator as codes 4500, 4510, etc.)

4610 Hydrogen cooling system piping and valves

4611 Hydrogen coolers

4612 Hydrogen storage system

4613 Hydrogen seals

4619 Other hydrogen system problems

4620 Air cooling system

4630 Liquid cooling system

4640 Seal oil system and seals

4650 Other cooling system problems

Controls

4700 Generator voltage control

4710 Generator metering devices

4720 Generator synchronization equipment

4730 Generator current and potential transformers

4740 Emergency generator trip devices

4750 Other generator controls and metering problems

Miscellaneous (Generator)

4800 Generator main leads

4810 Generator output breaker

4830 Major overhaul (use for non-specific overhaul only; see page B-1)

4840 Inspection

4850 Core monitor alarm

4899 Other miscellaneous generator problems

EXTERNAL

Use this set of codes to report events caused by external factors (flood, lightning, etc); economic factors (lack of fuel, labor strikes, etc.); operator training; and, transmission system problems external to the plant.

Catastrophe

9000 Flood

9010 Fire, not related to a specific component

9020 Lightning

9025 Geomagnetic disturbance

9030 Earthquake

9040 Other catastrophe

Economic

0000 Reserve shutdown

9110 Core coastdown (nuclear)

9120 Core conservation (nuclear)

9130 Lack of fuel

9150 Labor strikes

9160 Other economic problems

Miscellaneous (External)

9300 Transmission system problems other than catastrophes (do not include switchyard problems in this category; see codes 3600 to 3629)

9310 Operator training

9320 Other miscellaneous external problems

REGULATORY, SAFETY, ENVIRONMENTAL

Use these codes only for events not directly attributable to equipment failures. Inspections or testing of certain equipment due to regulation are reported using the appropriate equipment cause codes, and the fact that it was a regulatory requirement noted in the verbal description section.

Regulatory

9500 Regulatory (nuclear) proceedings and hearings - regulatory agency initiated

9502 Regulatory (nuclear) proceedings and hearings - intervener initiated

9504 Regulatory (environmental) proceedings and hearings - regulatory agency initiated

9506 Regulatory (environmental) proceedings and hearings - intervener initiated

9510 Plant modifications strictly for compliance with new or changed regulatory requirements (scrubbers, cooling towers, etc.)

9590 Miscellaneous regulatory (this code is primarily intended for use with event contribution code 2 to indicate that a regulatory-related factor contributed to the primary cause of the event)

Other Operating Environmental Limitations

9660 Thermal discharge limits

9670 Noise limits (not for personnel safety)

9680 Fish kill

9690 Other miscellaneous operational environmental limits

Safety

9700 OSHA-related retrofit or inspection

9710 Investigation of possible nuclear safety problems

9720 Other safety problems

PERSONNEL ERRORS

9900 Operator error

9910 Maintenance error

9920 Contractor error

PERFORMANCE

9999 Total unit performance testing (use appropriate codes for individual component testing)

BALANCE OF PLANT

Electrical

3600 Switchyard transformers and associated cooling systems

3611 Switchyard circuit breakers

3612 Switchyard system protection devices

3619 Other switchyard equipment

3620 Main transformer

3621 Unit auxiliaries transformer

3622 Station service startup transformer

3623 Auxiliary generators

3629 Other switchyard or high voltage system problems

3630 480-volt transformers

3631 480-volt circuit breakers

3632 480-volt conductors and buses

3633 480-volt insulators

3634 480-volt protection devices

3639 Other 480-volt problems

Note: for other voltages, see codes 3660-3689.

3640 AC instrument power transformers

3641 Circuit breakers

3642 Conductors and buses

3643 Inverters

3644 Protection devices

3649 Other AC instrument power problems

3650 DC instrument power battery chargers

3651 DC circuit breakers

3652 DC conductors and buses

3653 DC protection devices

3659 Other DC power problems

3660 4160-volt transformers

3661 4160-volt circuit breakers

3662 4160-volt conductors and buses

3663 4160-volt insulators

3664 4160-volt protection devices

3669 Other 4160-volt problems

3670 12kV-volt transformers

3671 12kV-volt circuit breakers

3672 12kV-volt conductors and buses

3673 12kV-volt insulators

3674 12kV-volt protection devices

3679 Other 12kV-volt problems

3680 other voltage transformers

3681 other voltage circuit breakers

3682 other voltage conductors and buses

3683 other voltage insulators

3684 other voltage protection devices

3689 other voltage problems

C COMPONENT AND DEGRADATION SCOPING TABLES

Table C-1
Scoping List By Component Type

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	***May* Have Scheduled Replacement, Rebuild, Refurbishment, Overhaul, Or Equivalent.**
Heat Exchanger - Feedwater Heater	Heat exchanger nozzle to nozzle, including shells and internal components	Control systems and devices, safety relief valves, insulation, and the main steam reheaters.	P	No
Heat Exchanger - General Tube Type	Heat exchanger nozzle to nozzle, including shells, supports and tubes	Control systems and devices, e.g. temperature and pressure control valves, safety relief valves, and insulation.	P	No
Heat Exchanger - Main Condenser	Condensers, including: water boxes, hot well, tubes and tube sheets, supports, cathodic protection, expansion seal, inlet and outlet nozzles, turbine exhaust flange connection, penetration bellows	Feedwater heaters, the water box vacuum priming system, and instrumentation, and any equipment exhaust or suction piping and their penetrations	P	No
Small Bore Piping	Piping and fittings (elbows, tees, couplings, etc.) of nominal pipe size less than or equal to 4 inches (NPS-4)	May be above ground or buried. Also may include pipe supports, insulation, linings, & corrosion protection coatings.	P	No
Large Bore Piping	Piping and fittings (elbows, tees, couplings, etc.) of nominal pipe size greater than 4 inches (NPS-4)	May be above ground or buried. Also may include pipe supports, insulation, linings, & corrosion protection coatings.	P	No
Heat Exchanger Components	Shells, Tubes & Supports	Shells similar to pressure vessels. Tubes and tube supports present wide variety of reliability concerns	P	No
Bolts and Fasteners	Wide variety of fasteners used in Nuclear Plant components for support & pressure retention.		P	Depends on application

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
Pressure Vessels	Elevated pressure tanks containing fluids or gases	May include bolting, flanges, gaskets, supports and insulation	P	No
Storage Tanks	Wide variety of atmospheric pressure storage tanks containing water and other fluids	May be above ground or buried. Also may include supports, insulation, linings, & corrosion protection coatings.	P	No
Pump Casings	Pressure boundary portion of pumps. Similar in function to Pressure Vessels, but generally castings.	May include bolting, flanges, gaskets, supports and insulation	P	No
Valve Bodies	Pressure boundary portion of valves. Similar in function to Pressure Vessels, but generally castings.	May include bolting, flanges, gaskets, supports and insulation	P	No – except for check valves
HVAC - Dampers & Ducting	Isolation and balancing dampers, actuators, and controls, turning vanes and flow straighteners, ducting	HEPA and the charcoal filters, and their by-pass dampers	A (Damper); P (Ducting)	No
Motor - Direct Current	Electric motor and motor shaft; all power, sensing, and control cables up to but not including the DC breaker; motor mounting and base; internal motor heaters.	Coupling to driven component.	A	No
Battery - Charger	Charger	Input breakers	A	No
Battery - Flooded Lead Acid - Lead Calcium/Antimony	Battery cells, inter-tier and inter-cell connectors, battery rack		A	No
Battery - Flooded Lead Acid - Plante	Battery cells, inter-tier and inter-cell connectors, battery rack		A	No
Battery - Inverter	Inverter, maintenance bypass switch, static switch, if installed.	Distribution panel, regulated rectifiers, and breakers	A	No

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
Battery - NICAD	Battery cells, inter-tier and inter-cell connectors, battery rack		A	No
Diesel - Small Standby	All components from the source of inlet air to the engine, intake and exhaust louvers, linkages and actuators, the engine coolant radiator/heat exchanger, engine, battery, fuel day tank, and local control panel, up to and including the external engine exhaust.	Engine driven component (e.g. pump, generator, compressor, gearbox); coupling to driven component; fuel supply storage tanks; fuel supply and transfer pumps and piping; the battery charger and controls; plant or raw water cooling system piping, valves, controls, along with the cooling water strainers to the heat exchangers used to cool engine fluids (e.g. oil, coolant); electrical controls and connections external to the engine (e.g. block heater); engine air-start devices; electronic, mechanical, and hydraulic governors.	A	No
HVAC - Air Handling Equipment	Inlet and outlet isolation dampers and their actuators, fan, coils, including inlet and outlet temperature/control valves, controls and wiring, filters, housing and pans	Fan motor, HEPA and charcoal filters, ductwork	A	No
Relay - Protective	Relay; external connectors.		A	No
Relay - Timing	Relay; external connectors.		A	No
Switchgear - Motor Control Centers	Bucket assembly including starters, contactors, relays, controls, power transformers, fuses; MCC housing including bus, power transformers, distribution panel board, and relays, if applicable.		A	No
Transformer - Station Type, Oil Immersed	Transformer; coolers; pumps; controls; fans; radiators; load tap changers; surge and lightning arrestors; pressure relief valves; sensors, monitors, alarms, and current transformers; protective, timing,	Line isolation breakers, iso-phase bus and cooling, generator relays, conductors, low voltage motor starters and contactors, and fire suppression	A	No

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
	and control relays.	equipment.		
Valve - Pressure Relief - Spring Actuated	Vent stack; pressure relief valve body; connection point to the piping; nozzle and disk.		A	No
Valve - Solenoid Operated - SOV	Actuator, including coil, switches, electrical connections and wiring, electrical conduit seal, control box, e.g. timer, voltage drop device, electronic components; Body Bonnet Assembly, including plunger, seat and trim, spring(s), and elastomers, if present.		A	No
Air Dryer - Heat Of Compression Drum Type	All components between the air inlet and air outlet valves of the dryer, as well as the bypass valve	Compressor after cooler, and the pre- and after-filters	A	No
Air Dryer - Heated	All components on the dryer skid or in the dryer package, including pre-filters and post-filters, and bypass valves.	Isolation and drain valves	A	No
Air Dryer - Unheated	All components on the dryer skid or in the dryer package, including pre-filters and post-filters, and bypass valves.	Isolation and drain valves	A	No
Compressor & Pump - Rotary, Liquid Ring	Compressor, cooler, moisture separator tank and recirculation pump, speed reducer, control components	Motor driver	A	No
Motor - Low Voltage - <600V	Electric motor and motor shaft; all connected cables up to but not including the supply device; motor mounting and base; bearing cooling water connections, if present; air filters, if present; internal motor heaters; detectors, if present, such as temperature, vibration, and alarms.	Coupling to driven component; if present, bearing cooling water connection valves and piping external to the motor's shell or frame.	A	No

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
Motor - Wound Rotor - <600V	Electric motor and motor shaft; all power, sensing, and control cables up to but not including the switchgear breaker; motor mounting and base; surge capacitors, if present; bearing and stator cooling water connections; air filters, if present; internal motor heaters; detectors such as, temperature, vibration, and alarms.	Coupling to driven component; bearing and stator cooling water valves and piping external to the motor's shell or frame	A	No
Pump - Horizontal with Couplings	Pump; coupling; discharge flange; inlet suction flange; external lubrication system; cooling water injection input to seals and bearings; pump foundation; detectors, sensors, and alarms (e.g. bearing temperature and vibration).	Motor or turbine driver.	A	No
Pump - Vertical	Pump and its mount; coupling; motor mounting or flange; discharge flange or head; inlet suction flange or bell.	Motor driver; seal water injection system.	A	No
Valve - Air Operated - AOV	Actuator assembly, (piston and diaphragm actuators), with or without spring return; valve body assembly; solenoid operated valve; manual operator; accumulators; pneumatic tubing; pneumatic switches; limit switches; positioner; booster; pressure regulator / filter canister; E-P/I-P transducer; position transmitters.	Controllers, hand and automatic switches, and the instrument air isolation valve.	A	No (Yes for actuator)
Valve - Motor Operated - MOV	Actuator, including gear box, switches (Limit and Torque), motor (not including motor power feed and control), hand wheel, wiring (internal to the operator), spring pack; Valve Body including guides; packing; seat; stem / stem nut.		A	No (Yes for actuator)
Valve - Power Operated Relief - Pneumatic Actuated	Actuator, including controls and sensing elements, valve and packing; attached piping, vents and drains.		A	No (Yes for actuator)

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
Valve - Power Operated Relief - Solenoid Actuated	Outlet / Atmospheric vent, attachment point to piping; actuator; controls and sensing elements; valve; vent stack drains and vents.	External drain systems, if present.	A	No (Yes for actuator)
Battery - Valve Regulated Lead Acid	Battery cells, inter-tier and inter-cell connectors, battery rack		A	Yes
Compressor - Centrifugal	All components on the compressor skid from the inlet air filter up to the discharge valve, inclusive.	Motor driver	A	Yes
Compressor - Reciprocating	Compressor, outlet flange of the after cooler, inlet air filter, compressor mounting and base, pulley including belts, controls	Air Dryers	A	Yes
Compressor - Rotary Screw	Compressor, outlet flange of the after cooler, inlet air filter, compressor mounting and base, pulley including belts or coupling, controls.	Air Dryers	A	Yes
HVAC - Chiller & Compressor	Inlet and outlet condenser cooling water valves, inlet and outlet chilled water valves, condenser, evaporator, compressor, refrigerant metering device or expansion valve, relief device, controls and wiring, refrigerant load control system	Chilled and condenser water pumps, motors, and isolation valves	A	Yes
Pump - Positive Displacement	Pump, power end and fluid cylinder; suction stabilizer; discharge dampener; pump coupling; pump gear reducer; oil cooler heat exchanger; oil filters, if present; packing coolant/lubrication piping and supply tank.	Motor driver.	A	Yes
I&C - DC Power Supply	Power Supply		A	Yes
I&C - Electrolytic Capacitor	Capacitor		A	Yes
I&C - Analog Electronic Controller	Controller	Manual-auto station	A	Yes

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
I&C - Booster	Booster		A	Yes
I&C - I/P and E/P Transducer	Transducer		A	Yes
I&C - Pneumatic Controller	Controller		A	Yes
I&C - Positioner	Positioner	I/P transducer and DVDT	A	Yes
I&C - Pressure Regulator	Regulator		A	Yes
I&C - Pressure Sensor And Transmitter	Pressure sensor, its transmitter, and their sensing lines, if present, including a 3 or 5 valve manifold, condensate pots, reference legs, and bellows.		A	Yes
I&C - Pressure Switch			A	Yes
I&C - Signal Conditioner		E/P and I/P transducers, PLCs, ADCs, and any sensors	A	Yes
I&C - Temperature Switch			A	Yes
Motor - Medium Voltage - <15kV	Electric motor and motor shaft; all power, sensing, and control cables up to but not including the switchgear breaker; motor mounting and base; surge capacitors, if present; bearing and stator cooling water connections; air filters, if present; internal motor heaters; detectors such as, temperature, corona, vibration, and alarms.	Coupling to driven component; bearing and stator cooling water valves and piping external to the motor's shell or frame	A	Yes
Relay - Control	Relay; external connectors.		A	Yes

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
Switchgear - Low Voltage	Switchgear enclosure including racking mechanism, bus bar and insulation, cabinets, interlocks and switches, lightning arrestors, bus potential and current transformers, load current transformers, and control wiring; circuit breaker including racking mechanism, truck, operating mechanism, main current components, arc chutes or arc quenching devices, and auxiliary switches and contacts; protective devices including relays, such as overcurrent, ground fault, control wiring, switches (e.g. auxiliary switches, control relay, trip coils), and local metering.		A	Yes
Switchgear - Medium Voltage - 1kV to 7kV	Switchgear enclosure including racking mechanism, bus bar and insulation, cabinets, interlocks and switches, lightning arrestors, bus potential and current transformers, load current transformers, reactor (if present), and control wiring; circuit breaker including racking mechanism (if attached to the circuit breaker), truck, operating mechanism, main current components, arc chutes or arc quenching devices including vacuum bottles, and auxiliary switches and contacts; electrical devices such as control wiring, switches (e.g. auxiliary switches, control relay, trip coils), and local metering; protective relays, such as undervoltage, overcurrent, ground fault, and field monitor.		A	Yes
Turbine - Main Turbine EHC Hydraulics	EHC fluid; fluid supply and treatment components; servo-valves; solenoid valves; mechanical shutoff valves; instrumentation; hydraulically operated components directly activated by the EHC fluid.	Valve bodies of steam valves, and electronic controls; low voltage motors.	A	Yes
Turbine - Terry - Single Stage	Turbine and exhaust hood; trip and throttle and governor valves; oil filtration unit; oil sump and pump; mechanical governor.	Coupling, drain valves, and piping.	A	Yes

Component Type	Generally Includes	Auxiliary Components Which Should Also Be Considered	Active / Passive	*May* Have Scheduled
Turbine - Feedwater Pump (Main)	Turbine and exhaust hood, including the expansion joint; stop and control valves; bearing oil filters (duplex filter assembly); oil sump and pump; controls (MHC), including vacuum trip; governor; turning gear.	Coupling, drain valves, and piping; auxiliary oil filtration systems such as a centrifuge or Bowser system.	A	Yes
Valve - Check - Duo	Valve body assembly and all internal subcomponents.		A	Yes
Valve - Check - Piston - Lift - Ball	Valve body assembly and all internal subcomponents.		A	Yes
Valve - Check - Swing	Valve body assembly and all internal subcomponents.		A	Yes
Valve - Check - Tilting Disk	Valve body assembly and all internal subcomponents.		A	Yes

This sample of degradation mechanisms for two components illustrates the potential range of such mechanisms, but these are offered only as examples, many of which will not be relevant for LCM applications.

Table C-2
Typical Degradation Mechanisms

Compressor - Reciprocating	Battery - Lead Acid
Broken	Broken
Burnt Contacts	Clogged
Clogged orifices	Contamination
Clogged supply lines and check valves	Copper contamination of negative plates
Clogged water cooling ports	Corrosion
Coil failure	Cracked
Cracked cylinder body or head	Disintegrated
Diaphragm failure of the regulator	Growth of grid
Drift	High electrolyte level
Elastomer and gasket failure	Hydration
Failed filter housing	Improper connection
Failed Sensors, Bourdon tubes	Low electrolyte level
Failed Sensors, Capsules	Mechanical damage
Failed Sensors, Diaphragms	Mechanical failure (broken and buckled)
Fails to reseat	Plate shedding
Gasket failure	Punctured or cracked
Inadequate disc clearance	Stratification
Incorrect oil	Sulfation
Journal wear	
Leak	

Leak-by	
Loose / Missing	
Loose connections	
Loose mounting bolts	
Loose tubing and fittings	
Low oil flow	
Low oil level	
Miscalibration	
Open or short circuit	
Packing failure	
Pitted or worn contacts	
Plugged orifices	
Plugged piping	
Scoring	
Seat wear or cracking	
Spring failure	
Stuck	
Stuck or loose contacts	
Stuck or plugged orifices	
Weak springs	
Wear	
Wear of inlet and outlet valves and check valves	
Wear of piston rings / liner	
Wear of scraper rings and packing	
Wear of sheaves and belts	

This sample of the stressors for two components illustrates the potential range of such stressors, but these are only examples, many of which will not be relevant for LCM applications.

Table C-3
Typical Stressors

Compressor - Reciprocating	Battery - Lead Acid
Aging	Acid leakage or spray
Aging (fatigue)	Aging
Aging (gasket failure)	Battery left in discharged condition
Aging (cycles)	Broken grounds
Aging (run time)	Corrosion
Aging (thermal cycling)	Cycling
Application error	Damage to protective paint
Assembly error	Excessive equalization
Corrosion	Excessive watering
Corrosion of O-ring grooves	Foreign material
Crud buildup	Foreign objects
Crushed lines	High temperature
Debris (oil, rust, metal particles, filter debris)	Improper application of corrosion inhibiting grease
Drift of lubricator settings	Improper cleaning
Environment (contaminated air)	Improper connector crimping
Environment (high temperature)	Improper design
Environment (ice)	Improper installation
Failure of arc suppression	Improper maintenance, e.g. wire brushing
Failure to maintain cathodic protection	Improper storage (open circuit)
Fluid Chemistry	Improper support
High temperature (friction)	Improper torque
High temperature (normally energized)	Improper training & procedures
Improper belt	Inadequate watering
Improper belt tension	Leaking jar

Improper torque	Loose hardware
Inactivity	Low temperature
Incorrect material / assembly	Manufacturing defect
Incorrect material / specifications	Mechanical damage
Installation error	Mossing
Installation method and location	Oil from separator decomposition (model specific)
Lack of lubrication	Over torqueing
Leakage	Overcharging
Low cooling water flow	Overcharging (high float voltage)
Manufacturing defect	Personnel error
Misalignment	Plate and post growth
Moisture from gasket failure	Poor seal design
Normal Wear (run time)	Rust
Personnel error	Shipping & handling
Pitting/contamination	Shock (electrical or mechanical)
Silt accumulation	Sulfate deposits from off gassing
Soft foot	Too high specific gravity
Vibration	Transportation damage
Wrong fasteners	Ultraviolet light
	Undercharging
	Undercharging at low specific gravity
	Use of solvents
	Vibration
	Water quality
	Wrong hardware

Table C-4
Long Term Degradation Mechanisms (>10 years) For A Range Of Component Types

Component Type	Failure Location	Degradation Mechanism	Stressors
HVAC Dampers and Ducting	Limitorque Type Actuators	Motor failure, but see MOV for other degradation mechanisms	Age
	Balancing Damper Blade to Control Shaft Connection	Shear	Vibration
	Tornado Dampers	Hard, dry lubricant in bearings	Age
	Tornado Dampers	Hard, dry lubricant in bearings	Accessibility: Lack of lubrication or movement
	Fire Dampers	Worn, bound or failed linkages	Vibration
	Fire Dampers	Worn, bound or failed linkages	Corrosion
	Fire Dampers	Worn, bound or failed linkages	Age
	Structure, Sheet Metal	Cracks at joints	Vibration
	Structure, Sheet Metal	Cracks at joints	Flow oscillation
	Structure, Sheet Metal	Cracks at joints	Operational transient
	Structure, Sheet Metal	Cracks at joints	Corrosion
	Access Doors	Leaky gasket	Age
	Flexible Boots	Tears	Age
	Flexible Boots	Tears	Vibration
	Flexible Boots	Tears	Environment

Component Type	Failure Location	Degradation Mechanism	Stressors
HVAC Dampers and Ducting (cont)	Turning Vanes & Flow Straighteners & Silencers (mufflers)	Weld failure	Vibration
	Turning Vanes & Flow Straighteners & Silencers (mufflers)	Weld failure	Flow oscillation
	Turning Vanes & Flow Straighteners & Silencers (mufflers)	Weld failure	Operational transients
	Turning Vanes & Flow Straighteners & Silencers (mufflers)	Weld failure	Corrosion
	Isolation Dampers	Worn, bound or failed linkages	Vibration
	Isolation Dampers	Worn, bound or failed linkages	Corrosion
	Isolation Dampers	Worn, bound or failed linkages	Age
	Isolation Dampers	Failed Bladder	Age
	Isolation Damper Blade to Control Shaft Connection	Shear	Vibration
	Balancing Dampers	Worn, bound or failed linkages	Vibration
	Balancing Dampers	Worn, bound or failed linkages	Corrosion
	Balancing Dampers	Worn, bound or failed linkages	Age
Terry Turbine	Oil	Degradation of additive package	Age
	Oil	Degradation of additive package	Temperature
	Rotor	Cracking	Stress concentration (design)
	Rotor	Cracking	Thermal cycling

Component Type	Failure Location	Degradation Mechanism	Stressors
Terry Turbine (cont)	Governor and Oil Pump Drive Gear	Wear	Misalignment of gears
	Governor and Oil Pump Drive Gear	Wear	Age
	Governor and Oil Pump Drive Gear	Wear	Misalignment of pump
	Governor and Oil Pump Drive Gear	Broken teeth	Misalignment of gears
	Governor and Oil Pump Drive Gear	Broken teeth	Age
	Governor and Oil Pump Drive Gear	Broken teeth	Misalignment of pump
	Turbine and Exhaust Hood Casing	Erosion	Normal wear
	Hydraulic Control System Components: Pistons, Pilot Valves, Vacuum Trip Mechanism, Servo Valves, and Fittings	Wear	Age
	Turbine Bearings	Wear	Age
	Turbine Bearing Labyrinth Seals	Excessive clearances	Wear
Swing Check Valve	Body	Leakage: cover gasket or hinge pin cover	Aging
	Body	Erosion	System conditions dependent on: fluid condition, high fluid velocity, valve location in reference to bends, transitions, etc
	Disk	Disk detachment	Vibration or oscillation
	Disk	Disk detachment	Corrosion

Component Type	Failure Location	Degradation Mechanism	Stressors
Swing Check Valve (cont)	Disk Arm	Wear in the disk post hole or the disk hinge pin hole	High duty cycles
	Hinge pin	Wear	Vibration or oscillation
	Hinge pin	Wear	High duty cycles
Station Transformer	Core	Loss of core ground	Vibration
	Core	Multiple core grounds	Assembly or shipping error
	Core	Multiple core grounds	Vibration
	Gaskets	Leakage	Aging from thermal cycling and stray eddy currents
	Transformer Oil (mineral)	Loss of dielectric strength	Heat from normal operation
	Transformer Oil (mineral)	Loss of dielectric strength	Low energy electrical discharge
	Core	Loose	Assembly or shipping error
	Core	Loose	Vibration
	Core	Loss of core ground	Assembly or shipping error
	Load Tap Changer	Damaged contacts	Normal wear
	Load Tap Changer	Leaking: pipes, tubing, fittings, gaskets, and valves	Aging
	Load Tap Changer	Leaking: pipes, tubing, fittings, gaskets, and valves	Wear

Component Type	Failure Location	Degradation Mechanism	Stressors
Station Transformer (cont)	Windings	Insulation breakdown	Aging: heat of operation, corona
	Oil Filled Bushings	Leakage	O-ring failure
	Fins and Tube Coolers	Loss of heat transfer	Internal oil sludging
	Fins and Tube Coolers	Loss of heat transfer	External corrosion
	Fins and Tube Coolers	Leaks: tube to header	Thermal expansion
	Fins and Tube Coolers	Leaks: tube to header	Vibration
	Fins and Tube Coolers	Leaks: tube to header	Dissimilar materials
	Fins and Tube Coolers	Leaks: tube to header	Manufacturing defect
	Fins and Tube Coolers	Leaking gaskets	Aging from thermal cycling and stray eddy currents
	Radiators	Loss of heat transfer	Oil sludging
	Fans and Motors	Winding insulation failure	Aging
	Fans and Motors	Fan blade cracks	Fatigue
	Fans and Motors	Fan blade cracks	Corrosion
	Fans and Motors	Motor power cable deterioration	Aging
	Fans and Motors	Motor power cable deterioration	Heat
	Fans and Motors	Motor power cable deterioration	Sunlight
	Pump and Motor	Bearing wear	Aging

Component Type	Failure Location	Degradation Mechanism	Stressors
	Pump and Motor	Impeller and volute wear	Aging
Station Transformer (cont)	Pump and Motor	Winding insulation failure	Aging
	Pump and Motor	Motor power cable deterioration	Aging
	Pump and Motor	Motor power cable deterioration	Heat
	Pump and Motor	Motor power cable deterioration	Sunlight
	Sudden Pressure Relay	Misoperation	Aging (switch, spring, and diaphragm)
	Conservator Tank	Bladder failure	Aging
	Conservator Tank	Fittings and connection leaks	Vibration
	Desiccant	Outlet breather valve fails to seal	Aging
	Desiccant	Outlet breather valve fails to seal	Environmental conditions
Control Relay	Mechanical Assembly	Spring Relaxation	Aging
	Coils	Insulation Degradation	Heat
Horizontal Pump	Shaft	Cracked	Bound shaft
	Diffusers, Volutes & Channel Rings	Erosion or damage to diffuser or volute inlets	Age
	Shaft	Cracked	Manufacturing defect
	Shaft	Cracked	Thermal fatigue
	Shaft	Cracked	Cyclic / torsional fatigue
	Shaft	Cracked	Cyclic bending

Component Type	Failure Location	Degradation Mechanism	Stressors
	Gaskets & O-Ring Leaks	Corrosion	Incorrect material
Horizontal Pump (cont)	Gaskets & O-Ring Leaks	Corrosion	Age
	Gaskets & O-Ring Leaks	Degraded material properties	Incorrect material
	Gaskets & O-Ring Leaks	Degraded material properties	Age
	External Pump Casing (barrel) and Closure Head	Discharge nozzle erosion	Age
	External Pump Casing (barrel) and Closure Head	Discharge nozzle erosion	Design
	External Pump Casing (barrel) and Closure Head	Damage to casing penetration	Fatigue
	External Pump Casing (barrel) and Closure Head	Damage to casing penetration	Erosion
	External Pump Casing (barrel) and Closure Head	Damage to casing penetration	Too frequent maintenance
	Pump / Motor Coupling	Fatigue failure of spring pack or nonmetallic parts	Age
	Pump / Motor Coupling	Fatigue failure of spring pack or nonmetallic parts	Excessive axial thrust
	Pump Base Plate and Foundation	Failed anchor or base plate	Loose bolts
	Pump Base Plate and Foundation	Failed anchor or base plate	Improper installation
	Pump Base Plate and Foundation	Failed anchor or base plate	Improper bolt tolerances
	Pump Base Plate and Foundation	Failed anchor or base plate	Vibration

Component Type	Failure Location	Degradation Mechanism	Stressors
	Pump Base Plate and Foundation	Failed anchor or base plate	Pipe stress
Horizontal Pump (cont)	Pump Base Plate and Foundation	Failed anchor or base plate	Age
	Pump Base Plate and Foundation	Failed anchor or base plate	Corrosion on bolts
	Pump Base Plate and Foundation	Failed anchor or base plate	Environment
	Connections & Piping	Leaks	Vibration
	Bearings - Antifriction	Wear - fatigue	Degraded lubricant - age
	Bearings - Sleeve	Wear	Degraded lubricant - age
	Bearings - Kingsbury type	Wear - fatigue	Degraded lubricant - age
	Pump Casing, Horizontal Split	Corrosion / Erosion or Damage to Internal Flow Passages (casing or rotor)	Age
Spring Relief Valves	Bellows	Leaks	Corrosion
	Plug to Stem Connection	Failure of Retaining Cotter Pin	Corrosion
	Plug to Stem Connection	Failure of Retaining Cotter Pin	Design
	Plug to Stem Connection	Failure of Retaining Cotter Pin	Personnel error
	Gasket	Leaks	Aging
	Spring	Broken	Chemical attack
	Spring	Broken	Fatigue
	Spring	Loss of Spring Constant	Aging due to creep
	Nozzle Disk Interface	Leak	Corrosion

Component Type	Failure Location	Degradation Mechanism	Stressors
	Body and Flanges	Corrosion	Chemical attack
Spring Relief Valves (cont)	Body and Flanges	Erosion	Misoperation
	Body and Flanges	Erosion	Contamination / Debris
Low Voltage Motor - <600V	Bearing Insulation	Insulation degradation	Contamination
	Bearing Seals	Wear	Age
	Bearing Seals	Wear	Bearing wear or failure
	Bearings - Antifriction	Wear	Normal Wear
	Bearings - Sleeve	Wear	Normal Wear
	Cast Rotor: Rotor bars and shorting rings	Corrosion	Environment
	Cast Rotor: Rotor bars and shorting rings	Cracked	Age, Cycle fatigue
	Cast Rotor: Rotor bars and shorting rings	Cracked	Number of starts, Thermal fatigue
	Cast Rotor: Rotor bars and shorting rings	Deformation	Excessive starts
	Electrical Connections	High resistance	Contamination
	Feeder Cables	Insulation degradation	Age
	Feeder Cables	Insulation degradation	Contamination especially water
	Feeder Cables	Insulation degradation	Temperature

Component Type	Failure Location	Degradation Mechanism	Stressors
	Gaskets	Material defect (cracks or porosity)	Age
Low Voltage Motor - <600V (cont)	Motor Leads	Insulation degradation	Age
	Motor Leads	Insulation degradation	Contamination
	Motor Leads	Insulation degradation	Temperature
	Space Heaters	Broken, loose or grounded connections	Personnel error
	Space Heaters	Broken, loose or grounded connections	Vibration
	Space Heaters	Open element	Age
	Stator Laminations	Breakdown of insulation	Contamination
	Stator Laminations	Breakdown of insulation	Heat
	Stator Laminations	Breakdown of insulation	Vibration
	Stator Laminations	Contamination	Environment (dirt build up)
	Stator: Windings, Blocking, Bracing, Wedges	Fretting of insulation materials	Movement during running and starts
	Stator: Windings, Blocking, Bracing, Wedges	Insulation degradation	Age
	Stator: Windings, Blocking, Bracing, Wedges	Insulation degradation	Contamination
	Stator: Windings, Blocking, Bracing, Wedges	Insulation degradation	Excessive starts

Component Type	Failure Location	Degradation Mechanism	Stressors
	Stator: Windings, Blocking, Bracing, Wedges	Insulation degradation	Heat above rated
Low Voltage Motor - <600V (cont)	Stator: Windings, Blocking, Bracing, Wedges	Insulation degradation	Radiation
	Stator: Windings, Blocking, Bracing, Wedges	Loose blocking and bracing	Age
	Stator: Windings, Blocking, Bracing, Wedges	Loose blocking and bracing	Excessive starts
Motor Control Center	Current carrying components, e.g. over current trip devices, contacts, lugs	High temperature damage	Fault current interruptions
	Contactors, Starters, and Relays	Coil failure	Temperature
	Contactors, Starters, and Relays	Coil failure	Age
	Operating Mechanism	Lubrication failure	Temperature
	Operating Mechanism	Lubrication failure	Age
	Current carrying components, e.g. over current trip devices, contacts, lugs	Loose connections	High cycle, e.g. incorrect application using circuit breaker to make/break direct loads
	Current carrying components, e.g. over current trip devices, contacts, lugs	Loose connections	Temperature cycling and high temperatures due to current loads
	Current carrying components, e.g. over current trip devices, contacts, lugs	Loose connections	Excessive loads

Component Type	Failure Location	Degradation Mechanism	Stressors
	Current carrying components, e.g. over current trip devices, contacts, lugs	Loose connections	Fault current interruptions
Motor Control Center (cont)	Current carrying components, e.g. over current trip devices, contacts, lugs	High temperature damage	High cycle, e.g. incorrect application using circuit breaker to make/break direct loads
	Current carrying components, e.g. over current trip devices, contacts, lugs	High temperature damage	Temperature cycling and high temperatures due to current loads
	Current carrying components, e.g. over current trip devices, contacts, lugs	High temperature damage	Excessive loads
Main Turbine EHC	Accumulators	Elastomer failures: bladder and O-rings	Fluid quality
	Accumulators	Piston/Cylinder Wear	Age
	Accumulators	Piston/Cylinder Wear	Fluid quality
	Accumulators	Elastomer failures: bladder and O-rings	Age
	Accumulators	Leaks	Loose fittings from vibration
	Elastomers, e.g. O-rings, Teflon, Gaskets, Bladders, and Seals	Deterioration of material properties	Age
	Coolers	Internal leak	Tube fretting
	Coolers	Internal leak	Corrosion from raw water
	Heaters	Gasket leak for immersion types	Age

Component Type	Failure Location	Degradation Mechanism	Stressors
	Heaters	Open heater element	Heat
	Heaters	Open heater element	Age
Main Turbine EHC (cont)	Tubing: Piping and Supports	Cracked tubing	Vibration, high cycle fatigue
	Tubing: Piping and Supports	Loose supports	Vibration
	Check Valve	Stuck	Fluid quality
	Check Valve	O-ring seal leaks	Age
	Relief Valves, Unloader Valves, and Flow Control Valves (hydraulically actuated)	Bound	Fluid quality
	Relief Valves, Unloader Valves, and Flow Control Valves (hydraulically actuated)	Plugged ports	Fluid quality
	Relief Valves, Unloader Valves, and Flow Control Valves (hydraulically actuated)	Wear	Fluid quality
	Solenoid Valves; e.g. Test, Trip, and Lockout	Failed coil	Age
	Solenoid Valves; e.g. Test, Trip, and Lockout	Failed coil	Heat
	Solenoid Valves; e.g. Test, Trip, and Lockout	Bound spool	Fluid quality
	Solenoid Valves; e.g. Test, Trip, and Lockout	Plugged part or orifice	Fluid quality
	Actuators	Scored cylinder	Debris

Component Type	Failure Location	Degradation Mechanism	Stressors
	Actuators	Scored cylinder	Fluid quality
Main Turbine EHC (cont)	Mechanical Actuated Valves, e.g. Trip and Shutoff	Loose linkages	Vibration
	Mechanical Actuated Valves, e.g. Trip and Shutoff	Bound spool	Fluid quality
	Mechanical Actuated Valves, e.g. Trip and Shutoff	Plugged part or orifice	Fluid quality
Main Feedwater Turbine	High and Low Pressure Control Valves	Valve seat seal weld or stellite cracking	Thermal cycling
	High and Low Pressure Stop Valves	Leak through	Valve body erosion
	High and Low Pressure Stop Valves	Seat seal weld and stellite damage	Thermal cycling
	High and Low Pressure Stop Valves	Seat seal weld and stellite damage	Mechanical impact during trip
	Rotor	Erosion	Wet steam flow (normal operation)
	Rotor	Cracking	Stress concentration
	Rotor	Cracking	Thermal cycling
	Governor and Oil Pump Drive Gear	Wear	Misalignment of gears
	Governor and Oil Pump Drive Gear	Broken teeth	Age
	Overspeed Trip Mechanism	Weak spring	Age
	Solenoid Valves; Overspeed Trip and Trip Reset	Coil failure	Heat

Component Type	Failure Location	Degradation Mechanism	Stressors
	Trip Reset		
	Solenoid Valves; Overspeed Trip and Trip Reset	Coil failure	Contamination
Main Feedwater Turbine (cont)	Solenoid Valves; Overspeed Trip and Trip Reset	Coil failure	Age
	Solenoid Valves; Overspeed Trip and Trip Reset	Binding	Heat
	Solenoid Valves; Overspeed Trip and Trip Reset	Binding	Contamination
	Solenoid Valves; Overspeed Trip and Trip Reset	Binding	Age
	MHC Motor Gear Unit (Motor speed changer)	Clutch and gear train slip or binding	Loose setscrew
	MHC Motor Gear Unit (Motor speed changer)	Insulation breakdown	Age
	MHC Motor Gear Unit (Motor speed changer)	Insulation breakdown	Contamination
	MHC Motor Gear Unit (Motor speed changer)	Insulation breakdown	Heat
	Other MHC System components: Pistons, Pilot Valves, Vacuum Trip Mechanism, Servo Valves, Fittings, and Speed Governor	Wear	Age
	Turning Gear Motor	Insulation breakdown	Heat
	Turning Gear Motor	Insulation breakdown	Age

Component Type	Failure Location	Degradation Mechanism	Stressors
	Turning Gear Motor	Insulation breakdown	Excessive grease
	Motor Driven Oil Pumps	Motor winding failure	Insulation breakdown
Main Feedwater Turbine (cont)	High and Low Pressure Shaft Driven Oil Pumps	Impeller wear and damage	Excessive clearances
	Oil	Degradation of additive package, or demulsibility (cannot dewater)	Age
	Oil	Degradation of additive package, or demulsibility (cannot dewater)	Temperature
	Oil Supply Spring Loaded Pressure Control and Pressure Regulating Valves	Weak spring	Age
	Oil Piping Rubber Boots	Material property change	Age
	Oil Piping Rubber Boots	Material property change	Heat
	Oil Piping Rubber Boots	Material property change	Chemical attack from oil and additives
	Turbine Bearings	Wear	Age
	Turbine Bearing Labyrinth Seals	Excessive clearances	Wear
Main Condenser	Water box Manways, Expansion Seals, Welds, and Liner	Corrosion	Water quality
	Water box Manways, Expansion Seals, Welds, and Liner	Corrosion	Improper or failed cathodic protection
	Water box Manways, Expansion Seals, Welds, and Liner	Elastomer aging / wear	Water quality

Component Type	Failure Location	Degradation Mechanism	Stressors
	Water box Manways, Expansion Seals, Welds, and Liner	Elastomer aging / wear	Improper or failed cathodic protection
Main Condenser (cont.)	Water box Manways, Expansion Seals, Welds, and Liner	Mechanical damage to liner/coating	Water quality
	Water box Manways, Expansion Seals, Welds, and Liner	Mechanical damage to liner/coating	Improper or failed cathodic protection
	Water box Manways, Expansion Seals, Welds, and Liner	Failed welds	Water quality
	Water box Manways, Expansion Seals, Welds, and Liner	Failed welds	Improper or failed cathodic protection
	Hotwell: Penetration Baffles and Spray Pipes	Cracking	Vibration
	Hotwell: Tube Support Plates, Support Hardware, Baffle Plates, Diffuser Shields, and Feed Heater Supports	Cracking of welds	Vibration
	Hotwell: Tube Support Plates, Support Hardware, Baffle Plates, Diffuser Shields, and Feed Heater Supports	Steam erosion	Design defect
HVAC Air Handler	Damper Linkage	Wear	Vibration
	Damper Linkage	Wear	Corrosion
	Damper Linkage	Wear	Age
	Damper Linkage	Bound	Vibration

Component Type	Failure Location	Degradation Mechanism	Stressors
	Damper Linkage	Bound	Corrosion
	Damper Linkage	Bound	Age
HVAC Air Handler (cont)	Damper Linkage	Failed	Vibration
	Damper Linkage	Failed	Corrosion
	Damper Linkage	Failed	Age
	Damper Seal	Failed bladder	Age
	Damper Seal	Failed bladder	Mechanical interference with the blade
	Damper Blade to Control Shaft Connection	Sheared	Vibration
	Drive Components (Fan Vane Axial)	Worn sheaves	Age
	Drive Components (Fan Vane Axial)	Worn sheaves	Belt overtension
	Drive Components (Fan Vane Axial)	Worn sheaves	Misalignment
	Drive Components (Fan Centrifugal)	Worn sheaves	Age
	Drive Components (Fan Centrifugal)	Worn sheaves	Belt overtension
	Drive Components (Fan Centrifugal)	Worn sheaves	Misalignment
Small Standby Diesel	Head gasket	Leak-by	Loss of preload in head bolts
	Valve seats	Leak-by	Wear or damage
	Valve seats	Leak-by	Misadjustment

Component Type	Failure Location	Degradation Mechanism	Stressors
	Valve stem	Stuck	Carbon deposits
Small Standby Diesel (cont)	Fuel tank	Contamination	Dirt, other solids, fuel degradation products, bacterial slime, rust
	Fuel tank	Wall corrosion and pitting	Rust and MIC
	Fuel lines	Leak	Moisture, vibration
	Rocker arms (with rollers)	Scuffing or surface wear of rollers	Oil quality
	Rocker arms (with rollers)	Scuffing or surface wear of rollers	Misadjustment
	Push rods	Worn or bent	Misadjustment
	Cam follower roller (if present)	Scuffing or surface wear of rollers	Oil quality
	Cam follower roller (if present)	Scuffing or surface wear of rollers	Misadjustment
	Injectors	Dirty nozzles	Fuel (highly dependent upon the sulfur content)
	Injector o-rings, if present	Degradation	Heat
	Oil pump	Wear	Oil quality and cleanliness
	Water pump	Loss of pressure	Worn impeller
	Vibration Damper (Harmonic balancer)	Loose bolts	Vibration from normal use
	Inlet Air Filters, Element Type	Failed filter housing	Corrosion

Component Type	Failure Location	Degradation Mechanism	Stressors
	Turbocharger	Bearing failure	Insufficient lubrication
	Voltage regulator, if present	Failed	Age, generator voltage problem
Small Standby Diesel (cont)	Injector o-rings, if present	Degradation	Presence of solvents in the fuel
Reciprocating Compressor	Lubrication	Low oil flow	Aging of pump
	Shaft	Journal wear	Run time
Centrifugal Compressor	Bull/Pinion gears	Wear	Aging
	Diffusers	Erosion	Dirt and moist air
	Impellers	Wear	Corrosion from atmospheric conditions
	Inlet Air Filters, Element Type	Failed filter housing	Corrosion
	Inlet nozzle	Erosion	Dirt and moist air
	Motor current transformer	Failure	Age
	Prelube pump - motor driven	Windings shorted or open	Age/contamination
Stationary Lead-Acid Battery	Jar and Lid	Cracked	Age
	Jar and Lid	Cracked	Plate and post growth
	Plates	Corrosion or growth of grid	Age
	Plates	Corrosion or growth of grid	Cycling
	Plates	Plate shedding	Cycling

Component Type	Failure Location	Degradation Mechanism	Stressors
	Rack	Corrosion	Rust
Heated Air Dryer	Drain Trap Strainer	Deteriorated screen	Age
	Desiccant Retention Screens	Collapse	Corrosion
Heated Air Dryer (cont)	Towers	Wall thinning	External corrosion
	Towers	Wall thinning	Internal corrosion
	Electro-Mechanical cam type timer	Component failure: micro-switch, gear, motor, cam, shaft	Age
	Pulleys and Belts	Wear of sheaves	Aging (normal wear)
	Blower motor	Failed windings - open or short	Insulation degradation
	Manual Bypass Isolation Valves	Leak	Wear of elastomers and other moving parts
	Manual Isolation Valves	Stuck	Infrequent operation

D
MONTE CARLO ANALYSIS

Monte Carlo simulation involves setting up a probabilistic model of a problem that is very similar to a deterministic model of the same problem. However, each of the variables in the analysis designated as a "random variable" is modeled by a probability distribution that best fits the range of possible values that variable could take, and the appropriate probability weighting within that range. Each probability distribution is then randomly sampled to produce thousands of scenarios (simulations or trials), and the result of each scenario is recorded. Statistics are computed based on the cumulative results of all the trials. Results are in the form of probability distributions. The mean value of the distribution can be viewed as a point-value estimate, but this result is enhanced by explicit treatment of uncertainties.

Some advantages of Monte Carlo analysis are:

- Distributions of the model's variables do not need to be approximated by some standard distribution form (such as Normal or Log-Normal)
- The level of mathematics required is quite basic (a computer does the statistics)
- Complex mathematical problems can be analyzed (which is often impossible with other statistical techniques)
- It is widely recognized as a valid technique
- The computer does all the work - increased precision merely requires more simulations
- Sensitivity studies are easy to perform.

Figure D-1 illustrates how values of the various parameters are sampled from a distribution for each Monte Carlo Simulation. The cumulative probability distribution is given by function F(x). A random number between zero and one is chosen for each simulation, for each random variable in the analysis. The random number determines a position on the vertical axis, from which the program computes the inverse of the probability distribution G(F(x)) = x, which is used as the parameter x for that specific simulation.

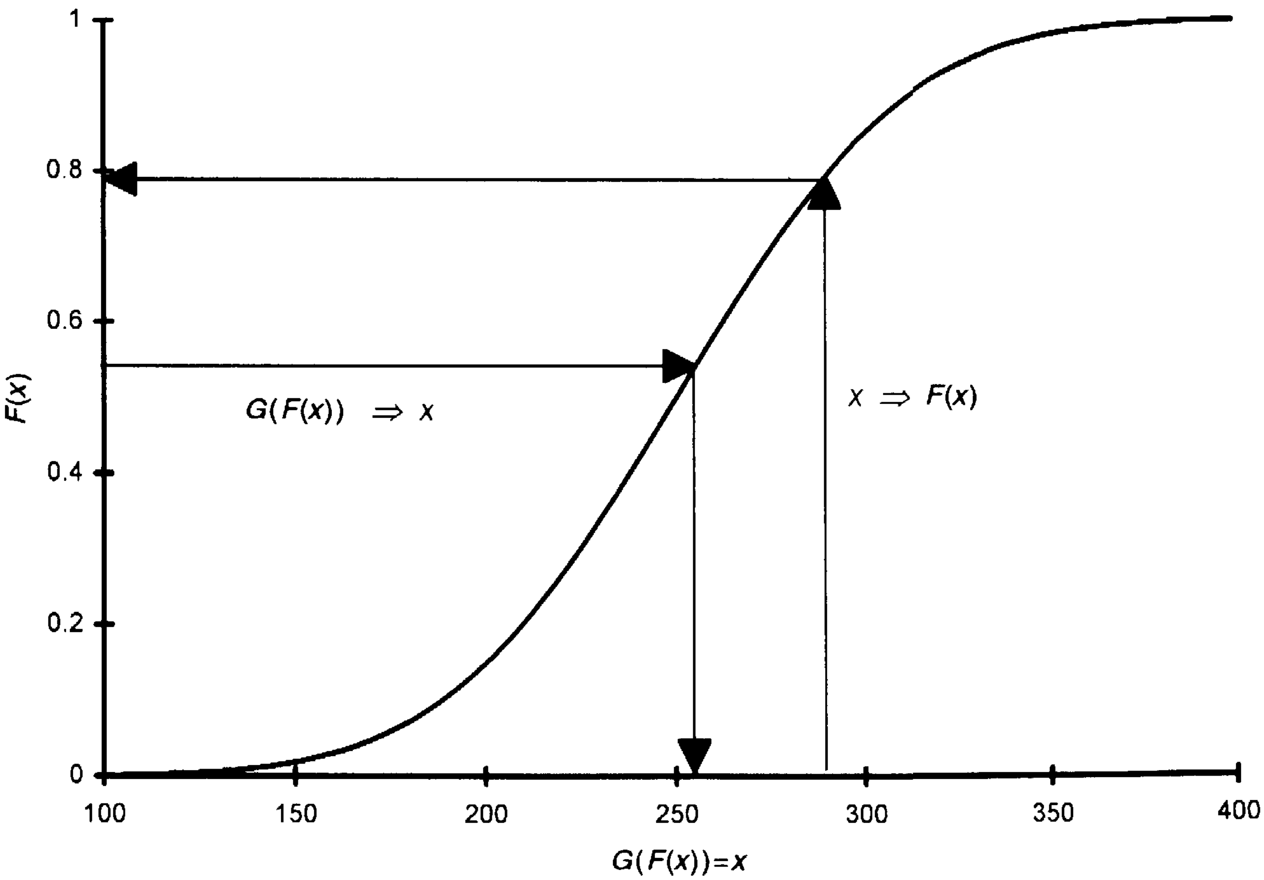


Figure D-1
Illustration of Monte Carlo Sampling from a Distribution

The following figures and tables illustrate the application of Monte Carlo analysis to a fairly simple overload problem of steel rod in tension. As illustrated in Figure D-2, the problem is a one inch diameter steel rod or strut under a uniform tensile load of 15,000 lbs,. The governing equation for this problem is:

$$\sigma = \frac{\text{Load}}{\text{Area}} = \frac{15{,}000\#}{0.785\ \text{in}^2} = 19{,}108\ \text{psi}$$

Assuming ductile behavior, overload failure will occur if the applied stress σ exceeds some limit stress, such as the flow stress of the material (typically taken to be the average of the yield and ultimate tensile strength).. Parameters in this problem to which uncertainties may be assigned include the diameter of the rod, the applied load, and the material flow stress. Figures D-3 through D-6 illustrate the distributions assigned to these variables.

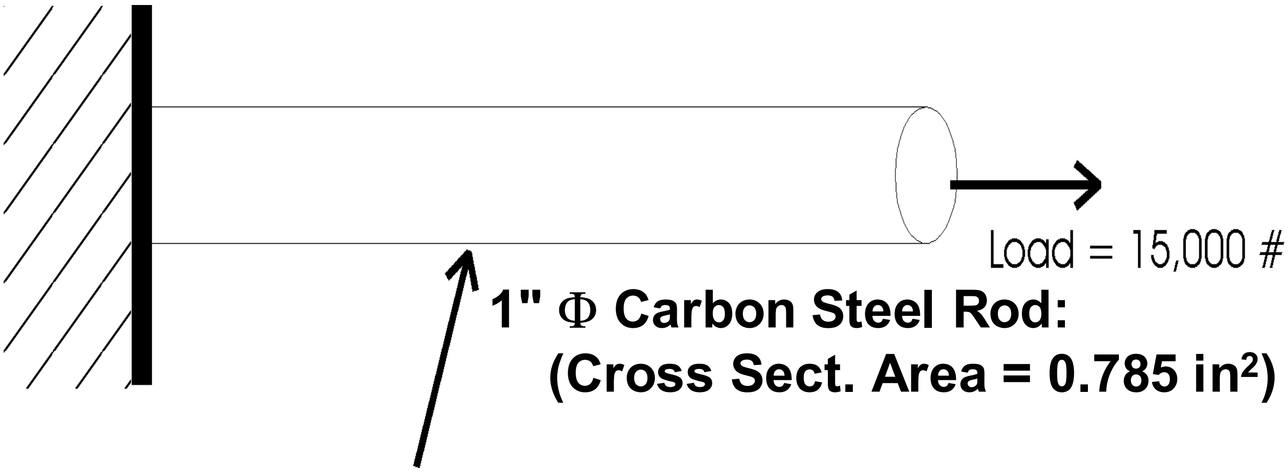


Figure D-2
Illustration of Axial Stress in a Rod Problem

Bar Diameter: Norm(1,.0625)

	pdf	spdf	cdf
0.8125	0.07091	0.004433	0.00135
0.875	0.863855	0.054006	0.02275
0.9375	3.871532	0.242036	0.158655
1	6.383076	0.39905	0.5
1.0625	3.871532	0.242036	0.841345
1.125	0.863855	0.054006	0.97725
1.1875	0.07091	0.004433	0.99865
	15.99567	1	

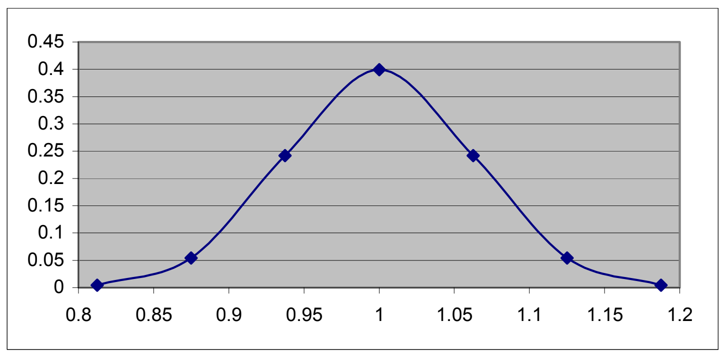


Figure D-3
Distribution Assigned to Rod Diameter

It is assumed for purposes of this example that the rod has a diametral tolerance similar to the wall thickness tolerance of a pipe (±12.5%), and that this tolerance corresponds to two standard deviations in a normal distribution. Thus the rod diameter is normally distributed, with a mean of 1" and a standard deviation of 0.0625" as illustrated in Figure D-3.

Load: Norm(15000,3750)			
	pdf	spdf	cdf
3750	1.18E-06	0.004433	0.00135
7500	1.44E-05	0.054006	0.02275
11250	6.45E-05	0.242036	0.158655
15000	0.000106	0.39905	0.5
18750	6.45E-05	0.242036	0.841345
22500	1.44E-05	0.054006	0.97725
26250	1.18E-06	0.004433	0.99865
	0.000267	1	

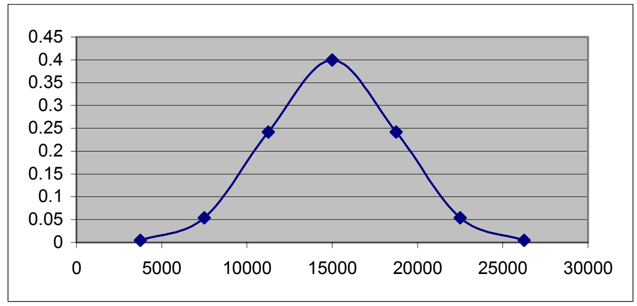


Figure D-4
Distribution Assigned to Applied Load

Also for purposes of this example, it is assumed that applied load is only known to an accuracy of ±50%, and that this uncertainty also corresponds to two standard deviations. Thus the applied load is assumed to be normally distributed with a mean of 15,000 lbs, and a standard deviation of 3,750 lbs, as illustrated in Figure D-4.

Flow Stress: Norm(53500,3250)			
	pdf	spdf	cdf
43750	1.36E-06	0.004433	0.00135
47000	1.66E-05	0.054006	0.02275
50250	7.45E-05	0.242036	0.158655
53500	0.000123	0.39905	0.5
56750	7.45E-05	0.242036	0.841345
60000	1.66E-05	0.054006	0.97725
63250	1.36E-06	0.004433	0.99865
	0.000308	1	

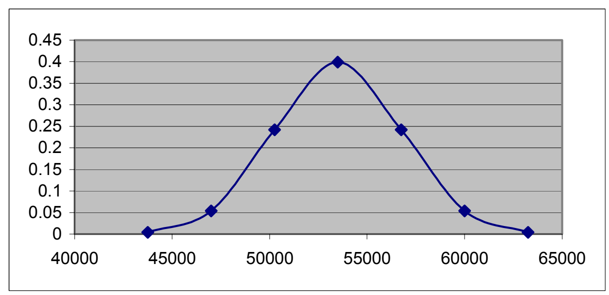


Figure D-5
Distribution Assigned to Flow Stress

Finally, referring to standard tables of material properties, such as Ref ___, the yield and ultimate tensile strength for mild carbon steel have ranges of 36,000 to 40,000 psi, and 58,000 to 80,000 psi, respectively. Averaging these two properties results in a range of flow stress of 47 to 60 ksi, which once again is assumed to correspond to ±two standard deviations in a normal distribution. Thus the flow stress is assumed to be normally distributed with a mean of 53,500 psi and a standard deviation of 3,250 psi, as illustrated in Figure D-5.

The Monte Carlo analysis of this problem was programmed into an MS Excel spreadsheet, the first page of which is shown in Table D-1. Each row in this table represents one Monte Carlo simulation. The first column under the "Load" heading is the random number that was chosen for load (0.701976), and the second represents the inverse of the normal distribution in Figure D-4 for this value of the random number (16,988 lbs). Note that the inverse normal distribution is a built-in function in the Excel software.

Table D-1
Monte Carlo Analysis of Stress in a Rod Problem

Load		Area		Stress	Flow Stress		Failures
Nom= 15,000		Nom= 0.785398		Nom= 19,099	Nom= 53,500		
0.701976	16,988	0.321767	0.7406	22,937	0.286422	51,667	0
0.316426	13,209	0.829932	0.8818	14,978	0.97662	59,962	
0.591677	15,869	0.074636	0.6502	24,407	0.210729	50,887	
0.781707	17,917	0.359914	0.7506	23,871	0.930799	58,316	
0.592365	15,876	0.823765	0.8793	18,055	0.409248	52,754	
0.436498	14,401	0.055637	0.6368	22,613	0.623763	54,525	
0.191471	11,728	0.644291	0.8221	14,265	0.791486	56,138	
0.393932	13,991	0.01702	0.5911	23,670	0.367279	52,398	
0.262792	12,620	0.089202	0.6588	19,154	0.268309	51,492	
0.276741	12,778	0.084217	0.6560	19,478	0.30314	51,825	
0.352624	13,582	0.329989	0.7428	18,284	0.031426	47,454	
0.842933	18,775	0.65495	0.8250	22,756	0.4754	53,299	
0.110889	10,418	0.254435	0.7219	14,432	0.01384	46,344	
0.129253	10,763	0.604773	0.8117	13,260	0.683792	55,055	
0.734239	17,346	0.171009	0.6949	24,963	0.690711	55,118	
0.685784	16,815	0.297053	0.7340	22,910	0.564404	54,027	
0.227114	12,194	0.695073	0.8363	14,580	0.525318	53,706	
0.361198	13,668	0.53288	0.7935	17,224	0.625683	54,541	
0.048898	8,791	0.438737	0.7703	11,412	0.048814	48,116	
0.609795	16,045	0.011338	0.5776	27,779	0.560813	53,997	
0.955447	21,376	0.658795	0.8261	25,876	0.240639	51,211	
0.529673	15,279	0.131574	0.6794	22,490	0.397037	52,652	
0.512231	15,115	0.836605	0.8846	17,086	0.51356	53,610	
0.882149	19,447	0.791888	0.8672	22,424	0.341191	52,170	
0.043688	8,590	0.272982	0.7272	11,811	0.166391	50,352	
0.336029	13,413	0.350179	0.7481	17,929	0.321187	51,991	
0.592085	15,873	0.079489	0.6532	24,301	0.871595	57,185	
0.148161	11,084	0.304726	0.7360	15,058	0.926683	58,217	
0.168342	11,397	0.495764	0.7844	14,531	0.106973	49,461	
0.789631	18,019	0.181063	0.6985	25,798	0.426665	52,899	
0.490413	14,910	0.559494	0.8002	18,634	0.998831	63,391	
0.726339	17,257	0.581839	0.8058	21,415	0.450397	53,095	
0.560607	15,572	0.937298	0.9431	16,512	0.411778	52,775	
0.283524	12,853	0.702701	0.8385	15,329	0.435048	52,969	
0.814127	18,350	0.756541	0.8551	21,458	0.20359	50,806	
0.669487	16,644	0.246549	0.7196	23,132	0.56791	54,056	

Similar random numbers and inverse normal distribution functions are given under Area and Flow Stress. In the case of Area, the random number and distribution were used to determine diameter of the rod, and the area was programmed into the cell as pi times the diameter squared divided by four. Finally, the applied stress is determined from the above fundamental equation in the column labeled "Stress", and this column is compared to the flow stress with the result yielding a 1 in the first column under failures if the stress exceeds the flow stress. (Note that no failures were observed in this first page of the spreadsheet. Finally, all of the "failures" are summed in the final column, and the probability of failure is the sum of the failures divided by the total number of simulations (zero in this case). Finally, the above procedure was performed for several applied load levels, with the results summarized in the following Table.

Applied Load (#)	No. of Failures	No. of Iterations	Prob. of Failure
15000	0	10000	0.00E+00
20000	6	10000	6.00E-04
25000	57	10000	5.70E-03

The above example illustrates, in a very simple way how Monte Carlo Analysis, together with a fundamental equation for the problem and assigned uncertainty distributions for key variables can be used to estimate failure probabilities of components.

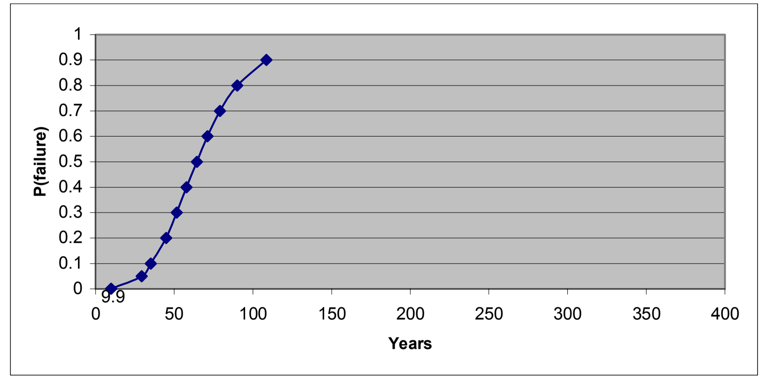
E

MONTE CARLO ANALYSIS OF WOLF CREEK BURIED PIPING (EXTERNAL CORROSION)

The following pages contain the first page of the spreadsheet that has been developed for Monte Carlo analysis of external corrosion of the Wolf Creek buried service water piping. The first spreadsheet was run for a case that is representative of the initial operation of the plant, in which the Cathodic Protection system was believed to be highly ineffective. In this case, the CP effectiveness was set as a maximum of 0.8, and a minimum of 0. The resulting failure probabilities versus time are illustrated in the figure. The initial point on the curve (9.9 years) corresponds to the point at which three failures would be expected, which is roughly consistent with the observed failure experience in the Wolf Creek buried service water piping. In the second spreadsheet, all of the other input data was kept the same, but the CP effectiveness was increased to a maximum of 0.8 and a minimum of 0.3. It is seen that this improvement in CP effectiveness results more than a doubling of predicted time to failure (24 years to three failures). Additional work must be performed to better estimate these CP effectiveness parameters (max and min) as a function of CP system specifics such as anode spacing, rectifier current and voltage, soil conditions, etc., however, this simple example illustrates the power of the analytical tool, and the significant effect that CP effectiveness has on piping corrosion life.

Monte Carlo Analysis of Wolf Creek Buried Piping (External Corrosion)

	Mean/ Constant	STD	n	Mean/ Constant	Mean +3 STD
Gen. Corr. Rate,ipy	-6.46	0.61767	0.9	0.001565	0.009982
Pitting Rate, ipy	-4.7795	0.545	1.06	0.008400	0.043088
Thickness (in)	0.375	0.023			
Total Length (ft)	3000				
# segments	3000				



F(coating damage)	Constr	per Yr
per mile	500	100
per segment yr	0.094697	0.018939

CP Effectiveness	Max	Min
	0.3	0

Segment	Coating Damage RN1	Yrs to CD	Corrosion Rate RN2	Pitting CR	CP Effectiveness RN3	CP Factor	CR(CP)	RN4	Thickns.	Corr Time (yrs)	Total Failure Time (yrs)
1	0.503846	21.60306	0.531165	0.008766	0.7804408	0.234132	0.006714	0.482163	0.373971	44.4	66.0
2	0.920858	43.62131	0.829653	0.014119	0.2320357	0.069611	0.013136	0.959436	0.415116	26.0	69.6
3	0.033687	-3.221332	0.65928	0.010506	0.9964224	0.298927	0.007366	0.050346	0.337245	36.9	36.9
4	0.076065	-0.983745	0.070715	0.003769	0.7005022	0.210151	0.002977	0.250062	0.359491	92.1	92.1
5	0.843905	39.55818	0.579893	0.009376	0.3413026	0.102391	0.008416	0.201748	0.355786	34.2	73.8
6	0.144582	2.633924	0.787374	0.012972	0.0161331	0.00484	0.012909	0.150145	0.351176	22.6	25.2
7	0.654134	29.53828	0.804695	0.013412	0.1165217	0.034957	0.012943	0.461419	0.372772	23.8	53.4
8	0.570644	25.13	0.763648	0.012424	0.0028808	0.000864	0.012413	0.504893	0.375282	24.9	50.1
9	0.503718	21.59633	0.169912	0.004993	0.9164818	0.274945	0.00362	0.228995	0.35793	76.2	97.8
10	0.979548	46.72015	0.238367	0.0057	0.2090596	0.062718	0.005342	0.354651	0.366426	54.0	100.7
11	0.386036	15.38268	0.755812	0.012254	0.0421022	0.012631	0.0121	0.466709	0.373078	25.4	40.8
12	0.697188	31.81151	0.844033	0.014576	0.4629477	0.138884	0.012551	0.292092	0.362412	23.9	55.7
13	0.820874	38.34216	0.444906	0.007789	0.6291595	0.188748	0.006319	0.016621	0.32603	41.3	79.6
14	0.187193	4.883792	0.618082	0.009895	0.3976189	0.119286	0.008714	0.633989	0.382876	35.5	40.4
15	0.226777	6.973817	0.835154	0.014289	0.2574258	0.077228	0.013185	0.386582	0.368371	23.1	30.1
16	0.389969	15.59037	0.408876	0.007409	0.784991	0.235497	0.005664	0.09889	0.345378	48.3	63.9
17	0.607844	27.09419	0.982322	0.026445	0.5940554	0.178217	0.021732	0.851417	0.398978	15.6	42.7
18	0.429695	17.68788	0.422302	0.007549	0.6424764	0.192743	0.006094	0.242665	0.358952	46.8	64.5
19	0.9723	46.33745	0.291616	0.006229	0.1698656	0.05096	0.005912	0.171579	0.353197	47.4	93.7
20	0.461326	19.358	0.486584	0.008248	0.9564268	0.286928	0.005881	0.8923	0.403494	54.0	73.4
21	0.278855	9.723566	0.484795	0.008227	0.3823498	0.114705	0.007284	0.850349	0.398872	43.7	53.4
22	0.269171	9.212235	0.834312	0.014263	0.9938584	0.298158	0.01001	0.740823	0.389855	31.7	40.9
23	0.894226	42.21514	0.89369	0.016569	0.1385709	0.041571	0.01588	0.405833	0.36952	19.5	61.7
24	0.116078	1.128893	0.801839	0.013337	0.0752044	0.022561	0.013036	0.208593	0.35634	22.7	23.8
25	0.793296	36.88604	0.941449	0.019733	0.1833936	0.055018	0.018647	0.173173	0.353341	16.0	52.9

Min	Mean	Max	Median
9.3	69.0	302.5	64.7

Percentiles		Segments
0.001	9.92144	3
0.05	29.4264	150
0.1	35.13113	300
0.2	44.84594	600
0.3	51.5198	900
0.4	57.73143	1200
0.5	64.46552	1500
0.6	71.1514	1800
0.7	79.12568	2100
0.8	90.03327	2400
0.9	108.6037	2700
0.95	122.4832	2850

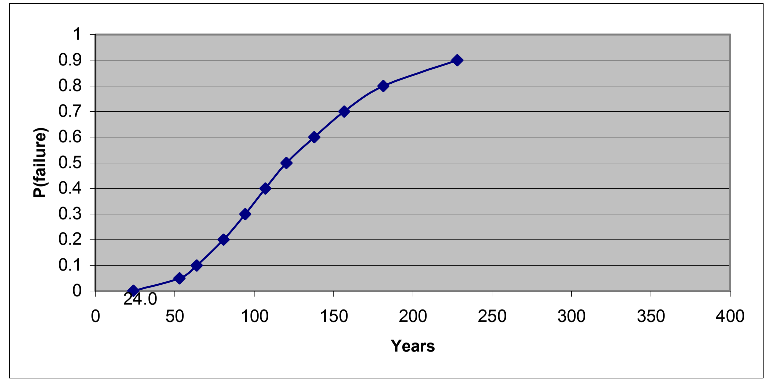
26	0.319404	11.86451	0.893129	0.016542	0.6334875	0.190046	0.013398	0.074502	0.34181	21.2	33.1
27	0.691848	31.52958	0.247986	0.005796	0.6794653	0.20384	0.004615	0.851343	0.398971	67.2	98.7
28	0.239829	7.662987	0.066651	0.003707	0.7937903	0.238137	0.002824	0.574876	0.379342	101.8	109.5
29	0.026343	-3.609109	0.551707	0.009017	0.5253993	0.15762	0.007596	0.922344	0.407683	42.8	42.8
30	0.157589	3.320699	0.132144	0.004572	0.9947491	0.298425	0.003207	0.892773	0.403552	95.7	99.0
31	0.64209	28.90235	0.426132	0.007589	0.2532386	0.075972	0.007013	0.177397	0.353717	40.4	69.3
32	0.267976	9.149142	0.381836	0.007131	0.2234491	0.067035	0.006653	0.005312	0.316239	38.2	47.4
33	0.704689	32.20757	0.650225	0.010367	0.071511	0.021453	0.010144	0.960945	0.41552	33.2	65.4
34	0.520626	22.48908	0.833656	0.014242	0.5463394	0.163902	0.011908	0.283843	0.361856	25.0	47.5
35	0.810647	37.80217	0.145867	0.004729	0.7739915	0.232197	0.003631	0.577837	0.379516	80.3	118.1
36	0.581935	25.72615	0.820358	0.013844	0.947228	0.284168	0.00991	0.390959	0.368633	30.3	56.0
37	0.937421	44.49581	0.149652	0.004771	0.9482426	0.284473	0.003414	0.619279	0.381983	85.7	130.2
38	0.902142	42.6331	0.102873	0.004215	0.5298136	0.158944	0.003545	0.14865	0.351028	76.3	119.0
39	0.511088	21.98542	0.709226	0.011343	0.5177794	0.155334	0.009581	0.602332	0.380966	32.3	54.3
40	0.323234	12.06674	0.095173	0.004115	0.903281	0.270984	0.003	0.690447	0.386434	97.9	109.9
41	0.333964	12.63331	0.612506	0.009816	0.6288556	0.188657	0.007964	0.073149	0.341587	34.7	47.3
42	0.201983	5.66472	0.927898	0.018618	0.1002765	0.030083	0.018058	0.889697	0.403173	18.7	24.4
43	0.027148	-3.566605	0.428549	0.007615	0.9890427	0.296713	0.005356	0.828146	0.396778	58.1	58.1
44	0.599294	26.64275	0.83434	0.014263	0.2623498	0.078705	0.013141	0.881949	0.40225	25.2	51.9
45	0.74853	34.5224	0.044476	0.003324	0.0066608	0.001998	0.003318	0.527119	0.376565	86.8	121.4
46	0.626922	28.1015	0.423071	0.007557	0.1956057	0.058682	0.007114	0.215173	0.356862	40.2	68.3
47	0.255127	8.470708	0.12399	0.004476	0.9205799	0.276174	0.00324	0.814063	0.395538	93.0	101.5
48	0.226979	6.984474	0.478218	0.008154	0.7862987	0.23589	0.00623	0.368829	0.367296	46.8	53.8
49	0.450467	18.78468	0.75048	0.012142	0.6766141	0.202984	0.009677	0.251659	0.359607	30.3	49.1
50	0.23865	7.600736	0.036387	0.003159	0.5666106	0.169983	0.002622	0.996011	0.43602	124.5	132.1
51	0.894105	42.20876	0.139639	0.004658	0.6010767	0.180323	0.003818	0.219319	0.357187	72.4	114.6
52	0.385529	15.35594	0.658612	0.010496	0.4359324	0.13078	0.009123	0.492969	0.374595	33.3	48.6
53	0.503738	21.59736	0.886832	0.016242	0.7889824	0.236695	0.012398	0.4208	0.370404	24.7	46.2

Monte Carlo Analysis of Wolf Creek Buried Piping (External Corrosion)

	Mean/ Constant	STD	n	Mean/ Constant	Mean +3 STD
Gen. Corr. Rate,ipy	-6.46	0.61767	0.9	0.001565	0.009982
Pitting Rate, ipy	-4.7795	0.545	1.06	0.008400	0.043088
Thickness (in)	0.375	0.023			
Total Length (ft)	3000				
# segments	3000				

F(coating damage)	Constr	per Yr
per mile	500	100
per segment yr	0.094697	0.018939

CP Effectiveness	Max	Min
	0.8	0.5



Segment	Coating Damage RN1	Yrs to CD	Corrosion Rate RN2	Pitting CR	CP Effectiveness RN3	CP Factor	CR(CP)	RN4	Thickns.	Corr Time (yrs)	Total Failure Time (yrs)
1	0.922818	43.72479	0.597302	0.009607	0.3166059	0.594982	0.003891	0.206841	0.356199	70.9	114.6
2	0.597565	26.55145	0.566636	0.009205	0.1445868	0.543376	0.004203	0.900555	0.404549	74.3	100.9
3	0.198318	5.471188	0.71609	0.011468	0.9286101	0.778583	0.002539	0.891916	0.403446	119.3	124.7
4	0.091398	-0.174179	0.554492	0.009052	0.8792422	0.763773	0.002138	0.832333	0.397159	138.2	138.2
5	0.248504	8.121037	0.693056	0.011059	0.7134228	0.714027	0.003163	0.774003	0.392298	94.4	102.5
6	0.736725	33.89909	0.415701	0.00748	0.8090003	0.7427	0.001925	0.588556	0.380148	146.4	180.3
7	0.402937	16.27507	0.620809	0.009933	0.1791746	0.553752	0.004433	0.455291	0.372417	65.4	81.7
8	0.884958	41.72577	0.178133	0.005081	0.6556615	0.696698	0.001541	0.381628	0.368072	175.2	216.9
9	0.46292	19.4422	0.432446	0.007656	0.2602521	0.578076	0.00323	0.552614	0.378042	89.4	108.8
10	0.147291	2.776941	0.434985	0.007683	0.2018396	0.560552	0.003376	0.751779	0.390642	88.4	91.2
11	0.477753	20.22536	0.390408	0.007218	0.4081038	0.622431	0.002725	0.22301	0.357472	99.5	119.8
12	0.198864	5.500017	0.90426	0.017118	0.9459826	0.783795	0.003701	0.25422	0.359791	75.0	80.5
13	0.706457	32.30091	0.419979	0.007525	0.8236485	0.747095	0.001903	0.322697	0.364416	142.2	174.5
14	0.263317	8.903142	0.719714	0.011536	0.5253944	0.657618	0.00395	0.248397	0.359371	70.5	79.4
15	0.109344	0.773376	0.714197	0.011434	0.3392871	0.601786	0.004553	0.081204	0.342869	59.0	59.7
16	0.34972	13.46522	0.146854	0.00474	0.4657403	0.639722	0.001708	0.81152	0.395321	170.1	183.6
17	0.246631	8.022102	0.259409	0.00591	0.8718155	0.761545	0.001409	0.371657	0.367468	190.3	198.3
18	0.311062	11.42405	0.102191	0.004206	0.8329926	0.749898	0.001052	0.14753	0.350917	240.1	251.5
19	0.031572	-3.333011	0.98836	0.028926	0.8938935	0.768168	0.006706	0.277546	0.361427	43.0	43.0
20	0.139469	2.363977	0.083646	0.003958	0.7006285	0.710189	0.001147	0.938893	0.410548	256.6	259.0
21	0.083981	-0.565794	0.181024	0.005112	0.0443911	0.513317	0.002488	0.990527	0.428972	128.8	128.8
22	0.176391	4.313453	0.769775	0.01256	0.1748343	0.55245	0.005621	0.548779	0.377819	53.0	57.3
23	0.258834	8.666451	0.419874	0.007524	0.791384	0.737415	0.001976	0.223013	0.357473	134.8	143.5
24	0.393445	15.77392	0.906906	0.017266	0.9352772	0.780583	0.003788	0.238743	0.358662	73.2	89.0
25	0.569116	25.04935	0.638062	0.010184	0.6195211	0.685856	0.003199	0.504269	0.375246	89.6	114.6
26	0.528502	22.90493	0.355018	0.006859	0.8420268	0.752608	0.001697	0.63437	0.382899	166.0	188.9
27	0.756696	34.95355	0.835292	0.014293	0.6159234	0.684777	0.004506	0.722902	0.388604	67.0	102.0
28	0.195459	5.32023	0.195475	0.005263	0.9723387	0.791702	0.001096	0.813154	0.39546	258.5	263.8
29	0.549379	24.00723	0.806106	0.013449	0.9735353	0.792061	0.002797	0.665166	0.384812	104.1	128.1

Min	Mean	Max	Median
18.7	138.9	1012.5	122.1

Percentiles		Segments
0.001	23.95139	3
0.05	52.97608	150
0.1	63.7986	300
0.2	80.71425	600
0.3	94.41979	900
0.4	107.0596	1200
0.5	120.3227	1500
0.6	137.8841	1800
0.7	156.6967	2100
0.8	181.4943	2400
0.9	228.0948	2700
0.95	271.763	2850

Target:
Nuclear Power

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