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# A Methodology for Evaluation of Inservice Test Intervals for Pumps and Motor-Operated Valves

0/1

DF02

**Oak Ridge National Laboratory**

**U.S. Nuclear Regulatory Commission**
**Office of Nuclear Regulatory Research**
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# A Methodology for Evaluation of Inservice Test Intervals for Pumps and Motor-Operated Valves

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# Abstract

Recent nuclear industry reevaluation of component inservice testing (IST) requirements is resulting in requests for IST interval extensions and changes to traditional IST programs. To evaluate these requests, long-term component performance and the methods for mitigating degradation need to be understood. Determining the appropriate IST intervals, along with component testing, monitoring, trending, and maintenance effects, has become necessary. This study provides guidelines to support the evaluation of IST intervals for pumps and motor-operated valves (MOVs). It presents specific engineering information pertinent to the performance and monitoring/testing of pumps and MOVs, provides an analytical methodology for assessing the bounding effects of aging on component margin behavior, and identifies basic elements of an overall program to help ensure component operability. Guidance for assessing probabilistic methods and the risk importance and safety consequences of the performance of pumps and MOVs has not been specifically included within the scope of this report, but these elements may be included in licensee change requests.

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# Acronyms

| | |
|---|---|
| AEOD | Office for Analysis and Evaluation of Operational Data |
| AFW | auxiliary feedwater system |
| ALARA | as low as reasonably achievable |
| ASME | American Society of Mechanical Engineers |
| BWR | boiling-water reactor |
| CCW | component cooling water system |
| CDF | cumulative distribution function |
| CFR | Code of Federal Regulations |
| CVCS | chemical and volume control system |
| EPIX | Equipment Performance and Information Exchange |
| EPRI | Electric Power Research Institute |
| ESA | electrical signature analysis |
| ESW | emergency/essential service water system |
| FFT | fast Fourier transform |
| FTIR | Fourier Transform infrared spectroscopy |
| GL | generic letter |
| GV | governor valve |
| HPSI | high-pressure safety injection system |
| HSSC | high safety significant component |
| IE | Inspection and Enforcement |
| IN | Information Notice |
| IST | inservice testing |
| JOG | Joint Owners Group |
| LPCS | low-pressure core spray system |
| LSSC | low safety significant |
| MCC | motor control center |
| MCSA | motor current signature analysis |
| MOV | motor-operated valve |
| MTBF | mean time between failures |
| NPAR | Nuclear Plant Aging Research |
| NPRDS | Nuclear Plant Reliability Data System |
| NSSS | nuclear steam supply system |
| NRC | Nuclear Regulatory Commission |
| OM Code | Operations & Maintenance Code |
| ORNL | Oak Ridge National Laboratory |
| PDF | probability density function |
| PRA | probabilistic risk assessment |
| PWR | pressurized-water reactor |
| RCIC | reactor core isolation cooling system |
| RCM | Reliability Centered Maintenance |
| RFRC | rate of failure rate change |
| RHR | residual heat removal system |
| RMC | rate of margin change |
| SWIM | selective waveform inspection method |
| TAN | total acid number |
| TTV | trip and throttle valve |
| WGTM | worm gear tooth meshing |

# Executive Summary

Issues related to verification of the design and operability of safety-related motor-operated valves (MOVs), and requests for changes to traditional inservice testing (IST) programs for pumps and valves have resulted in the need for an improved understanding of degradation effects on their performance. Proposed changes to traditional IST programs toward risk-informed IST and condition monitoring are resulting in relief requests for extended pump and valve test interval allowances. For example, requests are being made to change from traditional, relatively short, IST intervals (usually quarterly) to intervals of up to 5 to 10 years. Because component operability may be impacted by undetected degradation or failure between test intervals, an enhanced understanding of methods for mitigating/detecting potential component degradation or failure has become important. The effects of changes to IST programs on component operability therefore need to be assessed to evaluate the appropriateness of proposed test intervals.

Because risk-informed and condition monitoring methodologies represent fundamental changes in the implementation of IST programs, the fundamental bases of IST programs should be reexamined. These bases include failure modes, degradation mechanisms, condition assessment, and effectiveness of testing methods. Traditional prescriptive requirements (code-specified tests and quarterly test intervals) are being replaced by more flexible, judgement-based approaches. Thus, from an overall operability assurance perspective, integrated testing, monitoring, maintenance, and trending programs will be important in ensuring safe and reliable operation of pumps and MOVs. The Nuclear Regulatory Commission (NRC) recognized the need for a programmatic approach to operability assurance by providing guidelines for periodic verification programs in Generic Letter 96-05, "Periodic Verification of Design-Basis Capability of Safety-Related Motor-Operated Valves." Because the methodologies for implementation of IST programs rely less on prescription and more on engineering judgement, so too, will the bases for future IST program evaluation.

While current code and regulatory requirements/practices are included, this report focuses on the technical bases necessary to ensure component operability resulting from changes in IST philosophy. The information and guidelines are intended to support the assessment of licensee changes in IST programs.

The objective of this study is to provide guidelines to support the evaluation of IST intervals for pumps and MOVs. The study emphasis is on the complete pump and MOV assemblies (including the valve actuator and the pump driver) rather than on the basic valve and pump components themselves. It is anticipated that these guidelines will be useful to assess (1) proposed changes to IST programs based on risk-informed methodologies, (2) relief requests to extend IST intervals, and (3) issues related to margin availability. Accordingly, this report presents specific engineering information pertinent to the performance and monitoring/testing of pumps and MOVs, identifies the basic elements of an overall program to help ensure component operability between test intervals, and provides an analytical methodology for assessing the bounding effects of component aging on unavailability and margin behavior.

The evaluation of a licensee change request to extend IST intervals for a given set of components should consist of three basic elements:

1. evaluation of the licensee's engineering analysis used to determine IST interval allowances,
2. evaluation of the licensee's overall program to assure component operability, and
3. evaluation of the licensee's trending and feedback mechanisms that ensure that test intervals are reevaluated and updated as necessary.

Guidance for assessing probabilistic methods and the risk importance and safety consequences of the performance of pumps and MOVs has not been specifically included within the scope of this report, but these elements may be included in licensee change requests.

This report assumes that the evaluation of such licensee activities will focus primarily on these three basic elements (i.e., that a balanced evaluation should focus on the engineering and programmatic aspects of the activities as well as specific test intervals). The principles on which this approach is based follow. Sections 4.1–4.3 provide detailed guidelines for performing evaluations of licensee change requests.

## Basic principles of the report

The integrated operability assurance program should be applied rationally across component groups; that is, the greatest attention should be paid to the components that represent the greatest contributions to overall risk. The program should focus on detection of the failure modes that are most likely to occur and that would result in the greatest undesirable consequences.

"True component margin," or "true engineering margin," is defined as the difference between the capability (the level of performance that a component can achieve) and the requirement (the minimum acceptable level of performance). If a functional failure is defined as the inability of a component to fulfill a function to a desired acceptance criterion, then in terms of the component's margin, a functional failure has occurred when the capability drops below the requirement (i.e., the margin is less than zero). This does not mean that a complete loss of function has *necessarily* occurred, but that the desired level of performance cannot be achieved. To understand true component margin, the parameters that define capability, such as valve stem thrust, need to be measurable. The functional requirement also needs to be known (measured or calculated) and either be assumed or known to remain unchanged. It is important not to confuse design-basis margin adequacy issues (e.g., that a valve is capable of developing a required level of output thrust or torque to meet some design-basis criteria) and component operability issues (e.g., component condition). The requirement to verify the design basis of a pump or valve is a requirement to assure the functional operation of the component up to the design basis at that time and is not directly intended to assess the effects of future time, service, or environment on the progressive deterioration of the component. Also, the parameters monitored to indicate the design-basis performance may not necessarily be the same as those best suited to monitor progressive deterioration of performance (condition). Typically, there is no intent in design-basis performance testing to derive information about future performance.

There are important differences between diagnostic testing (e.g., condition monitoring) and performance testing (e.g., ISTs, margin testing). The objective of a performance test is usually to verify that equipment operations are "within specification" and/or within acceptable limits, that is, to verify that a functional failure has not occurred. The primary purpose of a diagnostic test is to gather information that, if correctly interpreted, can help to assess the general condition of the monitored equipment. A successful performance test cannot by itself guarantee that significant component degradation is not already present (i.e., the presence of "margin" does not necessarily ensure availability). If the location of the degradation is such that it does not impact the performance parameter being measured, the degradation may go undetected by the performance test and may subsequently lead to an unexpected functional failure. True diagnostic activities such as spectral vibration analysis and motor current signature analysis can provide much more sensitive indications of equipment health. Diagnostic testing results are particularly useful when trended. But even these much more sensitive diagnostic methods do not measure true engineering margin. Rather, they measure a parameter that gives a secondary or tertiary indication; when compared to historical data of the same sort, it provides some useful clues to the trained observer about component health. Spectral vibration analysis, for example, is a well-established approach to bearing condition monitoring, but it is essentially qualitative in nature and requires trend data to provide the greatest value. A true engineering margin cannot, however, be extracted from vibration spectral analysis, even when used by the most sophisticated and experienced practitioners. It is not possible with the current state of the art to accurately predict when a bearing will fail (or the exact amplitude of some particular spectral peak or combination of spectral characteristics that comprise the absolute limit). Because true engineering margin is in most cases difficult to measure, the best indication available to evaluate potential *changes* in margin may be that obtained through diagnostic techniques. It may be assumed that if the diagnostic-based indications of component or subcomponent condition remain unchanged, at least that aspect of the equipment margin for which the diagnostic method is sensitive is also unchanged.

It is important to emphasize that no individual or combination of performance testing and diagnostic methods is currently capable of monitoring for all potential degradation mechanisms. That is why it is essential that the most common failure and degradation modes be well documented and understood. It is equally important to clearly understand which performance testing or diagnostic measurements are effective at detecting and trending these failure modes (or alternatively, which preventive maintenance activities would ensure that the equipment does not degrade to an unacceptable state).

The intent of IST as required by the American Society of Mechanical Engineers (ASME) Code for pumps and valves is to demonstrate operability as an indicator of the ability of the component to meet its design requirements at a given point in time. That is, ISTs are by design "go/no-go" performance tests that indicate component functionality; but they are not generally conducive to providing information on component health and yield very little information worth trending. ISTs are not designed, in general, to provide information about true component margin. An outstanding exception is the pump flow/head if measured at reasonable flow rates, but these measurements only address the hydraulic margin for the impeller and diffuser/volute and provide no information about margins or capabilities for other failure sites and modes (such as shaft, bearings, mechanical seals, or packing integrity). ISTs by themselves do nothing to renew or refurbish the component being tested (unless an unsuccessful test results in successful maintenance actions being performed). In some cases, the test activity may actually alter the component condition or induce failure (i.e., either positive or negative reliability results). For example, simply rotating standby equipment periodically is a well-recognized good practice (to provide lubricant distribution, minimize the likelihood of certain bearing problems, minimize the likelihood of corrosion binding of the rotating to stationary elements). Alternatively, certain testing techniques such as low-flow testing of standby pumps are unquestionably significant stressors, because the pumps' hydraulic behaviors can adversely affect their mechanical subcomponents.

True component margin should not be confused with margin as determined by the comparison of torque switch trip measurement with other predetermined constants (i.e., the operator torque at design-basis motor torque, the design-basis stem factor, and the required stem torque) as outlined in ASME Code Case OMN-1. Trending data obtained in this fashion provides very little information on actual changes that may be occurring with true component margin, other than information possibly related to the condition of the torque switch itself. The difference between true component margin and OMN-1 margin is shown graphically in Fig. ES.1. The OMN-1 margin is shown by the dashed line.

Ideally, it would be desirable to have "generic" values for IST intervals that would be appropriate for large groups of components such as pumps or MOVs. Realistically, however, such estimates are inappropriate because of the range of variables influencing component behavior. As an example of the variability in failure experience for a particular group of pumps, the 23 significant failures of Byron Jackson pumps in the Emergency/Essential Service Water (ESW) system during a 4-year analysis period (1990–1993) may be considered. Of the 23 failures characterized as significant (in terms of extent of degradation to the pump itself), 17 occurred at *one plant* (plant "A"). All 17 of the failures were either explicitly or implicitly related to the high sand content of the river water being pumped. There were 187 pump-years of experience for Byron Jackson pressurized-water reactor (PWR) ESW applications during the analysis period, but plant A accounted for only 16 of the 187 pump-years. The 0.035 failures/pump-year value for all other PWRs (i.e., excluding plant A) is almost exactly equal to the overall pump population failure rate for all systems and all manufacturers. With plant A included, however, the Byron Jackson failure rate was *3.4 times the overall average*. The ratio of relative failure rate at plant A to all other PWRs is 30, which is obviously due to *system-specific* factors. Nothing about the pumps installed at plant A suggests that they should be problematic. The nature of the failures indicates that the local environment was the dominant, if not only, influence affecting pump performance. It is apparent from this example that what might be an appropriate interval for the

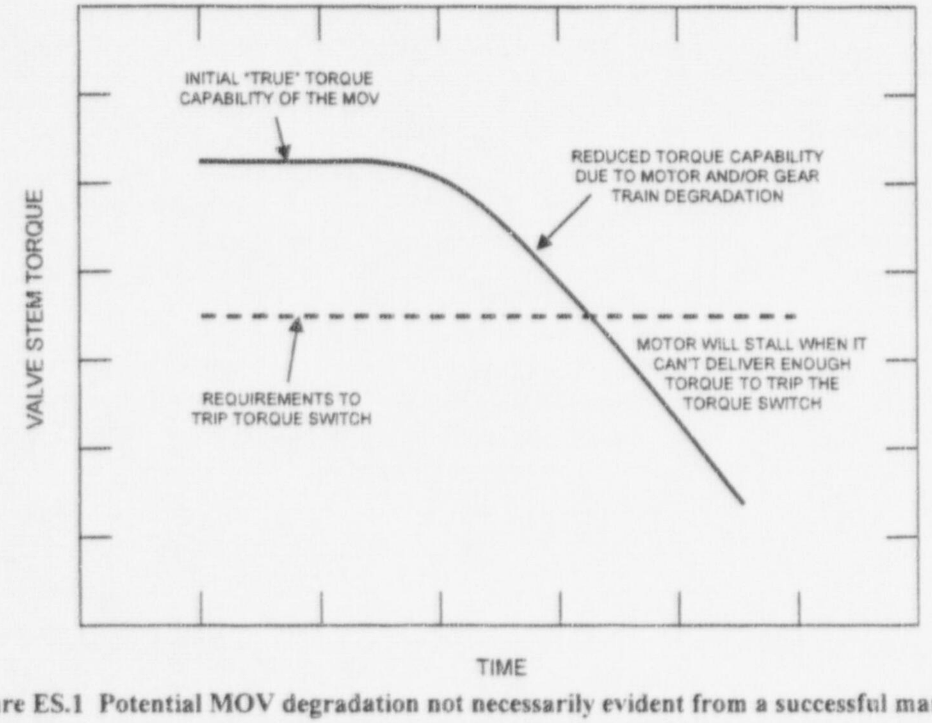


**Figure ES.1 Potential MOV degradation not necessarily evident from a successful margin test**

ESW pumps at plant A would probably be much too short for most other PWRs. Therefore, appropriate IST intervals should be determined on a component-specific basis (or by groupings of similar components by the parameters with which their performance is most likely to correlate).

Mathematical methodologies for estimating the probability of margin reduction due to age-related degradation should be based on an understanding of the physics involved in component deterioration and should use actual performance data as input. To be realistic, models for component capability and requirement should be developed using trendable test data. Available failure data from industry databases, however, does not currently support this effort because of the nature of the data (e.g., failures due to multiple failure modes and causes are combined; reporting practices are not necessarily consistent among the plants; design, service conditions, and maintenance effects may vary considerably from one component to another). While parametric studies for the probability of margin reduction with time are useful for investigating and bounding effects of test interval changes, their underlying assumptions and limitations should be kept in mind.

Oak Ridge National Laboratory (ORNL) studies have consistently shown that many factors both directly and indirectly contribute to component failure. These include operating practices, maintenance effects, transient (nonperiodic) events, and design flaws, along with changes occurring with time or use (aging). For most failures, a *combination* of factors is involved. According to J. Moubray in *Reliability Centered Maintenance*,

> One of the most challenging developments in modern maintenance management has been the discovery that very few failure modes actually conform to any of the (age-related) failure patterns (such as pattern 1 in Fig. ES.2). This is due primarily to a combination of variations in applied stress and increasing complexity.*

Moubray explains that *component deterioration is not always proportional to applied stress, and stress is not always applied consistently*. For example, many failures are caused by increases in applied stress, which may be due to incorrect operation, maintenance error, or external event. In these cases, there is little or no relationship between how long the component has been in service and the likelihood of its failure. If an event permanently reduces a component's resistance to failure but does not actually cause it to fail (e.g., a manufacturing defect results in a material inclusion in a pump shaft), the reduced resistance to failure may make it vulnerable to the next event or stress peak, which may occur before the component (or part) is replaced or refurbished for another reason. In some cases, a stress peak may only temporarily reduce a component's failure resistance (such as the additional stresses imposed on a pump while passing an entrained vapor pocket through the pump). A stress peak may also accelerate the decline of a component's failure resistance and eventually shorten the life of the component. This could happen, for instance, if a ball bearing were damaged by dropping it on a hard surface prior to installation. When this happens, the cause and effect relationship can be very difficult to establish, because the failure can occur months or even years after the initial stress peak. In these examples, the likelihood of a component failure is not dependent on its time in service, because the applied stress peaks (and any resultant changes in component condition) cannot be predicted (based simply on component age or time in service).

Failure processes such as pattern 1 in Fig. ES.2 apply to fairly simple mechanisms. In the case of complex components such as pumps and MOVs (which have been made more complex to improve their performance and to make them safer), the probability of failure becomes less predictable. The more complex the component, the more complex is its failure behavior, which is composed of the different behaviors of its subcomponents and auxiliary equipment. The resulting effects of all subcomponent failures produce a "near-constant" appearing failure rate curve such as those shown in Fig. ES.2, patterns 2 and 3.

The most important characteristic of failure patterns 2 and 3 shown in Fig. ES.2 is that after an initial period, there is little or no relationship between likelihood of failure and operating age (i.e., they are not age-related). Results of ORNL analyses of pump and MOV failure data show that these components generally conform to the behavior patterns 2 and 3 shown in Fig. ES.2. In other words, the ORNL analyses show that the probability of component failure does not necessarily increase with operating age.

**Report format**

Chapters 2 and 3 identify the significant failure modes, mechanisms, performance-affecting parameters, and condition indicator parameters for pumps and MOVs based on analyses of component performance data. Time dependence and failure

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* John Moubray, *Reliability-Centered Maintenance*, 2nd edition, Industrial Press Inc., New York, NY, 1997.

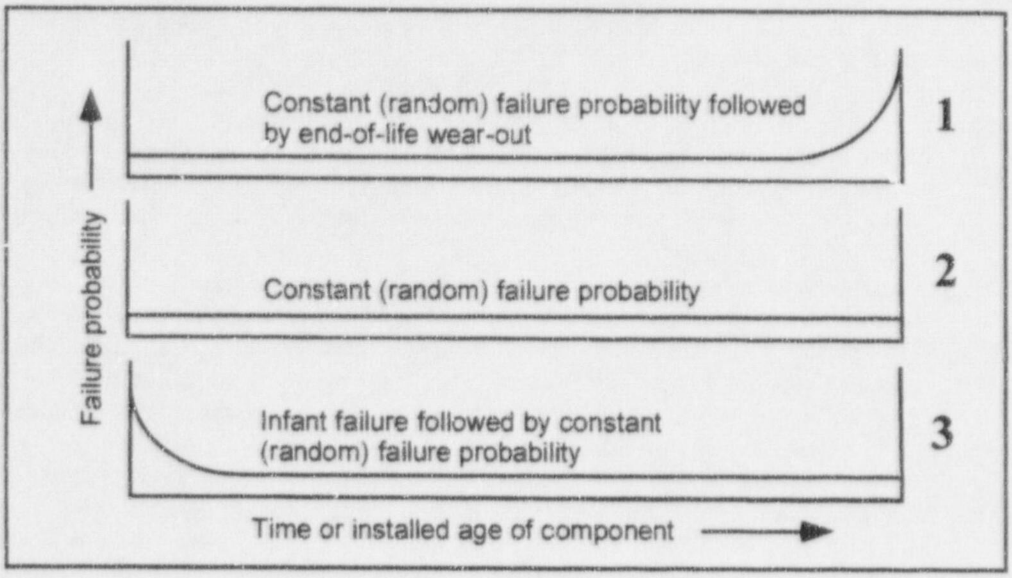


**Figure ES.2 Failure distribution patterns showing relationship between failure probability and component age**

behavior are also discussed, because research has shown that most failures occurring in complex components such as pumps and MOVs result from a combination of factors. Maintenance and testing practices (including margin analysis) are also discussed, as is the effectiveness of various diagnostic and monitoring methods. General guidelines for data collection and trending are also presented.

Chapter 4 contains guidelines to support an integrated regulatory evaluation of proposed changes to IST programs – that is, assessment of the technical bases for such changes, overall operability assurance programs (testing, monitoring, maintenance, and trending and feedback programs), and resulting test intervals. Attributes of well-founded, balanced engineering analyses (including component groupings and failure rate estimation) and operability programs are provided for evaluation of licensee submittals. Recommendations for minimum extension request content, the technical evaluation of such requests for pumps and MOVs, and general considerations for test interval extension are included.

Chapter 5 presents the bases for the computation of failure probabilities from margin trends and margin statistics and provides numerical results from parametric studies of the effects of test intervals and aging on the component margin and component unavailability. Models of exponential deterioration with age and lognormal distributions are used. The parametric studies explore the contributions of varying deterioration rates, statistical parameters, and length of the testing interval. These parameters were selected to assist in the evaluation of adequacies of margins, length of test intervals for margin assessment, and impact of changes in the length of IST intervals. Since actual data on component margin behavior with time is presently unavailable, the information presented in Chap. 5 is only intended to illustrate a potential methodology. Because the parametric studies cover different cases and include bounding cases, the appropriate qualifications and assumptions necessary for valid uses of the inputs and results of the studies are included. Results of evaluations of initial and time dependent probabilities of failure to provide adequate margin are presented. The unavailability of the component is also evaluated as a function of test interval and test downtime with and without repair maintenance.

Appendix A is a detailed discussion of signature analysis used as a condition indicator or diagnostic technique. Application of this technique in detecting abnormalities or degradations in MOVs is a particular example.

**Important results**

The following results should be useful in for evaluating the engineering and programmatic aspects (as well as specific test intervals) of licensee change requests to modify IST programs and for investigating issues related to margin availability:

- Because of unavoidable differences in maintenance practices, human interactions, system transients, and general operating modes and environments, individual components will exhibit individual performance characteristics. ORNL studies have shown that considerable variation exists in the relative performance measurement of components with various parameters and cross-correlations.

- Analysis has shown that in 92 of 246 (37%) significant* pump failures, the affected part was a pump bearing; in 36 of 78 (46%) significant pump motor failures, a motor bearing was the affected part. Yet the current regulatory/Code-required monitoring finds very few bearing problems. More significantly, there is no required monitoring for pump circuit breaker condition, and evidence is clear that circuit breaker failures are primary contributors to pump unavailability.

- Pump hydraulic performance does have potential for margin trending because pump performance can gradually deteriorate due to wear-related causes. Bearing life analysis and degradation in the pump motor, turbine drive, or circuit breaker, however, cannot be adequately assessed by margin trending unless detailed analysis, employing modern diagnostic techniques, is applied. Similarly, for MOVs, comparing developed and required torque may provide some indication of overall performance; however, margin testing alone (such as that described in ASME Code Case OMN-1) cannot likely detect all significant degradation that may be present in either the valve or the actuator. If a very high level of component availability is desirable, performance tests such as margin tests should be considered to be supplemental to, not replacements for, other types of proactive measures such as condition monitoring.

- By relying on torque measurements (converted to thrust via the design-basis stem factor) rather than direct thrust measurements, functional margin as defined in ASME Code Case OMN-1 is always verified under the assumption that the actual stem factor never exceeds the design-basis stem factor. If both torque and thrust are not measured simultaneously, the actual stem factor cannot be determined to prove that it is not greater than the design-basis stem factor. The possibility exists that if the actual stem factor were greater than the design-basis stem factor, insufficient thrust would be delivered to the valve under design-basis conditions, even though the torque-based functional margin was acceptable. The approach allowed by OMN-1 does not take into account a sudden loss of margin and MOV functionality due to degradations that do not directly impact the OMN-1 margin measurement. For example, if the location of the degradation is such that it does not impact the performance parameter being measured, the degradation may go undetected by the performance test and may subsequently lead to an unexpected functional failure.

- A successful performance test cannot by itself guarantee that significant equipment degradation is not present (i.e., the presence of "margin" does not necessarily ensure availability). For example, a successful margin test, as prescribed by OMN-1, can confirm that the MOV motor and gear train together can deliver the desired torque to the stem nut, but it cannot identify degradation in these areas as long as sufficient torque is still delivered to trip the torque switch. In this case, the true MOV capability is limited (hidden) by the torque switch. If the degradation has increased so that not enough torque is delivered to the stem nut and the torque switch does not trip the motor, the motor may stall and be at risk of failing catastrophically (if not adequately protected by a thermal overload device). This case is illustrated in Fig. ES.2.

- An effective program to assure component operability should be *integrated*; that is, it should consider maintenance, operation, failure prediction, and failure detection. In general, proactive measures that seek to prevent failures should take precedence over those reactive ones that can only detect or correct them.

- For many failure modes, it is possible to identify suitable condition monitoring (diagnostic testing) methods to detect potential failures so that action may be taken to prevent a functional failure from occurring.

- Performance tests need to be able to determine whether any part of a component assembly (i.e., the pump or valve and its associated subcomponents and supporting components) has failed. Of equal importance is that the process of checking for functional failure or performance acceptance not induce failure or degradation. The possibility that the component might be left in the failed state because of the test should also be considered.

- The required frequency of failure detection activities such as margin tests or ISTs is dependent upon two parameters—the desired availability of the component and its reliability (i.e., frequency of failure). Appropriateness of test intervals is determined by the importance of the component and its likelihood of failure.

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* "Significant" in this context means that at least some degradation in pump performance occurred and/or near-term operation of the pump was jeopardized. No plant or system effects were analyzed.

- Failure and diagnostic data trending and feedback mechanisms are necessary to validate and, where required, to modify test intervals. Both plant-specific and industry data should be considered.

- Within the assumptions and limitations of the mathematical models and parametric analyses discussed in Sect. 5, the following observations were made for the virtual component considered:

For an inadequate margin failure mode, it was shown that when the margin is near 1, the failure probability due to inadequate margin has high values when the standard deviation is not low (the margin is not accurately known). For instance, for a mean margin of 1.25, the failure probability due to inadequate margin increased from $10^{-4}$ to $10^{-1}$ as the relative standard deviation of the margin increased from 6% to 12%. Margin reduction due to aging further increases the sensitivity to the accuracy of the margin. High failure probabilities can be expected when the margin is low and/or not accurately known, when the test intervals are too large, and when margin degradation is not controlled by renewal or by other means.

Parametric studies of relative changes in unavailability show clearly the positive effect of renewal after testing. With a test interval of 5 years and rate of failure rate change (RFRC) of 10%, the unavailability is approximately a factor of 6 lower when renewal is performed. The effect of testing downtime increased the unavailability in proportion to the downtime duration for all test intervals where the downtime contribution was significant. For the same RFRC of 10% and test interval of 5 years, the unavailability is approximately a factor of 2 lower for no downtime than for 8 hour downtimes.

# 1 Introduction and Background

## 1.1 Background

Past failures of motor-operated valves (MOVs) have resulted in significant maintenance efforts and, on occasion, have led to the loss of operational readiness of safety-related systems. Numerous Nuclear Regulatory Commission (NRC) communications issued since 1979 are indicative of MOV problems during this period and of the NRC's continued interest in identifying and resolving these issues. Generic Letter (GL) 89-10, "Safety-Related Motor-Operated Valve Testing and Surveillance," and its supplements requested that licensees verify the design-basis capability of safety-related MOVs by reviewing their design bases, verifying switch settings, testing, improving evaluations of failures and corrective actions, and trending MOV problems.[1] As a followup to GL 89-10, the NRC issued GL 96-05, "Periodic Verification of Design-Basis Capability of Safety-Related Motor-Operated Valves," which requested that licensees establish a program (or ensure the effectiveness of their current program) to periodically verify that safety-related MOVs can maintain capability of performing their safety functions within current licensing bases.[2] The program should ensure that changes in performance resulting from degradation (such as that caused by aging) are identified and accounted for. This action allowed licensees to close GL 89-10 in a timely manner, yet still address the pertinent long-term issues as outlined in GL 89-10. One of the primary reasons for the issue of GL 89-10 was the recognition that "(code) testing alone is not sufficient to provide assurance of MOV operability under design-basis conditions."

The existing American Society of Mechanical Engineers (ASME) Code inservice testing (IST) requirements and philosophy are, in essence, unchanged from the Code of 20 years ago. Readily measurable, single-value parameters of pumps and valves are to be measured on a quarterly basis (with extension to longer intervals when quarterly testing is not feasible). The measured values are compared with absolute limits and/or previous measurements. The results of this comparison are then used to define whether the component is acceptable, unacceptable, or needs more frequent attention. The scope of the pump and valve testing program includes those components that are needed to safely shut down the plant, maintain the shutdown condition, or mitigate the consequences of an accident. There is no distinction among the components regarding their relative importance to plant safety or risk. ASME Code-specified IST intervals (and to some extent, the tests themselves) were originally developed based on the recognition that little performance experience existed; until it did, a conservative approach (e.g., short test intervals) to component testing was necessary.

This general IST philosophy has been historically used in many industrial processes (whether mandated by code or not) to provide some level of confidence of continuing satisfactory performance. Two particular developments have, however, led the engineering community to recognize that alternatives can be employed in assuring equipment reliability.

1. **Condition monitoring**—The field of diagnostic-based condition monitoring has grown tremendously in the last 10–15 years. For example, many industrial facilities now routinely use digitally based spectral vibration analysis in evaluating the condition of critical pieces of rotating machinery, in lieu of the single-value (root-mean-square) measurement that was previously used. To simplify the analysis of the spectral data, several regions of the spectrum can be evaluated (by software), and compared with previous measurements; trend plots can be generated and, when appropriate, alarms indicated. This type of analysis is commonly automated and provides orders-of-magnitude greater sensitivity to certain developing problems (such as in bearings) than does the single-value, historically applied method.

   Other diagnostic sensing techniques that are now being practiced include thermal imaging, motor current or power spectral analysis, and magnetic flux analysis. All of these methods depend heavily on digital microprocessors to provide results. Successful implementation of these methodologies depends upon knowledgeable personnel who have been trained in diagnostic equipment operation and also in how to ensure that the measurements are valid, to interpret the results, and perhaps most importantly, to understand the fundamental capabilities and limitations of the diagnostic equipment and methodologies.

   Many industries, including nuclear facilities, have already employed nonintrusive diagnostic techniques to assess obturator position in check valves using acoustical methods, pump bearing condition using spectral vibration analysis, and MOV gearcase condition using electrical signature analysis (ESA). In many cases, applications of these diagnostic techniques are in addition to code or regulatory requirements and are commonly used on balance-of-plant equipment where no specific testing requirements exist. A condition monitoring provision has already been approved in the ASME Code for IST of check valves.[3] If implemented, a licensee would be allowed to customize its IST program testing strategy for valves with similar designs, performance histories, and testing limitations in lieu of prescriptive code requirements that do not account for these parameters.

2. **Probabilistic Methods**—Both the nuclear industry and the NRC have recognized that the current operational, regulatory, and economic environment may be conducive to the application of probabilistic technologies for IST. These risk-informed technologies would provide tools intended to focus licensee resources in areas of high safety significance. According to ASME, these efforts would be aimed toward enhancing safety while lowering overall operation and maintenance costs.[4] ASME has recognized that integrated risk-informed operation, maintenance, and regulation offers the potential for maintaining safety while lowering operating costs and optimizing resources for both licensees and regulators. Risk-informed IST programs are intended to help achieve these benefits by basing test requirements on the failure modes of a component and the component's associated risk rather than on a prescriptive set of general requirements that were developed using implicit risk insights.

   Two pilot plant initiatives were undertaken to allow the use of risk-informed IST programs. These programs at Palo Verde and Comanche Peak would involve the classification of components into high and low risk-significant categories, then develop testing strategies based on the risk category. This approach involves testing essentially the same number of components as in the traditional IST program, but extends the test interval for the components with lower safety significance (as determined by the licensees).

   > The new risk-based testing strategy is structured to improve testing for the more safety-significant components and reduce unnecessary testing requirements for the less safety-significant components. This approach is not an attempt to simply reduce costs by relaxing safety standards. Whereas the current programs based on the prescriptive requirements demand an inordinate amount of resources throughout plant organizations, implementation of risk-based IST programs will allow plant operators a degree of flexibility in concentrating their resources on the more safety-significant components and their inherent failure modes.[4]

   Code Cases are currently being prepared by ASME to allow implementation of risk-informed methodologies in lieu of traditional code requirements for IST. The Code Case for check valves, which would combine risk insights with condition monitoring, has already been approved by the ASME Board of Nuclear Codes and Standards.

Supplementing these two developments is an improved knowledge of actual performance data that provides insights into such areas as relative component reliability, principal failure modes, and the effectiveness of historically applied methods in detecting specific failure modes. New approaches to IST such as condition monitoring and risk-informed testing are intended to optimize tests and test intervals while maintaining no net loss in reliability or safety. These approaches would therefore incorporate the performance experience and data accumulated during the past years of nuclear facility operation.*

The condition monitoring and probabilistic approaches provide an opportunity to simultaneously improve reliability and reduce costs. Like most other changes, however, there are attendant costs. In spite of the significant improvements in condition monitoring capabilities, condition monitoring has not developed to the point where data collection and interpretation can be performed without human intelligence and energy. This implicitly means that rigid, prescriptive regulations or codes cannot be written. Successful implementation of these approaches will depend on the availability and use of accurate historical data, committed management, and well-trained staff with the freedom to exercise engineering judgement. The NRC has already endorsed this approach in GL 89-10:

> Assurance of MOV operability is a complex task. It involves many factors such as development of strong testing and maintenance programs, management support, and coordination of engineering, maintenance, and testing. This effort should be viewed by all concerned as a long-term ongoing program. Licensees that have already implemented extensive programs on MOVs have found it very beneficial and cost-effective to require that all maintenance and adjustments on the MOVs be performed by technicians who have received specific training.

Because initiatives such as risk-informed methodologies represent fundamental changes in the implementation of IST programs (from traditional prescriptive requirements to more flexible, judgement-based approaches), the fundamental bases

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* It is important to recognize that different operability assurance programs and testing strategies would apply to different components (or groups of similar components). Various combinations of condition monitoring, predictive/preventive activities, failure detection, and/or corrective maintenance might be included in a program for any component. Individual programs could include all or parts of these elements, depending on important failure modes, safety significance, historical performance, cost/benefit analysis, etc.

on which IST programs are developed should be reexamined. These bases include failure modes, degradation mechanisms, condition assessment, and effectiveness of testing methods. Thus, from an overall operability assurance perspective, integrated testing, monitoring, maintenance, and trending and feedback programs will be important in assuring safe and reliable operation of pumps and MOVs. The NRC has recognized the need for a programmatic approach to operability assurance by providing guidelines for periodic verification programs in GL 96-05 and by defining an integrated, iterative approach to risk-informed decision making in NRC Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis."[5] Because the methodologies for implementation of IST programs are relying less on prescription and more on engineering judgement, so too, will the bases for future IST program evaluation. Accordingly, the NRC sought assistance in developing guidelines to support the evaluation of proposed IST intervals and methods of testing, monitoring, maintaining, and trending pump and MOV performance.

The issues regarding verification of the design and operability of safety-related MOVs and requests for changes to traditional IST programs for pumps and valves have resulted in the need for an improved understanding of degradation effects on their performance. Proposed changes to traditional IST programs have resulted in relief requests for extended pump and MOV test interval allowances. For example, licensees have begun making requests for changes from traditional, relatively short, IST intervals (usually quarterly) to intervals of up to 5 to 10 years. Because component operability may be impacted by undetected degradation or failure between test intervals, an enhanced understanding of methods for mitigating/detecting potential significant component degradation or failure is important. The effects of changes to IST programs on component operability therefore need to be assessed to evaluate the appropriateness of proposed test intervals. This report provides guidelines for making such an assessment.

## 1.2 Objectives and Scope

The objective of this study is to provide guidelines to support the evaluation of IST intervals for pumps and MOVs. It is anticipated that these guidelines will be useful in assessment of (1) proposed changes to IST programs based on risk-informed methodologies, (2) relief requests to extend IST intervals, and (3) issues related to margin availability. Accordingly, this report presents specific engineering information pertinent to the performance and monitoring/testing of pumps and MOVs, identifies the basic elements of an overall program to help ensure component operability between test intervals, and provides an analytical methodology for assessing the bounding effects of component aging on unavailability and margin behavior. The emphasis is on the engineering and programmatic aspects of the evaluations as well as on specific test intervals. Guidance for assessing probabilistic methods and the risk importance and safety consequences of the performance of pumps and MOVs has not been specifically included within the scope of this report, but these elements may be included in licensee change requests.

While current code and regulatory requirements/practices are included, this report focuses on the technical bases necessary to ensure component operability resulting from changes in IST philosophy. The information and guidelines are intended to support the assessment of licensee changes in IST programs.

The focus of this study is on the pump, MOV, and key pump and MOV subcomponents and auxiliary equipment (the complete component *system* or *assembly*), not simply on the basic valves or pumps themselves. The pump assembly includes the pump, motor or turbine drive, and the related circuit breaker. The MOV assembly includes the valve, actuator, and electrical components. The overall pump assembly is considered because research has shown that the pump-related circuit breakers, pump motors, and turbine drives account for many of the failures that prevent pumps from operating (i.e., failure anywhere in the assembly can lead to loss of function or operability). A recent study[6] showed that the number of significant pump circuit breaker failures exceeded the number of significant pump failures during a 2-year period (1994–1995). The failure rate of the pump turbine drives was several times greater than any other pump component, including the pump itself. These observations confirmed the importance of considering all parts of the pump assembly. Similarly, for MOVs, recent studies showed that failures in the valve itself accounted for less than 40% of the total failures; those involving the actuator made up over 60% of the total. Failures involving electrical components outside the actuator housing (motor starters, circuit breakers, switches, etc.) accounted for another 3%.[7,8]

The approach outlined here recognizes important differences between diagnostic testing (e.g., condition monitoring) and performance testing (e.g., ISTs, margin testing). The objective of a performance test is usually to verify that equipment operations are "within specification" and/or within acceptable limits (i.e., to verify that a functional failure has not occurred). The primary purpose of a diagnostic test is to gather information that, if correctly interpreted, can help to assess the general condition of the monitored equipment. As required by the ASME Code for pumps and valves, the intent of IST is to demonstrate operability, on a continuing basis, as an indicator of the ability of the component to meet its design requirements at a given point in time. Likewise, the requirement to verify the design basis of a pump or valve is a requirement to assure the functional operation of the component up to the design basis at that time and is not directly intended to assess the effects of future time, service, or environment on the progressive deterioration of the component. Also, the parameters monitored to indicate the design-basis performance may not necessarily be the same as those best suited to monitor progressive deterioration of performance. Typically, the intent in design-basis performance testing is not to derive information about future performance. Efforts to integrate these two types of tests should recognize these distinct differences. To achieve an integrated program, both diagnostic and performance testing should therefore be included.

## 1.3 Report Use and Format

### 1.3.1 Report Use

This report assumes that the evaluation of licensee requests for proposed changes to IST programs based on risk-informed methodologies, relief requests to extend IST intervals, and/or issues related to margin availability will focus primarily on the three elements outlined below (i.e., that a balanced evaluation should focus on the engineering and programmatic aspects of the activities as well as specific test intervals). Although beyond the scope of this report, a fourth element related to the evaluation of unavailability and risk analyses and their implications should also be considered as part of the movement toward risk-informed ISTs.

The evaluation of a licensee change request to extend IST intervals for a given set of components should consist of three basic elements:

1. evaluation of the licensee's engineering analysis used to determine IST interval allowances,
2. evaluation of the licensee's overall program to assure component operability, and
3. evaluation of the licensee's trending and feedback mechanisms that ensure that test intervals are reevaluated and updated as necessary.

This approach is consistent with guidance for assessing the impact of proposed risk-informed licensing basis changes in NRC Regulatory Guide 1.174.[5] This document affirms the NRC's desire to make decisions on licensing basis changes using a comprehensive approach, including "the results of traditional engineering evaluations, supported by insights (derived from the use of [probabilistic] methods) about the risk significance of the proposed changes." Decisions concerning proposed changes are expected to be reached in an "integrated fashion, considering traditional engineering and risk information, and may be based on qualitative factors as well as quantitative analyses and information."[5]

The five key principles of a risk-informed decision-making process as outlined in the regulatory guide are shown in Fig. 1.1. Within the scope of these key principles, the NRC has identified its expectations:

- The scope and quality of the ***engineering analysis*** (including traditional and probabilistic analyses) conducted to justify the proposed licensing basis change should be appropriate for the nature and scope of the change, should be based on the as-built and as-operated and maintained plant, and should reflect the operating experience of the plant.

- Appropriate consideration of uncertainty is given in analyses and interpretation of findings, including using a ***program of monitoring, feedback, and corrective action*** to address significant uncertainties.

The guidance provided here for evaluation elements 1–3 is therefore consistent with and supportive of an approved NRC decision making process. Emphasis is on the support of principle 5 (Fig. 1.1), the use of performance measurement strategies to monitor the impact of proposed changes, but the integration of probabilistic insights is also considered in Chap. 5 of this report.

### 1.3.2 Format

Chapter 2 presents some of the results of analyses of performance data for pumps and MOVs and identifies important failure modes, mechanisms, and parameters with which component performance may correlate. A discussion of time dependence and failure behavior is included, along with a general discussion of the limitations of the available performance data.

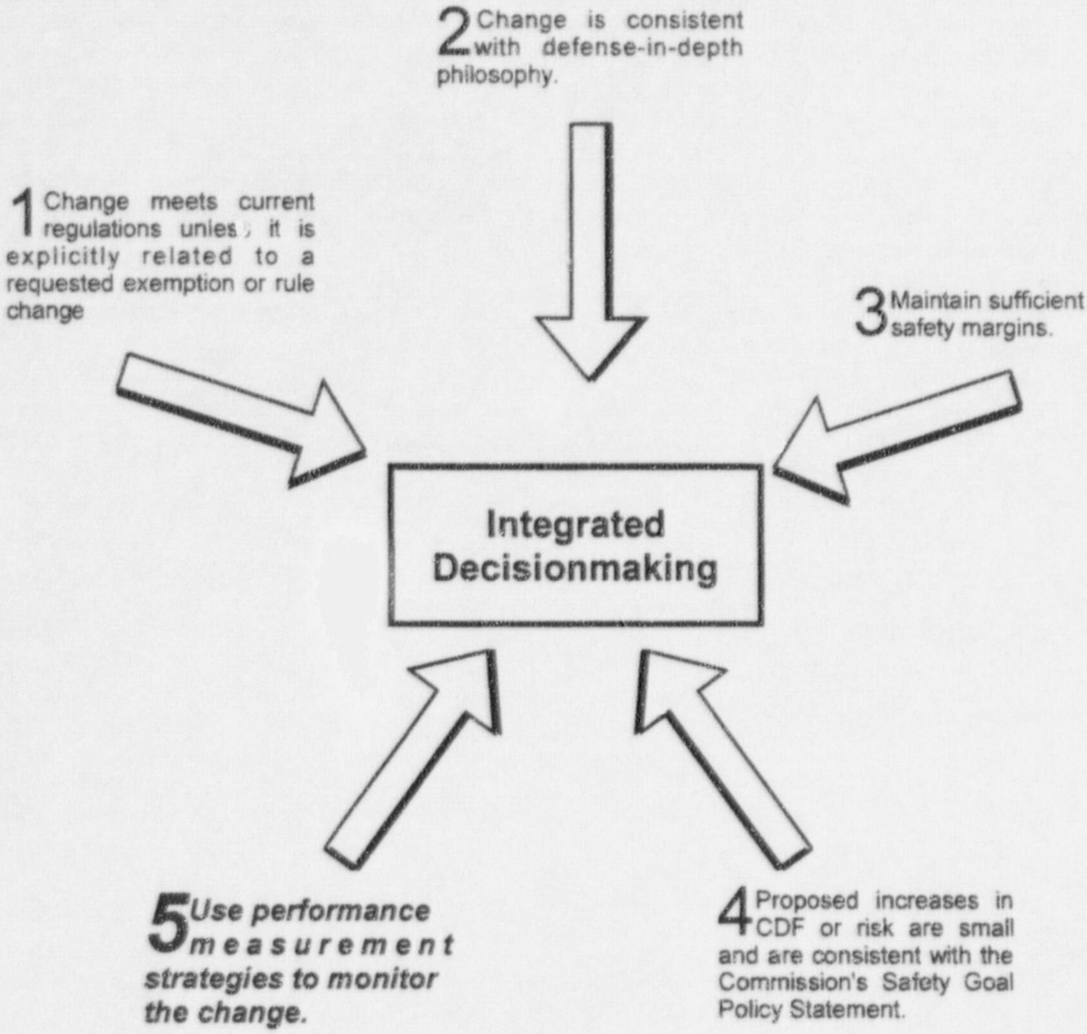


**Figure 1.1 Principles of risk-informed integrated decisionmaking**. *Source*: Redrawn from Regulatory Guide 1.174 (Fig. 1).

Chapter 3 provides testing and maintenance practices applicable to pumps and MOVs. Current preventive, predictive, and corrective maintenance and testing practices are discussed, along with a general assessment of their effectiveness. Margin analysis is also discussed, and the effects of maintenance on component margin trending are identified. Although it is recognized that margin is not a direct indicator of component condition, the definition and measurement of margin for pumps and MOVs are also discussed, because a margin test may generally provide some gauge of component *functionality*. Condition monitoring and diagnostic methods applicable to pumps and MOVs are discussed in detail, and the recently approved ASME Code Case OMN-1 for MOV testing is reviewed. General guidelines for data acquisition and trending are also included.

Chapter 4 contains guidelines to support an integrated regulatory evaluation of proposed changes to IST programs – that is, assessment of the technical bases for such changes, overall operability assurance programs (testing, monitoring, maintenance, and trending and feedback programs), and resulting test intervals. General guidelines for evaluation of licensing basis change requests are provided. Attributes of well-founded, balanced engineering analyses (including component groupings and failure rate estimation) and operability programs are provided for evaluation of licensee submittals. Recommendations are included for minimum extension request content, the technical evaluation of such requests for pumps and MOVs, and general considerations for test interval extension.

Chapter 5 presents the bases for the computation of failure probabilities from margin trends and margin statistics and provides numerical results from parametric studies of the effect of test intervals and aging on the component margin and component unavailability. Models of exponential deterioration with age and lognormal distributions are used. The parametric studies explore the contributions of varying deterioration rates, statistical parameters, and length of the testing interval. These parameters were selected to assist in the evaluation of adequacies of margins, length of test intervals for margin assessment, and impact of changes in the length of IST intervals. Because the parametric studies cover different cases and include bounding cases, the appropriate qualifications and assumptions necessary for valid uses of the inputs and results of the studies are included. Results of evaluations of initial and time dependent probabilities of failure to provide adequate margin are presented. The unavailability of the component is also evaluated as a function of test interval and test downtime with and without repair maintenance. The results presented in this chapter are not based on actual plant data. *The analytical methods outlined in this chapter should be considered supplemental to, not replacements for, the overall programmatic approach outlined in Chap. 4.*

Appendix A is a detailed discussion of signature analysis used as a condition indicator or diagnostic technique. Application of this technique to MOVs is used as a particular example.

# 2 Failure Modes and Mechanisms for Pumps and MOVs

## 2.1 Analysis of NPRDS Data

During the past several years, the Oak Ridge National Laboratory (ORNL) has analyzed thousands of failure records from the Nuclear Plant Reliability Data System (NPRDS) for many components, including pumps and MOVs. The ORNL approach was based on the manual review and characterization of individual failure records, primarily from failure narratives. In this way, the utility descriptions of component failures were used to characterize such parameters as failure cause and failure detection method rather than the relatively simplistic and sometimes unreliable category codes used in NPRDS. This section discusses some of the results of those analyses and identifies important failure modes, mechanisms, and parameters that may significantly affect pump and MOV performance. Time dependence and failure behavior are also discussed, as are the limitations of the available component performance data.

### 2.1.1 Data Limitations

Past ORNL pump and MOV studies[6-9] were accomplished by downloading, filtering, characterizing (according to several parameters), and analyzing "raw" data from NPRDS. Raw data is available in the form of engineering and failure records for each component within the scope of NPRDS for each operating nuclear plant unit. A typical pump population at any point in time (number of components available to fail, considering all operating units) might be approximately 2,000, and an average MOV population might be around 15,000 (valves plus actuators).* These estimates, of course, will fluctuate depending on the number of nuclear units in operation, changes due to plant modifications, etc. By comparison, the number of failure records available for analysis is relatively small, averaging only a few hundred failure records per component type per year.

Parameters derived from the raw NPRDS data and analysis of the failure narratives include component engineering data (e.g., size, system, manufacturer, installation date) and information about failure events such as failure modes, affected areas, failure causes, and detection method. This information lends itself well to analysis of relative performance indicators such as those derived by cross-correlation of parameters (e.g., valve size vs failure mode) and is useful in assessing the effectiveness of test and inspection requirements, factors affecting performance, and overall component reliability.

ORNL component studies have focused on relative failure rates rather than absolute failure rates because of the nature and limitations of the available data. Where possible, the data was normalized to account for both population sizes and service life of the components. By normalizing, a good indication of how a particular category (e.g., valves ≤ 2-in.) within a field compares with other categories in the field is developed. A relative failure rate of unity indicates that the particular category's failure rate is equal to the failure rate of the population as a whole. The normalizing process was employed to allow ease of comparison across a field with numerical values unlikely to be misinterpreted or misapplied. It was deemed inappropriate to calculate generic absolute failure rates because of variability in plant reporting practices, varying service conditions, maintenance effects, types of failures reported, plant refueling outage schedules, special inspections, changes in NPRDS reporting requirements, and diversity and size of component populations relative to the failure rates experienced. The numerical results derived from these studies were therefore not intended to represent absolute reliability estimates. As an example of the variability in reporting practices, Table 2.1 shows the number of MOV failures reported among similar units during a 3-year period. All of the reactors are approximately the same size and were manufactured by the same nuclear steam supply system (NSSS) vendor, yet the total number of failures reported varied by more than a factor of 17 from the plant with the highest to the plant with the lowest number of reported failures.

Combined with the uncertainty in calculation of component age because of NPRDS accounting limitations, parts replacement/maintenance activities, and the lack of demand data (number of actual operating hours or cycles), the factors previously discussed make it almost impossible to establish accurate failure rates or trends based on installed age. In fact, analyses of a considerable amount of failure data for various types of valves and pumps have shown very little general correlation between either component or plant age and failure rate.[6-11] Also, estimations of component margin changes with time cannot be determined from NPRDS data because the reported failures are diverse in nature and do not, in general, involve information on trendable parameters such as thrust or torque.

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* The populations analyzed represented only a selected portion of the industry population; nonsafety-related equipment was excluded, and not all safety-related equipment was analyzed.

**Table 2.1 Variability in MOV failure reporting: number of failures reported by unit per year**

| Unit | Year of reported failure 1990 | 1991 | 1992 | Total |
|---|---|---|---|---|
| A | 13 | 11 | 11 | 35 |
| B | 18 | 10 | 4 | 32 |
| C | 8 | 2 | 18 | 28 |
| D | 5 | 16 | 5 | 26 |
| F | 9 | 3 | 4 | 16 |
| E | 2 | 6 | 7 | 15 |
| G | 2 | 4 | 1 | 7 |
| H | 0 | 2 | 0 | 2 |

## 2.1.2 Time Dependence and Failure Behavior

### 2.1.2.1 Results of ORNL Performance Data Studies

A "failure" can be defined as the inability or interruption of ability to perform a design function within acceptance criteria.* Previous ORNL pump and MOV performance analyses[6-9] have consistently shown that many factors both directly and indirectly contribute to component failure. These may include operating practices, maintenance effects, transient (nonperiodic) events, and design flaws, along with changes occurring with time or use (aging). For most failures, a *combination* of factors is involved.

ORNL's performance data characterization studies of pump and MOV assemblies used a *significance* or an "extent of degradation" category to distinguish minor or annoyance failures from more serious failures. Although five levels or categories were used in the pump studies, these are ultimately reduced to two for most analysis applications: significant or insignificant. *Significant* failures are those that involve at least some degradation in performance, and/or near-term operation is jeopardized or is not possible. The *insignificant* failures, in addition to minor nuisance failures, may entail discernible levels of degradation, but the degradation has no effect on operability and is not expected to affect near-term operation.

**Pumps**

In many applications pumps represent one of the more energetic components from which work is required, sometimes in severe service conditions (e.g., pumping at high head/flow or pumping of abrasive river water). For this reason, pumps are considered prime candidates to exhibit symptoms of degradation and eventually wear-out. Figure 2.1 shows relative failure rates from a 2-year (1994-1995) study of pressurized-water reactor (PWR) and boiling-water reactor (BWR) pumps based on the number of years since installation (age groups).[6] Figure 2.2 shows the same information based on an earlier 4-year study (1990-1993).[9] The first chart of both studies applies to PWR pumps; after an initially high failure rate and subsequent drop, a trend is evident where the failure rate increases in a regular fashion for the age groups shown. The only exception is that, for the 1990-1993 study, the "all failures" group remained fairly constant. This constant failure rate pattern is more common for BWR pumps, as indicated in the second chart in the figures. Both studies show a fairly constant failure rate for significant failures after the initial period. That no apparent wear-out trend exists over the 20 + year "pump installed" period might be explained as follows: (1) testing and maintenance practices are so effective in BWR plants that pump renewal precludes such a trend, (2) the combination of pump designs in BWR plants masks the trend more effectively (for unknown reasons), and/or (3) the applications (e.g., duty and load cycles) in BWRs reduce the trend relative to PWRs. Of course, some level of wear-out (aging) exists in BWR pumps – it is only the absence of an apparent trend that needs explanation.

As alluded to above, relative failure rates for the youngest pumps (<5 years) are higher than those for any other age group (regardless of reactor type); this is evidence of an infant mortality distribution. Rather than a result of degradation mechanisms or wear, these failures can be primarily attributed to manufacturing defects and human error. The number of pump-years of service indicated by the line plot in the figures is determined by reviewing the period of service of each

* The significance of each failure was characterized in ORNL studies in terms of its effect on the *component* functionality, not any resultant effect(s) on the plant or system(s).

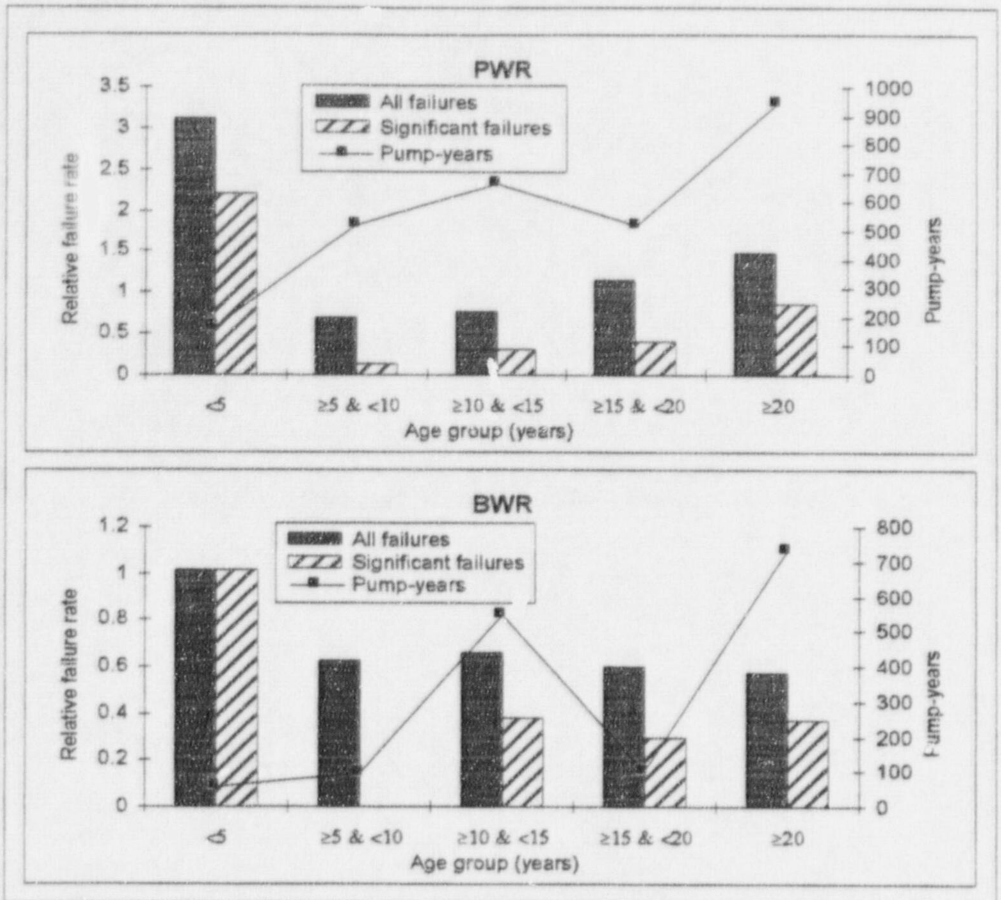



**Figure 2.1 Relative failure rate for PWR and BWR pumps by age group for 1994–1995**

individual pump in the time period of interest and summing the totals for all pumps in a particular category. The number of pump-years is generally low for the infant failures, which places significant uncertainty on that category of failures.

The 1990–1993 pump study[9] seems to show a wear-out or aging trend for some nuclear systems such as the Auxiliary Feedwater (AFW) - PWR (Fig. 2.3) and Component Cooling Water (CCW) - PWR (Fig. 2.4) but not for others, including CCW-BWR, Emergency/Essential Service Water (ESW) - BWR, and Chemical and Volume Control (CVCS) - PWR High-Pressure Safety Injection (HPSI) - PWR, as shown in Figs. 2.5-2.7, respectively. However, although the ESW data does not show a wear-out trend, many ESW pumps experience rapid wear-out,* especially in locations where water quality is poor (e.g., those on the Missouri River). Conversely, although AFW data may indicate wear-out, these pumps are operated only about 5% of the time, therefore it is unlikely that the trend actually reflects degradation because of wear-out (especially relative to ESW). These findings suggest that (1) it is important to understand the characteristics of each system and each plant and not to rely entirely on available pump performance data, and (2) wear-out may not be a significant problem in spite of apparent trends shown by the data.

The 1990–1993 study also shows no clear wear-out trend for pump motors, regardless of the motor manufacturer. This is to be expected, because performance data has indicated for several years that the pump motors are the most reliable performers in the pump assembly. Figure 2.8 shows the relative failure rates of motors from different manufacturers in use at PWR and BWR plants. Although there is considerable variation – especially in the PWR motor failure rates – this may be because of differences in motor applications, service conditions, and duty cycles.

* A review of 1990–1993 NPRDS pump failure data showed that the ESW system at a particular plant experienced 14 wearout failures. Reports on 10 of these failures made explicit reference to the high sand content of the river water feeding the ESW system as a contributing cause to failure. Three additional failures involved pumps that became inoperable after becoming clogged with sand. The 14 wearout failures typically involved erosion of the impeller and certain stationary surfaces such as the volute.

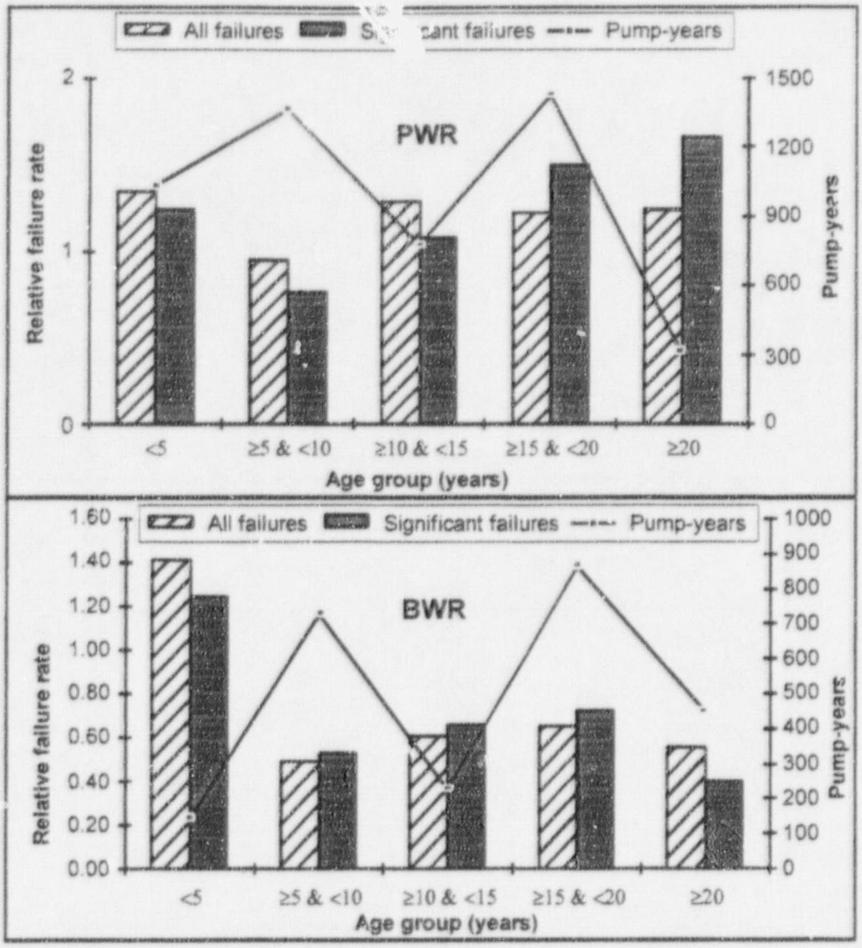



**Figure 2.2 Relative failure rate for PWR and BWR pumps by age group for 1990–1993**

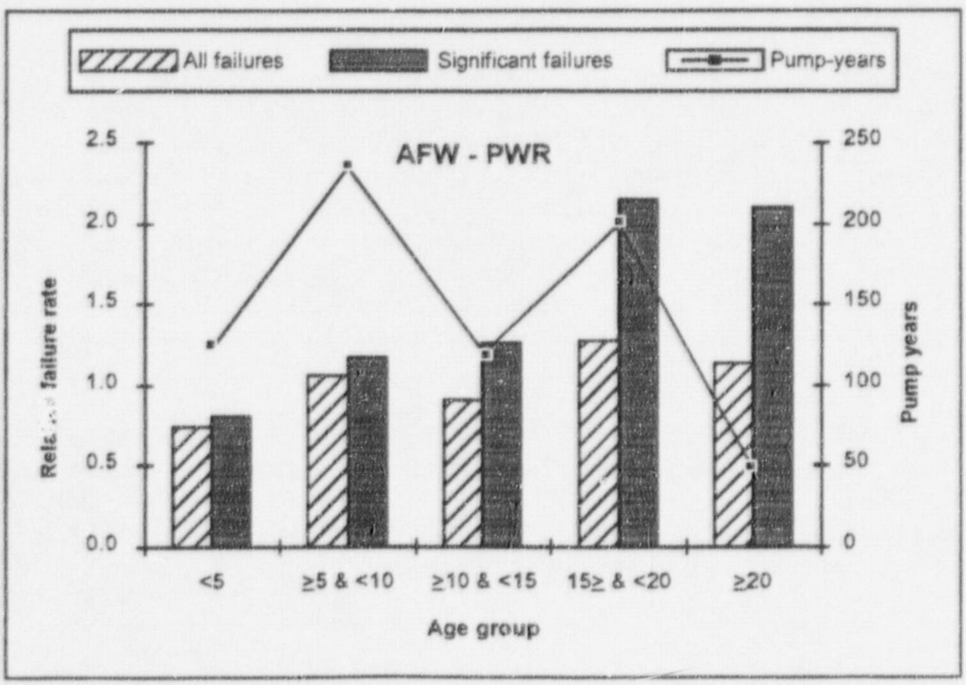



**Figure 2.3 Relative failure rate for PWR AFW pumps by age group for 1990–1993**

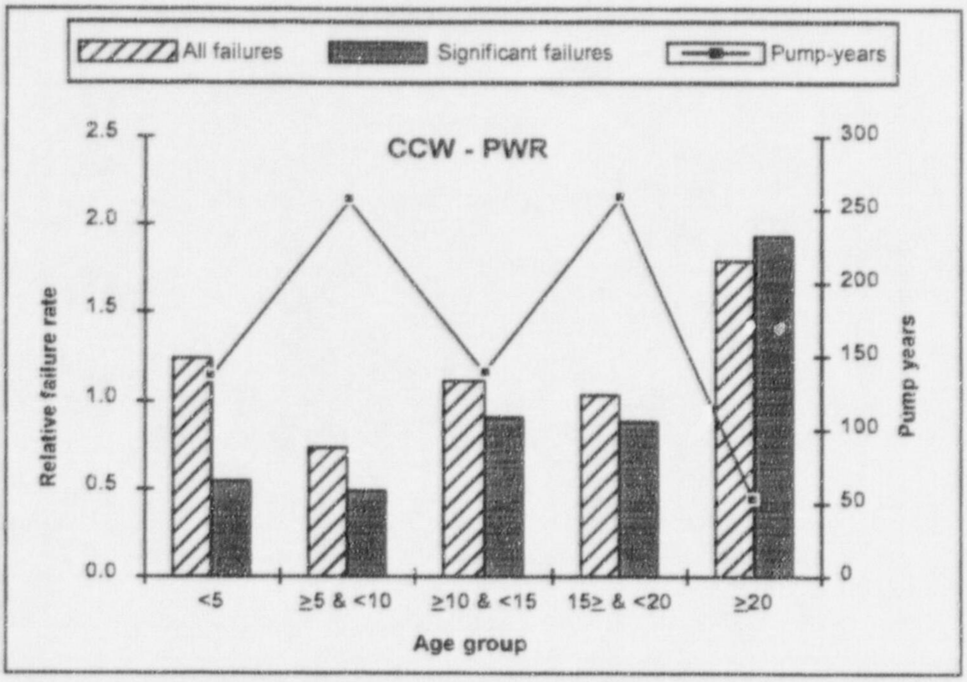



**Figure 2.4 Relative failure rate for PWR CCW pumps by age group for 1990–1993**

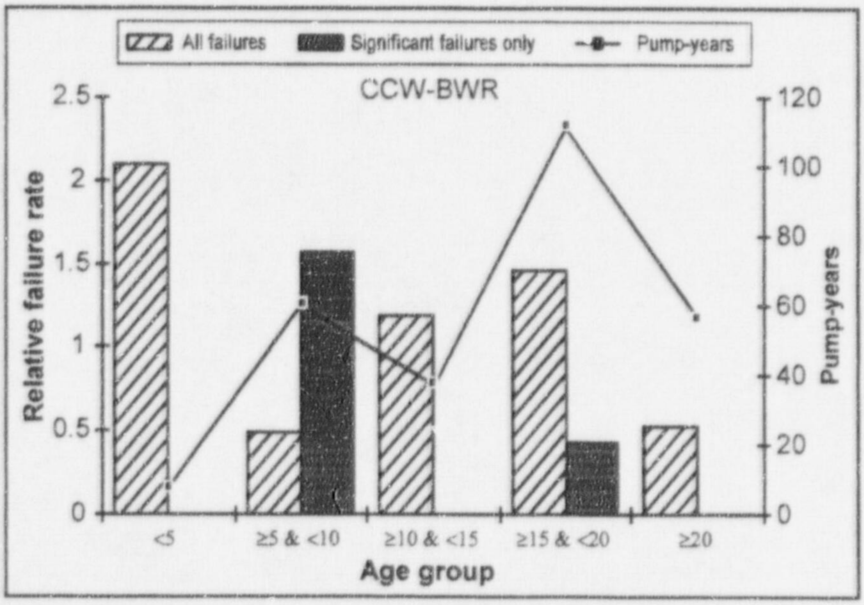



**Figure 2.5 Relative failure rate for BWR CCW pumps by age group for 1990–1993**

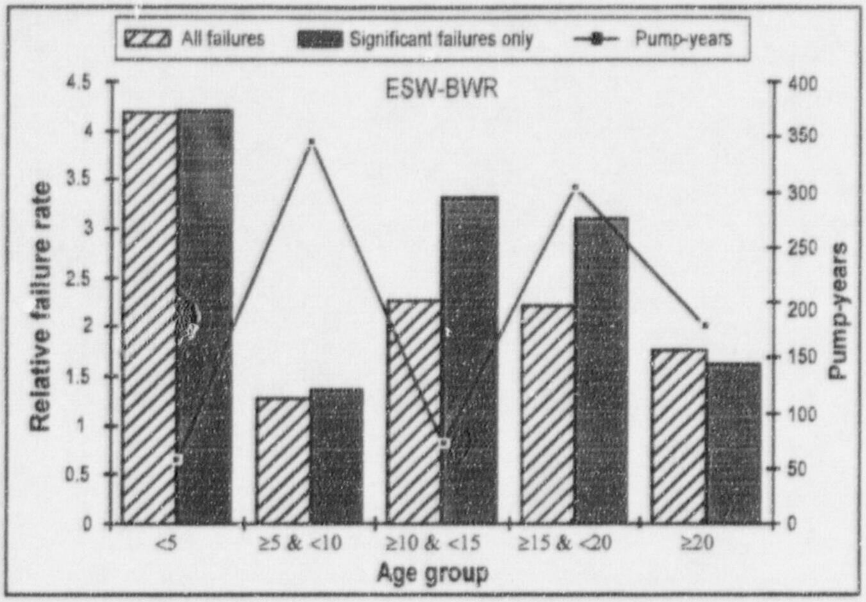
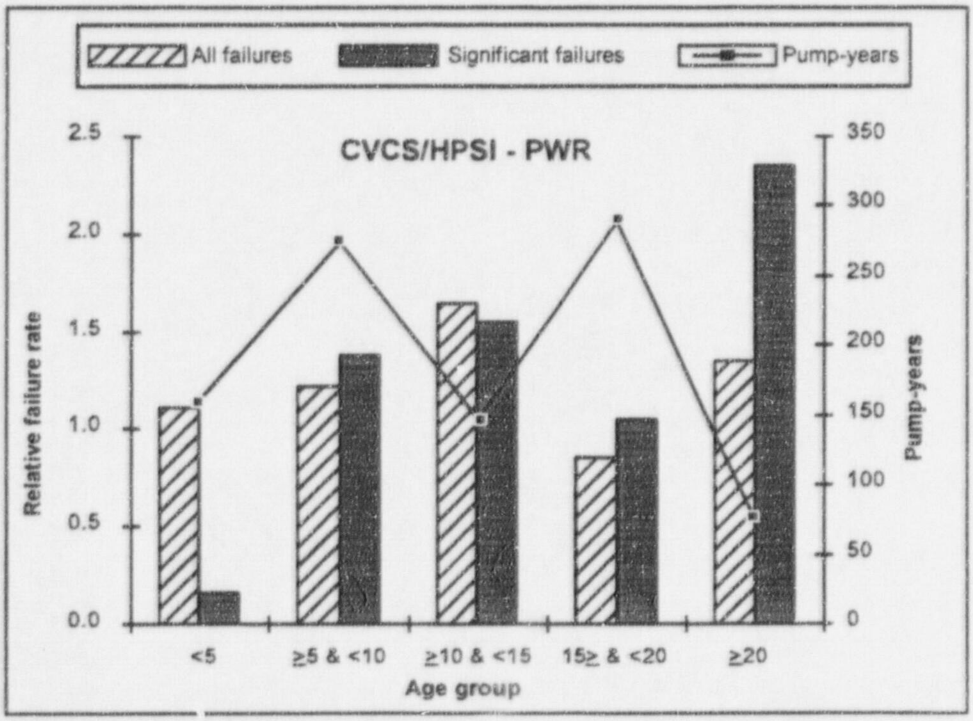



**Figure 2.6 Relative failure rate for BWR ESW pumps by age group for 1990–1993**




**F.:gure 2.7 Relative failure rate for PWR CVCS/HPSI pumps by age group for 1990–1993**

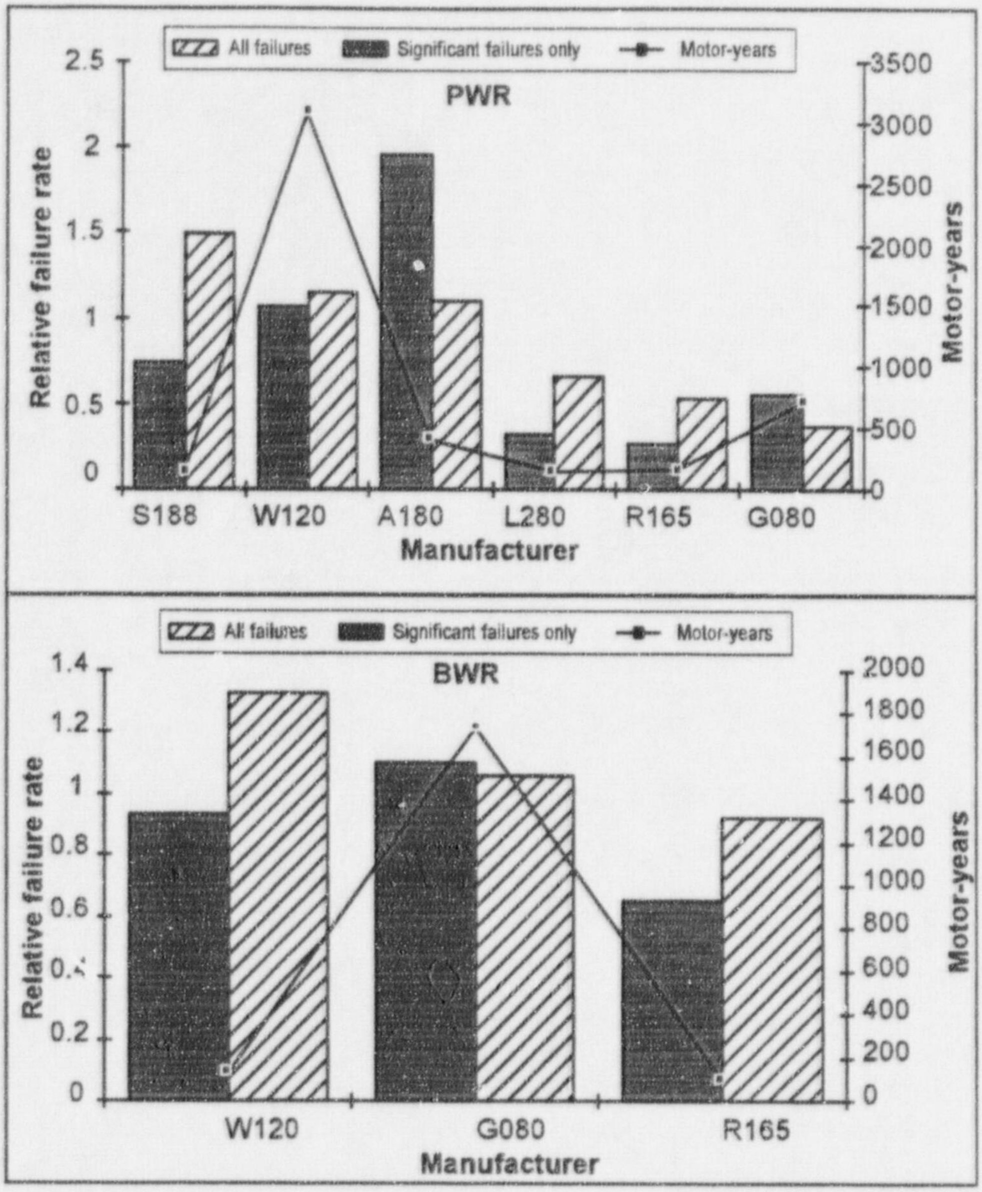



**Figure 2.8 Relative failure rate for pump motors by manufacturer for 1990–1993**

A 1995 study[12] of pump-related turbine drives finds, in general, a decreasing rate of failure with increasing service time as shown in Fig. 2.9 (note that the line plot indicates the actual number of failures). This decreasing failure rate is not unexpected considering that these drives (and the corresponding pumps) are generally used for emergency service and are therefore not subject to significant wear-out.

**MOVs**

Figure 2.10 shows relative failure rates by MOV type (gate, globe, and butterfly valves) and age group for failures from 1990–1992.[7] The data shows no wear-out trends for any valve type, although, like pumps, the youngest valves do tend to have higher relative failure rates than do those in any other age category.

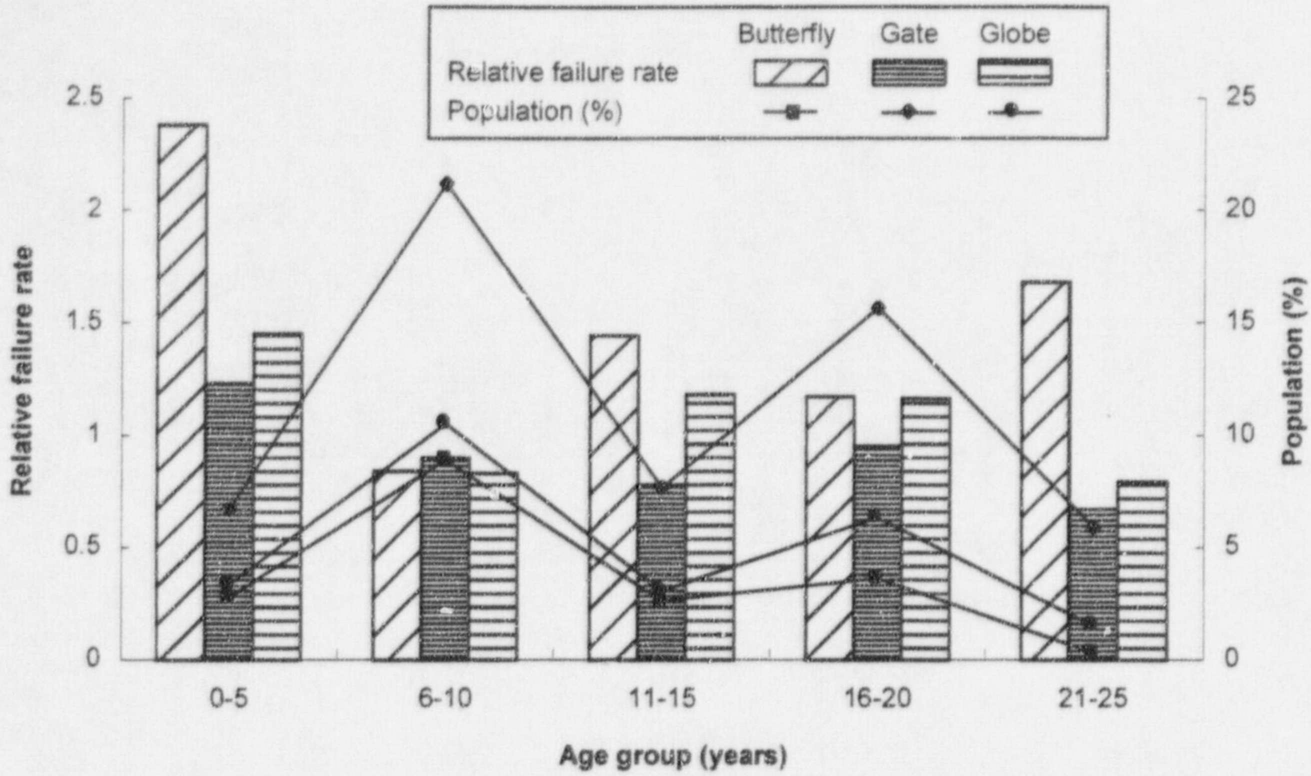



Figure 2.9 Relative failure rate for pump turbine drives by age group, 1995 study

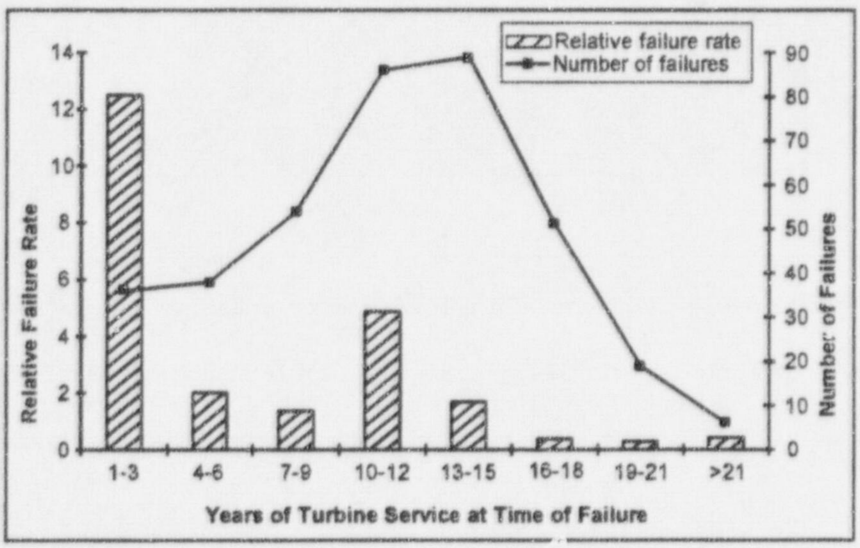



Figure 2.10 Relative failure rate for MOV age group vs valve type for 1990–1992

Figure 2.11 shows percentages of MOV failures by subcomponent and age group for 1993–1995.[8] Failures grouped by four subcomponents (switches, gear train, motor, and valve trim) account for 73% of all failures for the period. Of the failures in these four groups, 100% are distributed across six age groups in Fig. 2.11. For example, 12% of the switch failures occurred in MOVs in the 0- to 5-year age group; 43% of the switch failures occurred in the 6- to 10-year group; and so on, totaling 100% across the six groups. Plotting the data in this fashion illustrates major subcomponent behavior with time. The data shows that only the valve trim and actuator motor subcomponents exhibit slight increasing trends with age. This is expected because these subcomponents would generally be subject to service-related wear or aging.

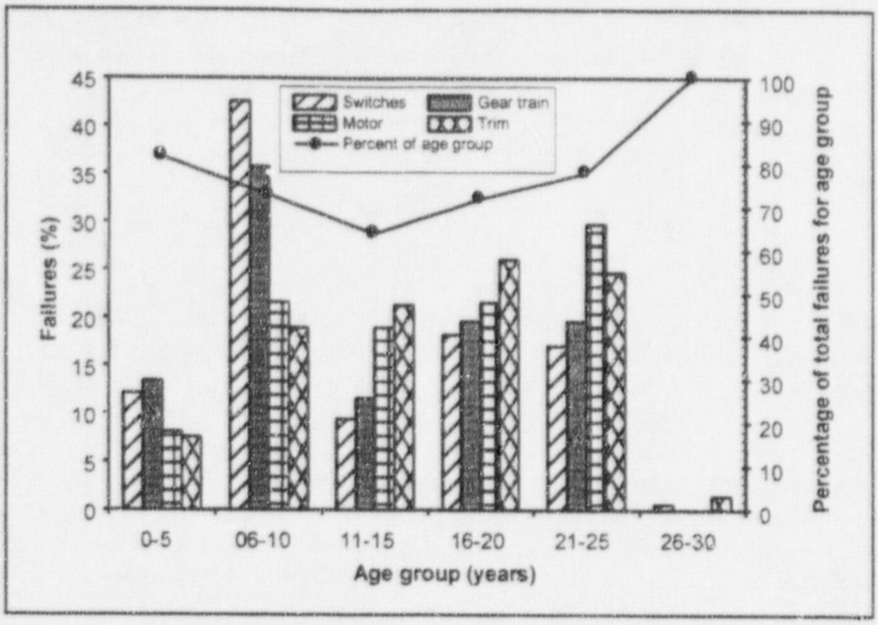



**Figure 2.11 MOV failures by major subcomponent and age group for 1993–1995**

Normal degradation in these subcomponents would not be expected to result in complete functional failure in a demand situation without exhibiting warning symptoms prior to failure.

Figure 2.11 also shows the percentage of total failures for each age group that the four subcomponents comprise. For example, 82% of the failures for MOVs with 0–5 years of service occur in the four subcomponents; 73% of the failures of MOVs with 6–10 years of service occur in these subcomponents; and so on. Table 2.2 lists MOV failures by all subcomponent areas for 1993–1995. The "Other" category for actuators includes 17 subcomponents.

### 2.1.2.2 Behavior Characteristics of Complex Components

Age- or use-related mechanisms such as wear of internal parts (either in contact with some other subcomponent or the process fluid itself), debris accumulation, and corrosion may degrade component performance or result in failure if left uncorrected. However, the presumption that aging is the dominant factor influencing failure probability for such complex systems as pumps or MOVs has not been substantiated. The traditional view of failure behavior (that most components'

**Table 2.2 MOV failures by subcomponent and age group for 1993–1995**

| | | Age group (years) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Component | Subcomponent | 0-5 | 6-10 | 11-15 | 16-20 | 21-25 | 26-30 | Total |
| Actuator | Torque switch | 9 | 44 | 11 | 20 | 21 | 1 | 106 |
| | Limit switch | 13 | 33 | 6 | 13 | 10 | 0 | 75 |
| | Gear train | 2 | 7 | 7 | 9 | 12 | 0 | 37 |
| | Motor | 4 | 9 | 7 | 7 | 10 | 0 | 37 |
| | Other | 3 | 25 | 20 | 17 | 16 | 0 | 81 |
| Electrical supply | Controls | 1 | 4 | 2 | 3 | 0 | 0 | 10 |
| | Fuse/relay | 0 | 1 | 4 | 2 | 0 | 0 | 7 |
| | Switch | 0 | 1 | 1 | 2 | 0 | 0 | 4 |
| | Connection | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| | Potentiometer | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Valve | Trim | 12 | 31 | 38 | 48 | 42 | 3 | 174 |
| | Packing | 2 | 6 | 6 | 2 | 7 | 0 | 23 |
| | Body | 3 | 4 | 1 | 8 | 4 | 0 | 20 |
| | Other | 0 | 5 | 3 | 4 | 0 | 0 | 12 |
| | Total | 49 | 170 | 108 | 135 | 122 | 4 | 588 |

behaviors conform to the so-called "bathtub" curve) is illustrated in Fig. 2.12. While simple components and some equipment with dominant failure modes may operate reliably for a period of time and then wear out (i.e., exhibit increasing failure probability with time), for most complex components and systems in nuclear power plants the probability of failure is not a simple, predictable function of component age or service time. This is true because a combination of factors is involved in most component failures. Figure 2.13 illustrates the individual failure distribution patterns that comprise the bathtub curve shown in Fig. 2.12.

According to Moubray,[13]

> One of the most challenging developments in modern maintenance management has been the discovery that very few failure modes actually conform to any of the (age-related) failure patterns (such as Fig. 2.12 and pattern 1 in Fig. 2.13). This is due primarily to a combination of variations in applied stress and increasing complexity.

Moubray explains that *component deterioration is not always proportional to applied stress, and stress is not always applied consistently*. For example, many failures are caused by increases in applied stress, which may be caused by incorrect operation, maintenance error, or external event. In these cases, there is little or no relationship between how long the component has been in service and the likelihood of its failure. If an event permanently reduces a component's resistance to failure but does not actually cause it to fail (e.g., a manufacturing defect results in a material inclusion in a pump shaft), the reduced resistance to failure may make it vulnerable to the next event or stress peak, which may or may not occur before the component (or part) is replaced or refurbished for another reason. In some cases, a stress peak may only temporarily reduce a component's failure resistance (such as the additional stresses imposed on a pump while passing an entrained vapor pocket through the pump). A stress peak may also accelerate the decline of a component's failure resistance and eventually shorten the life of the component. This could happen, for instance, if a ball bearing were damaged by dropping it on a hard surface before installation. When this happens, the cause-and-effect relationship can be very difficult to establish, because the failure can occur months or even years after the initial stress peak. In these examples, the likelihood of a component failure is not dependent on its time in service, because the applied stress peaks (and any resultant changes in component condition) cannot be predicted (based simply on component age or time in service).

Failure processes such as those shown in Fig. 2.12 and Fig. 2.13 pattern 1, apply to fairly simple mechanisms. In the case of complex components such as pumps and MOVs (which have been made more complex to improve their performance and to make them safer), failure probability becomes less predictable. The more complex the component, the more complex is its failure behavior, which is composed of the different behaviors of its subcomponents and auxiliary equipment. The inclusion of the subcomponents and auxiliary equipment that make up the component assembly (such as the pump, motor, turbine drive, circuit breaker, valve actuator) results in a composite failure curve with a near-constant failure rate (such as patterns 2 and 3 in Fig. 2.13) because random failures tend to predominate as long as they occur before the earliest wear-out failure of the whole assembly. The most important characteristic of failure patterns 2 and 3 shown in Fig. 2.13 is that after an initial period, there is little or no relationship between the likelihood of failure and component operating age.

Figure 2.14 may represent pump and MOV population (or a single component assembly) behavior with time, considering the individual contributions from maintenance activities, infant failures, and random and wear-out failures of various subcomponents. If the probability of failure from multiple causes were considered in combination, the superposition would result in a curve similar to pattern 2 or 3 in Fig. 2.13, as shown by the curve labeled "Conceptual failure rate for a component population," in Fig. 2.14.

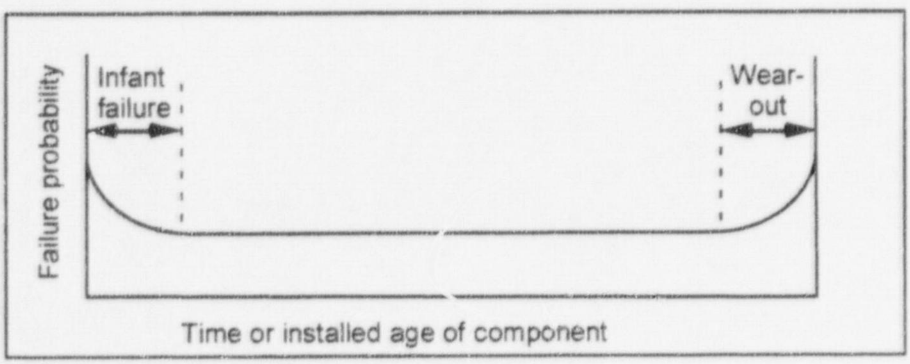



**Figure 2.12 Traditional or "bathtub" component failure pattern (failure probability vs age)**

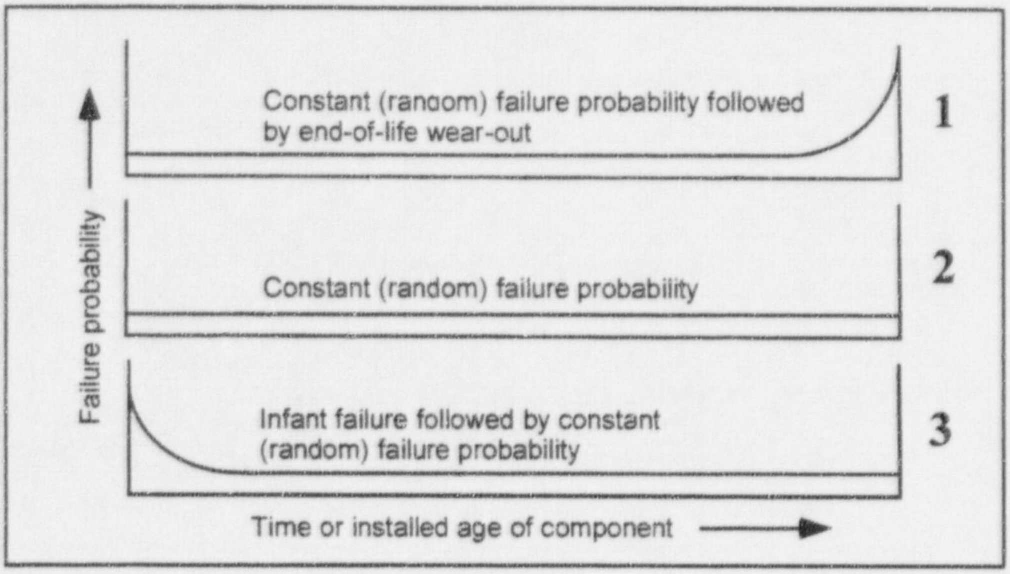



**Figure 2.13 Failure distribution patterns showing relationship between failure probability and component age**

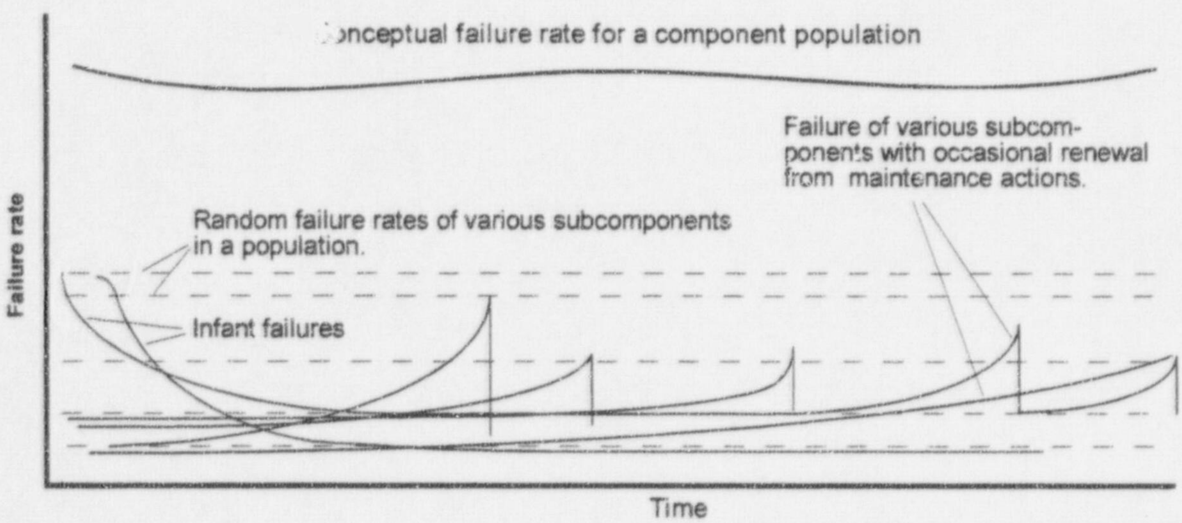



**Figure 2.14 A conceptual representation of MOV and pump failure probability**

In practice, determining a component's operating age is often difficult, considering the effects of maintenance activities, partial refurbishment, subcomponent replacement, and other factors. Figure 2.15 illustrates the difficulty in determining the operating age for a particular component because any of the horizontal lines could represent its "age" at any given point in time. The effects of erratic stress application, maintenance, and refurbishment, combined with the complex component behavior already discussed, help to account for the near-constant failure rates across age groups for pumps and MOVs in the ORNL performance data studies discussed in Sect. 2.1.2.1.

The results of ORNL studies for pumps and MOVs show that these components generally conform most closely to the failure behavior characterized by patterns 2 and 3 shown in Fig. 2.13. *The point is that although changes in condition, characteristics, or performance may occur with time or use (i.e., aging), component failure rates do not in general exhibit increasing failure rate trends with time because of a variety of factors.*

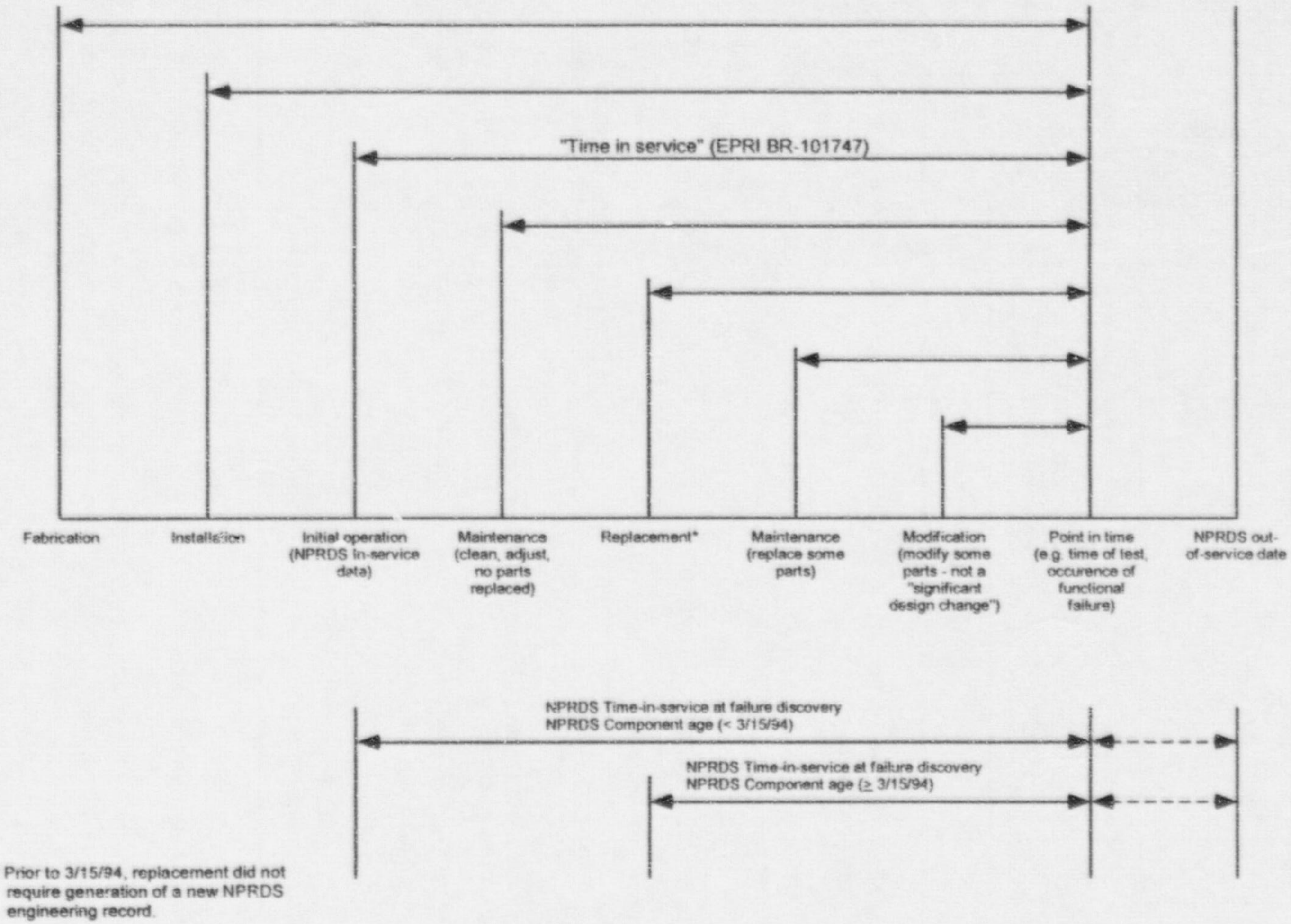



Figure 2.15 Component age

These observations do not imply, however, that most failures are either completely unpredictable or have no time dependence. On the contrary, many of the failure modes affecting pumps and MOVs do involve some time element (i.e., progressive deterioration), and early warning indications are available if the proper parameters are monitored. Depending on the sensitivity of the monitoring system, these predictive indications usually provide enough lead time before failure that actions can be taken to prevent the failure from occurring. One purpose of this study is to identify those parameters that can be advantageously monitored and their correlation to component performance and reliability. These parameters and the available technologies are discussed in detail in Chap. 3.

### 2.1.3 Significant Failure Modes and Degradation Mechanisms

**Pumps**

Degradation or failure in the pump assembly components may be caused by many diverse mechanisms. Table 2.3 lists failure mechanisms and resultant failure modes for a pump and pump motor based on analysis of historical NPRDS data. Similarly, Table 2.4 provides this information for a pump turbine and circuit breaker. It is important to recognize that most of these failure modes can be monitored or predicted using suitable techniques, because some time element (i.e., progressive deterioration) is usually involved. Several of the failures listed in the tables may also occur on a less predictable basis, however; and it may be difficult to distinguish those occurrences from true age-related events. In fact, to discern the two, a root cause analysis (a course of action that is usually pursued for only the most serious component failures) may be required. Examples of failures shown in the tables that are less predictable include

- bearing failures caused by manufacturing defects,
- motor insulation and winding failures caused by manufacturing defects,
- circuit breaker switch failures that do not involve gradual deterioration,
- failures in circuit breaker relays and coils caused by preexisting weaknesses in the wire or wire insulation, and
- electronic governor failures in a turbine drive.

For these failures, there would typically be little or no indication that a failure was imminent.

**MOVs**

About one-third of the total failures in MOV assemblies (valve, actuator, and electrical components combined) examined during a 2-year study period from 1993–1995[8] were shown to involve the valve trim area (disc, seats, guides, and stem). Another one-third of the failures involved either the limit switch or torque switch. During this same time period, the dominant failure modes were failure to stroke and internal leakage. Other common, but less frequent, failure modes included failure to stroke completely, external leakage, and breaker/fuse problems. Analysis of the data shows that almost 56% of the actuator failures (32% of all failures) involved the limit switch and/or torque switch. Actuator failure commonly involves switch misadjustment, set point shift, and dirt or corrosion on the switch contacts. Such degradation usually results in failure of the actuator to stroke or failure to stroke completely. When failures caused by leakage (both internal and external) and complete or partial failure to stroke are combined, approximately 76% of the total MOV failures between 1993 and 1995 are accounted for by these failure modes.

Although a rigorous analysis of the root causes of MOV failures has not been undertaken, analysis of valve assembly data for failures from 1990–1992[7] shows that seat and/or disc wear problems were cited as the cause of failure for more than one-half the failures examined (51%). Those attributed to "other/unknown" (an NPRDS designation) causes accounted for another 38% of the total failures. Table 2.5 lists degradation mechanisms and resultant failure modes for MOVs based on analysis of historical NPRDS data.

It is important for the purposes of this study to recognize that not all of the component failures attributed in NPRDS to "age/normal use" are actually aging related. Often, failures are categorized as "age/normal use" for convenience by utility personnel. For example, analysis of repeat failure records for the same valve at a certain plant showed that the valve failed a local leak rate test on the ninth of one month. The disc and seats were lapped, and the valve was returned to service. The coding supplied to NPRDS by the utility stated that the cause of the failure was "age/normal use." Fifteen days later the same valve again failed a seat leakage test, and again the failure was classified as "age/normal use," but the damage to the seat and disc area was the same as in the previous failure. This is only one example of how the term "age/normal wear" can

**Table 2.3 Failure modes and mechanisms in a pump assembly (pump and motor)**

| Component | Failure mechanism | Failure mode |
|---|---|---|
| Pump | | |
| Bearing | Mechanical wear | Ball to race fretting and abrasive wear (accelerated by high vibration levels) |
| Bearing | Mechanical defect | Manufacturing defect or handling related damage |
| Bearing lube | Diverse types of degradation of the lubrication system | Degradation of system due to lowflow in the oiler, foreign particles, wear debris, water, wrong viscosity, acid, loss of antioxidation/antirust additives, etc. |
| Impeller/diffuser/volute | Erosion | Erosion due to energetic flow and abrasion by particles in the fluid |
| Impeller/diffuser/volute | Abnormal erosion | Accelerated erosion due to cavitation, suction recirculation, and/or discharge recirculation |
| Wear ring | Wear from metal-to-metal contact | Impeller/casing clearance increases, and consequently recirculation also increases due to excessive abrasive wear of the ring. Pump performance drops significantly. |
| Foreign debris | Chemical bonding | Smooth, optimized contour of internal components (e.g., impeller) degraded |
| Shaft, coupling, keys | Fatigue failures | Dynamic hydraulic loading, misalignment, unbalance |
| Mechanical seal/packing | Abrasion | General abrasive wear of packing by rotating shaft |
| | | |
| Motor | | |
| Bearing | Mechanical wear | Ball to race fretting and abrasive wear |
| Insulation | Degradation of material properties | Leakage, winding shorts, arcing in the rotor or stator |
| Stator insulation and windings | Material defect | Defect results during manufacturing |
| Bearing lube | Diverse mechanisms | For oiler systems see pump bearing lube. Otherwise, lubricant may have dried due to heat and/or lack of maintenance so that it could not flow through the bearing elements |

**Table 2.4 Failure modes and mechanisms in a pump assembly (pump turbine and circuit breaker)**

| Component | Failure mechanism | Failure mode |
|---|---|---|
| Turbine drive | | |
| Linkages, fasteners | General wear | Abrasive wear – normal wear process and/or due to poor lubrication |
| Miscellaneous parts | Loss of adjustment | Vibration, impacts, poor fastener design, and poor lubrication may all lead to loss of adjustment in linkages, switches, etc |
| Governor valve | Corrosion | Galvanic corrosion leads to early wear-out (i.e., pitting corrosion in the valve stem). Incompatible materials used for the valve packing (i.e., carbon spacer ring and washer materials with different purity levels for sulfur) in high moisture environment lead to corrosion. |
| TTV[a] | Aging/unknown | Potential aging failure causes include "aging" (9%) and "unknown" (27%)[b] – failure mechanism(s) not understood (NPRDS category designations) |
| Governor | Aging/unknown | Potential aging failure causes include aging (33%) and "unknown" (53%)[b] – failure mechanism(s) not understood except, for electronic governors, some appear to be statistically random component failures (NPRDS category designations) |
| | | |
| Circuit breaker | | |
| Switches, contacts | Unknown | Potential causes: arcing, wear on moving parts, loss of grease, dirt, design weakness |
| Switch | Mechanical defect | Manufacturing defect leads to possible early failure |
| Relays, coils | Generally coil failure | Winding opens or shorts due to thermal stress and/or manufacturing/design weaknesses |
| Lubrication | Gummed or missing | Degraded lubrication causes wear and degraded mechanical movement and/or electrical contact |
| Miscellaneous parts (hardware) | General wear | Wear can result in abrasion, binding, loss of alignment, higher stresses, etc. Ultimately, mechanisms may become inoperable. Parts include trip hardware, rail hardware, and spring charging components. |
| Miscellaneous parts (hardware) | Cracks or total fractures | Vibration, impacts, and high number of loading cycles lead to material and stress fatigue cracking |

[a] TTV = trip and throttle valve.

[b] Based on NPRDS data from 1994 and 1995.

**Table 2.5 Failure modes and mechanisms in an MOV assembly**

| Component | Failure mechanism | Failure mode |
|---|---|---|
| Valve | | |
| Disc/seats | Wear, erosion, corrosion | Wear of the sealing surface, which results in leakage |
| Guides | Wear | Guide wear can increase the requirement for seating and may allow the edge of the disc to hit the edge of the seats, obstructing proper seating |
| Stem | Finish/surface defects | Increased drag, damage to packing |
| Packing | Embrittlement | Loss of ability to seal against the stem, resulting in leakage |
| Actuator | | |
| Limit switch | Broken rotor, dirty contacts, incorrect setup | Failure mode may be loss of control function. Incorrect setup may cause failure to stroke or failure to stroke completely |
| Torque switch | Roll pin failure, set point shift | Roll pin failure may prevent torque switch trip at the end of the valve stroke. This could result in a stall condition for the motor, thus tripping the breaker or degrading the motor due to the elevated temperatures that result from the application of locked rotor current for more than a few seconds. |
| Motor | Complete failure/degraded output | Failure to stroke, failure to stroke completely, or insufficient margin to perform safety function |
| Gears | Wear, broken teeth | Broken gear teeth can result in the inability of the actuator to stroke the valve |
| Spring pack | Spring relaxation, incorrect preload | Change in torque switch trip point; potentially resulting in partial stroke or failure to properly seat disc |
| Stem nut | Wear | Thread wear may increase friction, and thus increase the thrust required to stroke a valve |
| Lubrication | Deficient/degraded | Inadequate lubrication may cause increase in friction at the stem-to-stem nut interface. This will decrease the amount of torque converted to thrust. Hardening of lubricant that has migrated into the spring pack can prevent torque switch trip. |
| Wiring | Loose connectors | Can result in loss of or intermittent control function; may cause motor to short or trip circuit breakers |

be misapplied, because it is obvious from the multiple failure records that the root cause was never properly identified. Analysis of "raw" data can, therefore, be misleading when the root cause of component failures has not been rigorously investigated.

### 2.1.4 Significant Performance-Affecting Parameters

Because of differences in component design, manufacture, installation, operating environment, and other parameters, no two components will ever exhibit exactly the same long-term behavior. Even two "identical" pumps that have the same design specifications, manufacturer, etc., will not necessarily perform equally over a long period. Because of unavoidable differences in maintenance practices, human interactions, stress applications, and general operating modes and environments, individual components will exhibit individual performance characteristics. For example, review of NPRDS failure records for a particular unit shows problems with repeat packing leaks in one MOV, while an identical valve in another train in the same application has no record of a similar problem.

ORNL studies have shown that variation exists in the relative performance measurement (characterized by estimations of relative failure rates across categories) of components based on various parameters and cross-correlations. Two significant parameters influencing component performance have been shown to be design and service conditions (application). Upon inspection, however, it becomes evident that these are very broad categories. For example, "component design" might include subcategories such as size, type (e.g., gate vs butterfly valves), motor or actuator design, and materials of construction. "Service conditions" might take into consideration process fluid, temperature, pressure, flow, proximity to upstream disturbances, orientation, and service duty (constant, intermittent, or standby service). As all these factors are considered, it becomes evident that describing MOV or pump performance is a multivariable task. Accordingly, there is no "correct" answer to questions such as, "What is the failure rate for *pumps*?" or "What are the monitoring requirements for *MOVs*?" The answer depends on the scope of the question: the more specific the question (the greater the number of parameters specified), the more accurate and useful the answer, provided adequate data exists.[14]

Because component performance has shown correlation with various parameters, some attempt should be made to more accurately define the parameters of interest. ASME recognized this problem in its 1996 Addenda to the Operations and Maintenance (OM) Code,[3] which discussed requirements for grouping of check valves to be included in sample disassembly examination and/or condition monitoring programs. According to ASME, check valve groupings must consider parameters such as valve manufacturer, design, service, size, materials of construction, and orientation. Additional suggestions for grouping considerations are maintenance and modification history, failure rates, exercise limitations, and recorded behavioral anomalies. ASME's intent in grouping components by these parameters is twofold:

1. It recognizes that although all components do not behave identically, similar behavior patterns can be expected for groups of similar components.

2. It optimizes resources spent on component testing, examination, and maintenance by recognizing that if groupings are done correctly, then a test or examination of one group member should provide representative information about for all (or most) group members.

GL 96-05 and the optional ASME Code Case OMN-1, "Alternative Rules for Preservice and Inservice Testing of Certain Electric Motor-Operated Valve Assemblies in Light Water Reactor Power Plants,"[15] discuss grouping considerations for testing MOVs. According to GL 96-05, the selection of MOVs for testing and their test conditions should consider safety significance, available margin, environment, and benefits and potential adverse effects of testing. Code Case OMN-1 requires MOV grouping to be justified by an engineering evaluation, alternative testing techniques, or both. When grouping MOVs, parameters such as motor operator type and service conditions must be considered.

Grouping of components also allows a corresponding grouping of performance data. This ultimately enhances the analysis and narrows the confidence bounds on estimated failure rates. Specific grouping considerations for pumps and MOVs are discussed in more detail in Sect. 4.1.1.

Some of the correlations in pump and MOV performance with various parameters (e.g., system of service) observed in ORNL studies are discussed in the following sections.

### 2.1.4.1 System Effects

**Pumps**

The system and specific application that a particular pump operates in determines its duty cycle, service conditions, and the quality of fluids (e.g., clean and chemically treated, river water, brine) under which it must operate. Figure 2.16 shows the relative failure rates of PWR and BWR pumps in various systems based on data from the 1994–1995 study.[6] As indicated in the study, pumps in high usage systems with poor water quality have a substantially higher failure rate than pumps that operate infrequently and pump clean water. Hence, in just five or six systems with the highest relative failure rates, the rates vary by a factor of 5 for PWRs and 7 for BWRs. In the 1990–1993 pump study,[9] relative rates ranged from 2.43 for the PWR ESW to 0.08 for the PWR Containment Spray system, which differ by a factor of 30 (see Fig. 2.17). This illustrates the importance of proper selection of component groupings and the problem with the application of a *generic* failure rate to pumps in any system at a plant.

In the 1994–1995 study,[12] the relative failure rates for turbine drives that are operated infrequently range from 0.668 for the BWR Reactor Core Isolation Cooling system (RCIC) system to 1.13 for the PWR AFW system (i.e., differing by a factor of 1.7 as shown in Fig. 2.18).

**MOVs**

The system of service for MOVs can also have an impact on MOV failure rates. For example, the system of service can affect how often a valve is cycled. A valve could be cycled every day or as little as once a refueling outage to comply with testing requirements. Also, system operation will determine whether a valve operates against high differential pressures, high flow rates, or with very fast cycle times. All of these parameters can affect MOV performance. The system of service will also dictate the quality of the water flowing through the valve. Raw water systems tend to erode valve internals more rapidly than clean and chemically treated water systems under similar flow rates and pressures.

Figure 2.19 shows relative failure rates for the six systems in the MOV study from 1993–1995.[8] Relative failure rates for the systems varied from approximately 0.8 for the Residual Heat Removal system (RHR) to almost 1.4 for the Main Steam system. Note, however, that many of the Main Steam system failures were attributed to internal leakage (normally considered a moderate or insignificant type failure); almost one-half of the failures in the RHR system were failures to fully stroke (considered a significant failure). Although failure rates for MOVs do exhibit variation by system, the variability is not as pronounced as it is in the pump population. This may be in large part because actuators account for more of the MOV assembly failures than do the valves themselves.[7,8] Because actuator failures are generally not a function of the system parameters (not usually affected by pressure, flow rate, water quality), the overall variability in relative failure rates for MOVs by system is less than that for pumps. The effects of different system parameters already discussed would therefore be expected to be more observable in failures of the valves themselves.

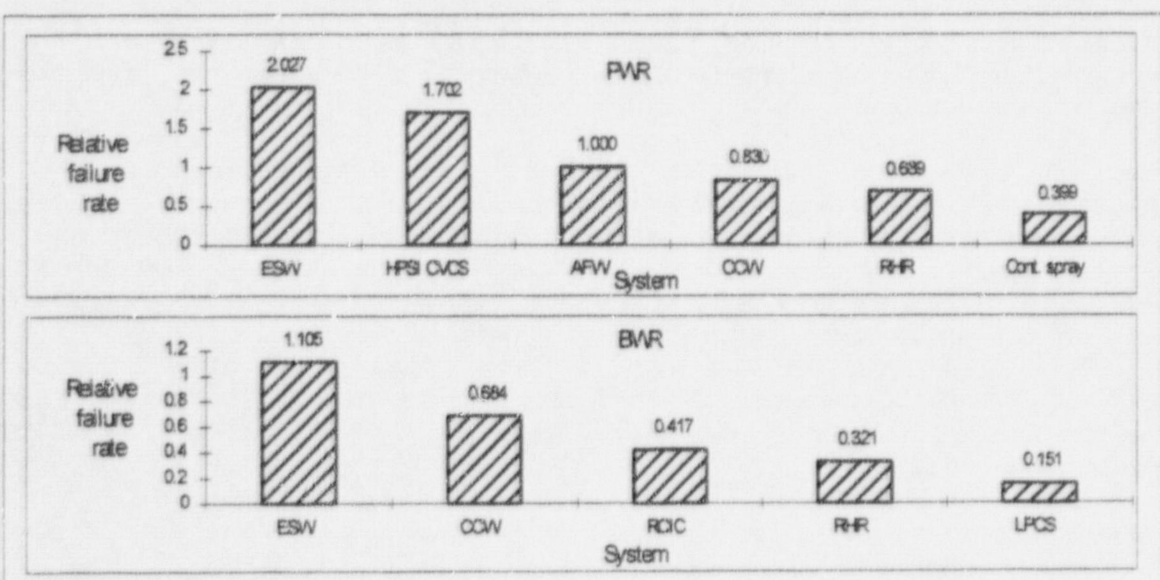



**Figure 2.16 Relative failure rates for PWR and BWR pumps by system for 1994–1995**

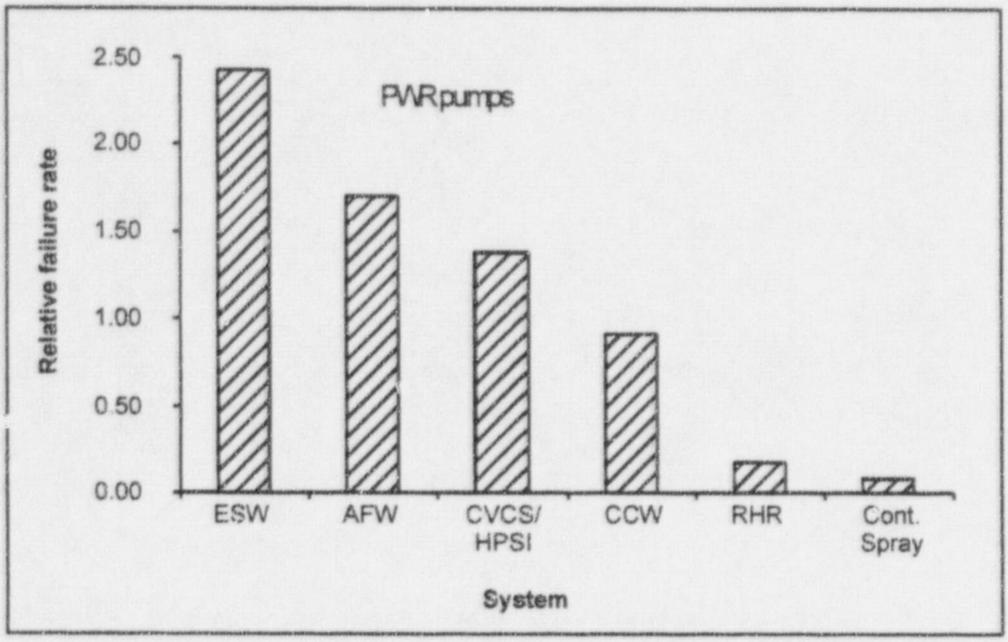



**Figure 2.17 Relative failure rates for PWR pumps by system for 1990-1993**

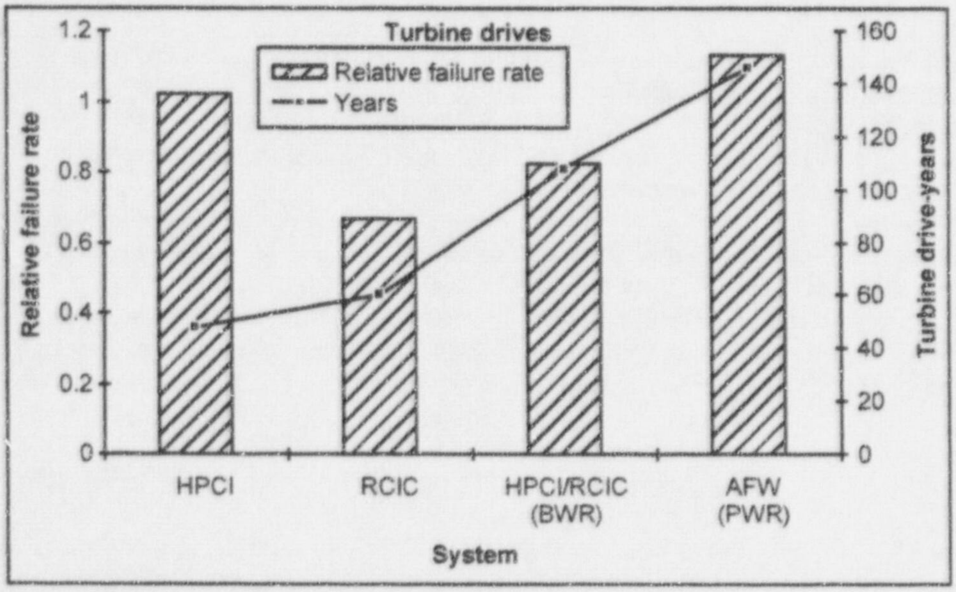



**Figure 2.18 Relative failure rates for pump turbine drives for 1994-1995**

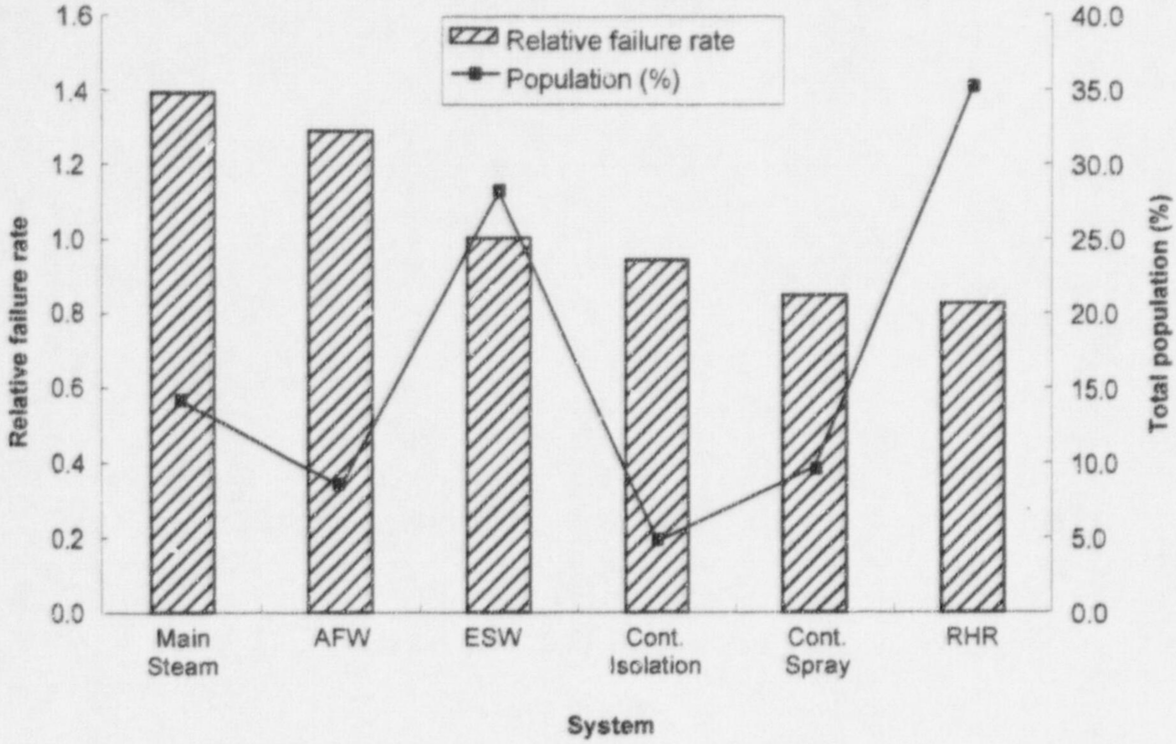



**Figure 2.19 Relative failure rates for MOVs by system for 1993–1995**

#### 2.1.4.2 Other Effects

**Pumps**

In addition to grouping pumps by system, failure rates may also vary when grouping pumps by installed time or age groups, plant type (as indicated previously), service condition (as partially indicated by system), duty cycle (as partially indicated by system), and manufacturer. Figure 2.20 shows relative PWR and BWR pump failures by manufacturer (NPRDS codes are used in place of actual manufacturer's names) during 1994–1995. For PWR pumps, the relative failure rates for significant failures vary by a factor up to 14 and BWR rates vary by a factor up to 12.

As a specific example of the variability in failure experience for a particular group of pumps, consider the 23 significant failures of Byron Jackson pumps in the ESW system during a 4-year analysis period (1990–1993).[9] Of the 23 failures characterized as significant (in terms of extent of degradation to the pump itself), 17 occurred at *one plant* (plant A). All 17 of the failures were either explicitly or implicitly related to the high sand content of the river water being pumped. There were 187 pump-years of experience for Byron Jackson PWR ESW applications during the analysis period, but plant A accounted for only 16 of the 187 pump-years. A comparison to overall industry data yields the following results:

| Plant | Significant failures | Pump-years | Failures/pump-year |
|---|---|---|---|
| Plant A | 17 | 16 | 1.063 |
| All other PWRs | 6 | 171 | 0.035 |

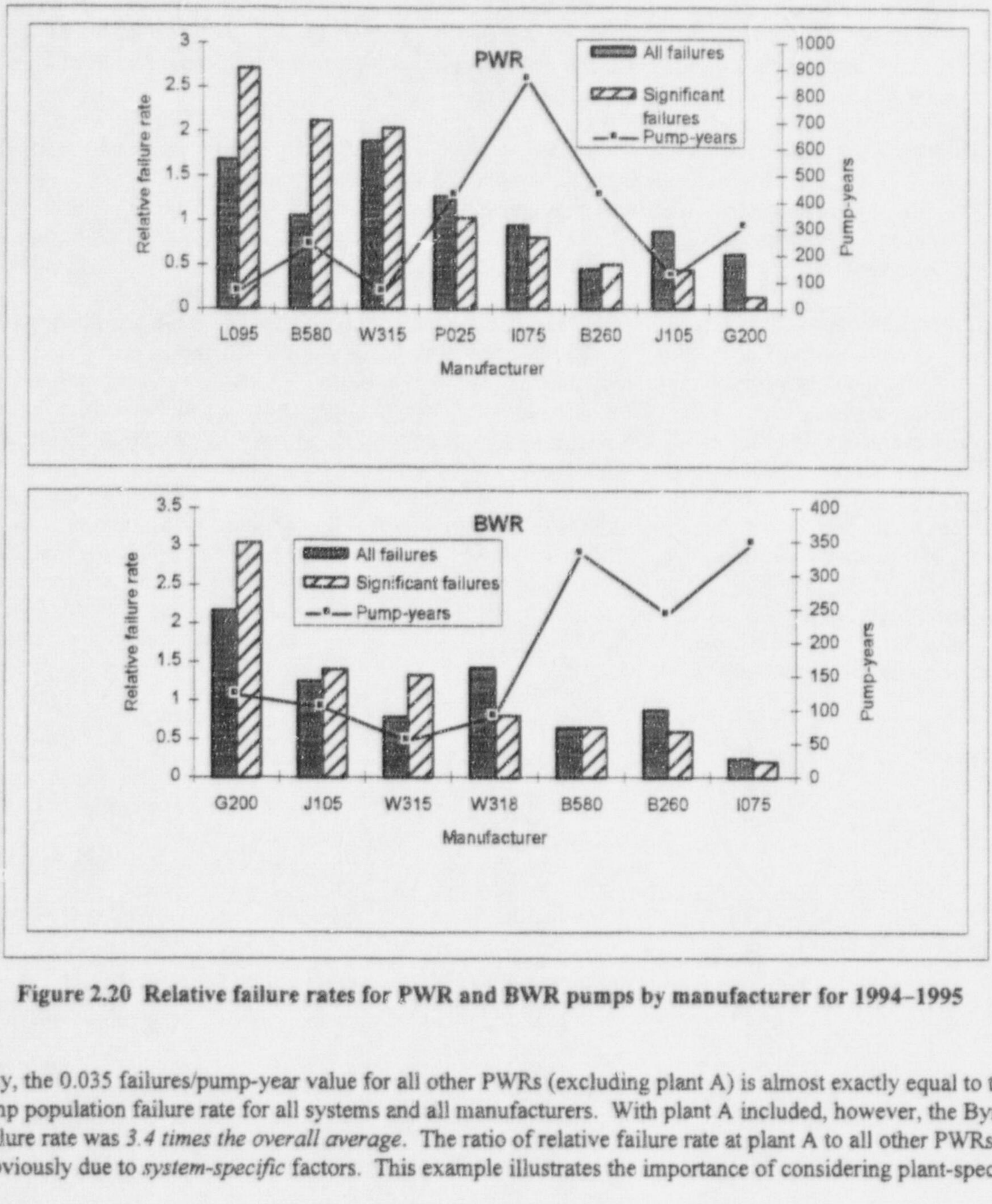



**Figure 2.20 Relative failure rates for PWR and BWR pumps by manufacturer for 1994–1995**

Interestingly, the 0.035 failures/pump-year value for all other PWRs (excluding plant A) is almost exactly equal to the overall pump population failure rate for all systems and all manufacturers. With plant A included, however, the Byron Jackson failure rate was *3.4 times the overall average*. The ratio of relative failure rate at plant A to all other PWRs is 30, which is obviously due to *system-specific* factors. This example illustrates the importance of considering plant-specific data.

Review of the nominal design pump head/flow values for plant A showed the water horsepower at rated conditions to be just over 160 (the second smallest group in the Byron Jackson ESW population) compared to an average water horsepower of 438 for all Byron Jackson ESW pumps, and a maximum water horsepower of 1367. The point is that nothing about the plant A pumps per se suggests that they should be problematic. The nature of the failures supports the fact that the local environment was the dominant, if not entire, influence affecting pump performance.

Although the failures cited in this example are clearly service wear failures, there is no discernible trend for ESW PWR pumps. The single *component* age group that exhibited the highest overall relative failure rate during the 1990–1993 study was also the *plant* age group that included plant A (15–20 years.).

**MOVs**

In addition to system effects, relative failure rates for MOVs have shown performance variability based on other parameters, including valve size, valve type, and reactor type. Figure 2.21 shows that the relative failure rates varied from about 0.6 for the largest valves (≥20 in. and < 40 in.) to approximately 1.1 for valves in the smallest size range (≥2 in. and < 4 in.) during the 1993–1995 MOV study.[8] Relative failure rates for actuators (valves and actuators were examined separately in the 1993–1995 study) did not display as much variation as those for valves, ranging from about 1.1 for actuators in the ≥2-in. and < 4-in. size group to nearly 1.3 for those ≥12 in. and < 20 in. in size.

Another interesting observation is the variability in relative performance of MOVs based on valve type (gate, globe, and butterfly valves). Figure 2.22 illustrates the variation in relative failure rates by system and valve type for failures occurring from 1990 – 1992.[7] Relative failure rates ranged from greater than 2.5 for butterfly valves in the Containment Isolation system to less than 0.5 for gate valves in the HPSI system. Again, this illustrates the importance of selecting appropriate component groupings.

Studies of MOV failures during both time periods showed that reactor type (BWR vs PWR) can also have an effect on MOV failure rates. For failures examined during the 1993–1995 time period, BWR plants exhibited higher failure rates for valves than did PWRs, but PWR plants had higher failure rates for actuators than did BWRs (actuators and valves were examined separately during this study). The analysis of failures occurring from 1990–1992 (which combined valve and actuator failures) showed that BWR plants had a higher overall relative failure rate for MOVs than did PWRs. PWRs account for slightly over 60% of the total installed MOV population.

The preceding discussion and data indicate that when determining a failure rate for application to a specific component or grouping of components, for example in an IST program, it would be best to be specific in defining the component or groupings and estimating/selecting the corresponding rate based on the parameters with which its performance correlates. In practice, however, becoming too specific reduces the amount of data from which to estimate the failure rate; therefore, a balance should be achieved. Care should be used in pooling data from component populations to ensure that operational performance parameters are well matched.

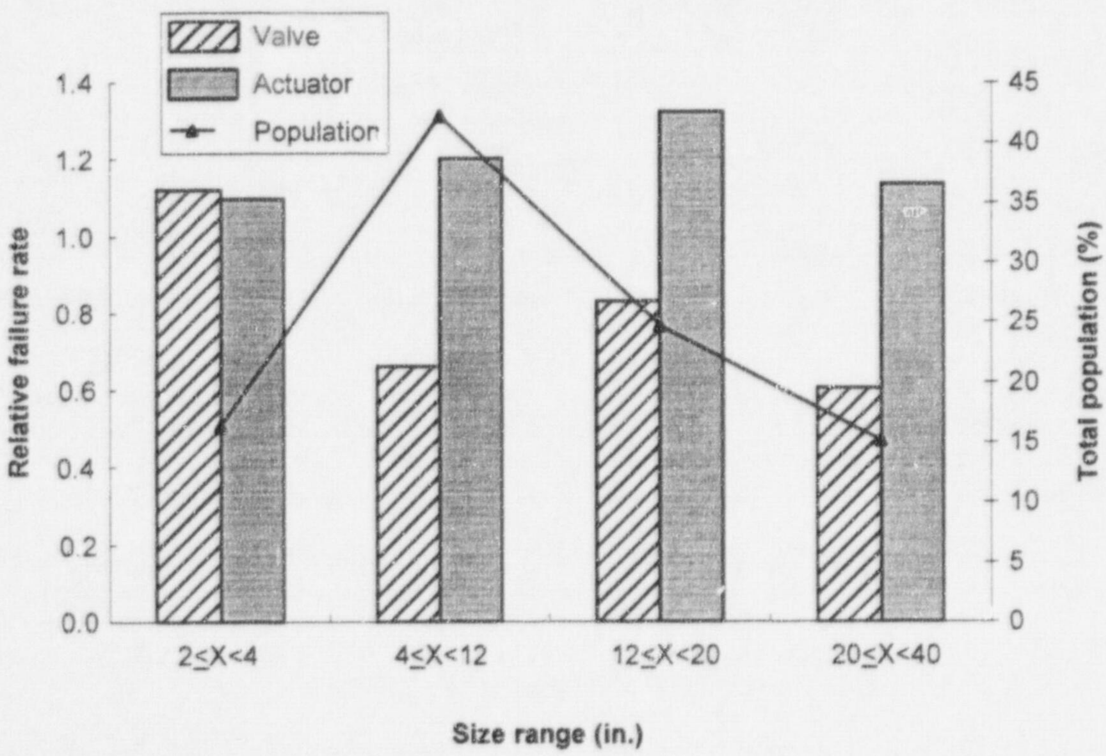



**Figure 2.21 Relative failure rates for MOVs by valve size range for 1993–1995**

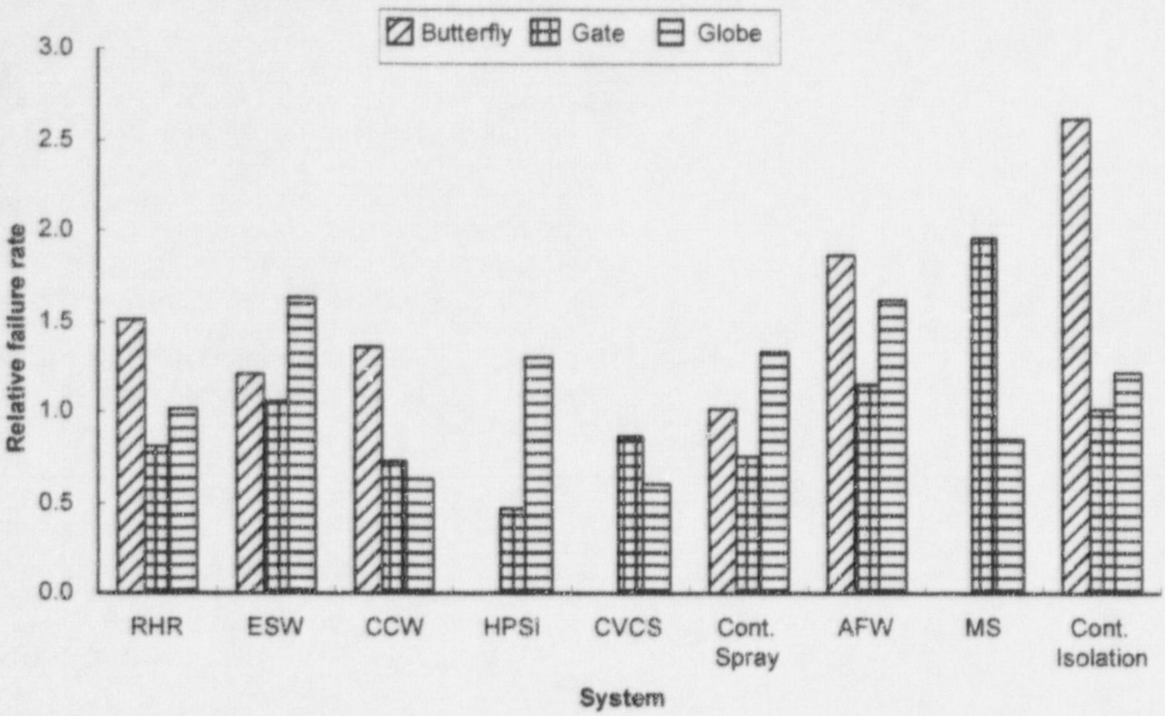



**Figure 2.22 Relative failure rates for MOVs by system and valve type for 1990–1992**

## 2.2 Summary

Table 2.6 Summarizes key points and important results from Chap. 2.

**Table 2.6 Summary of key points and results**

| Section | Key points and results |
|---|---|
| Data limitations | ❑ Available data is useful for analysis of relative performance indicators, assessing effectiveness of test and inspection requirements, and evaluating factors that affect performance.<br>❑ Available data does not allow determination of some failure causes and root causes (e.g., testing-induced failures), maintenance effects, or component margins. |
| Time dependence and failure behavior | ❑ Most failures involve a combination of factors.<br>❑ The probability of component failure does not necessarily increase with operating age.<br>▪ ORNL pump and MOV studies show no general increase in failure probability for older components with the exception of PWR pumps. |

**Table 2.6 Summary of key points and results (continued)**

| Section | Key points and results |
|---|---|
| Significant failure modes and degradation mechanisms | ❑ Degradation of internal parts and bearing failures have been shown to be the most frequent significant failure modes for pumps.<br>❑ When failures of valve, actuator, and electrical components combined were examined, dominant MOV failure modes were failure to stroke and internal leakage.<br>❑ Seat/disc wear problems were cited in many cases as MOV failure causes.<br>❑ When failures of valves and actuators were separated, failures involving the MOV actuator accounted for over 60% of the combined total. |
| Significant performance-affecting variables | ❑ Failure rates are clearly related to certain characteristics and features such as component design and service application.<br>▪ Component groupings should be considered in determination of testing, monitoring, and maintenance activities to account for correlation in performance with various parameters (e.g., system, manufacturer, valve type). |

# 3 Testing and Maintenance Practices for Pumps and MOVs

Chapter 3 provides testing and maintenance practices applicable to pumps and MOVs. Current preventive, predictive, and corrective maintenance and testing practices are discussed in Sect. 3.1, and a general assessment of their effectiveness is presented. Component margin analysis is also discussed, and the effects of maintenance on margin trending are identified. Although it is recognized that margin is not a direct indicator of component *condition*, the definition and measurement of margin for pumps and MOVs are also discussed because a margin test may generally provide some gauge of component *functionality*. The recently approved ASME Code Case OMN-1 for MOV testing is reviewed. Condition monitoring and diagnostic techniques are discussed in detail in Sect. 3.2. General guidelines for data acquisition and trending are also included.

## 3.1 Current Practices

Two of the basic elements of any program to address component operability issues are testing and maintenance. Testing activities may include failure prediction (such as diagnostic testing and condition monitoring) and performance testing (such as inservice tests and margin tests). Maintenance practices, including preventive, predictive, and corrective activities, play an important role in assuring the continued safe and reliable operation of components such as pumps and valves. Without proper maintenance, components would undoubtedly exhibit higher failure rates. Without testing, many failures would remain hidden until the component was required to operate in a demand situation.

As discussed in Sect. 1.2, there are important differences between failure prediction activities and performance testing. Diagnostic tests are usually designed to collect information that will provide some indication of component health or condition. Performance tests, on the other hand, are usually used to verify that a component has not undergone functional failure (these activities are usually considered failure detection tasks). The important point to be considered, however, is that all of these activities (failure prevention, prediction, and identification) are *complementary* to each other – each plays a part in a successful integrated component operability assurance program.

Current IST practices for pumps and MOVs are based on the requirements contained within the ASME Boiler and Pressure Vessel Code and the ASME OM Code, as discussed in the following. Other testing activities have resulted from regulatory recommendations outlined in GLs, such as GLs 89-10 and 96-05 for MOVs. Recent developments in new technologies for nonintrusive testing and diagnostics have also begun to play a key role in licensees' overall testing and maintenance programs. It is the intent of this section to discuss these practices and assess their effectiveness. Emphasis here is placed on testing activities, but because of their critical contribution to overall component performance, maintenance practices are also discussed. The complete pump and MOV *assemblies* are considered because failure of any subcomponent may lead to loss of function or operability. It is important to recognize, however, that with this broadening of scope, an increase in the base of failure modes and mechanisms is inherent, which makes it necessary to broaden the parameters (and thus available technologies) used to diagnose component assembly problems.

**Pumps**

IST is performed periodically on pumps as required by the ASME OM Code, Subsection ISTB.[16] Apart from Code testing, certain utilities and plants are taking advantage of diagnostic and monitoring technologies and techniques to predict pump failure and perform timely preventive maintenance. The more aggressive predictive maintenance programs involve major changes in equipment, procedures, and personnel qualifications. These programs may include monitoring of the following parameters:

- spectral vibration,
- ESA,
- thermography, and
- bearing oil.

In the absence of an effective predictive/preventive program, corrective maintenance, unscheduled unavailabilities, and repeat failures may result.

**MOVs**

MOV testing at most plants falls under a licensing commitment to either Section XI of the ASME Boiler and Pressure Vessel Code or the ASME OM Code, Subsection ISTC. MOV parameters subject to monitoring are the stroke time and seat leakage. IST usually occurs at pressures and flow rates that are less than those witnessed during a design-basis transient. The typical uses of an MOV are to isolate flow during design-basis conditions and in mitigating accident events. Unless the valve is normally (and successfully) operated at design-basis pressure and flow conditions, sufficient evidence will not exist as a result of testing at reduced conditions to demonstrate that the valve would close against the increased pressure or flow experienced during a design-basis event. Technologies do exist that can quantify excess capability (margin) in the valve actuator. Various diagnostic technologies are available that can measure stem thrust, actuator torque output, seating and pullout thrust, and stroke time. These devices also can acquire data that can indicate degradation within the motor before there is a subsequent loss of motor output torque. Spectral analysis of acquired waveforms can also give an indication of gear train, bearing, and seating surface wear before performance degrades to the point of failure. The use of such devices is not required by either of the above Code references.

### 3.1.1 Preventive, Predictive, and Corrective Maintenance Practices and Effectiveness

**Pumps**

This section presents an example of an effective predictive maintenance-informed pump testing program, including IST, implemented at the Palo Verde nuclear plant. This information was presented to the ASME OM Special Committee on Standards Planning in March 1998 and also presented by H. Maxwell to the OM Main Committee in June 1998. The collected pump data includes 144 data values; 83 of these are compared with two alarm values or reference standards. The types of data collected from the pump and pump driver follow:

- ten vibration measurements, providing overall amplitude;
- ten sets of five frequency-band vibration energy measurements;
- two bearing noise measurements, providing overall amplitude;
- two sets of five frequency-band bearing noise energy measurements;
- three sets of lubrication properties—total acid number (TAN), Karl Fischer Water, and kinematic viscosity;
- three sets of twenty small particle wear metal content by emission spectroscopy; and
- thermography measurements of motor termination temperature and motor switch gear temperature.

The diagnostic data obtained in the predictive maintenance testing program is broad in scope and includes the following types of data:

- spectral shapes;
- major component frequencies;
- bearing fault frequency data;
- sets of spectral trends;
- waveform shapes, modulations, impacting indications, and bearing fault symptoms;
- motor current signature (i.e., ESA);
- trending of broken rotor bars;
- lubricant condition (visual evaluation);
- trending of lubricant property data sets;
- trending of small wear particles data sets;
- analysis of lubricant chemistry using Fourier Transform infrared spectroscopy (FTIR); and
- trending of thermography data—motor termination temperature and pattern and switchgear temperature and pattern.

The testing program relies on comprehensive evaluations that lead to four condition ratings: *(1) acceptable condition, (2) condition may lead to failure or reduction in long-term reliability, (3) condition will probably lead to failure eventually (i.e., in 3 to 12 months), and (4) condition will soon lead to failure.* The last two ratings also specify the symptoms, probable causes, recommended action, and estimated time to failure.

The program was reported to have intercepted about 50 bearing failures in a recent 3-year period. The technology has matured to the point where it can detect normal bearing wear failures with up to 5% remaining bearing life at about a 90%

confidence level. Imminent failures can be detected with nearly 100% confidence. The predictive capabilities of an aggressive maintenance program such as that used at Palo Verde can be summarized for vibration, oil analysis, and thermography as shown in Table 3.1.

**MOVs**

Maintenance on MOVs, such as lapping seats, replacing packing, or replacing a motor, can significantly alter when or how often failure occurs. For example, raw MOV NPRDS failure data for 1986–1996 was examined for repeat failures that might provide some indication of component degradation over time (aging). Each component in the database was uniquely identified, and all failures for that component during the extended time period were reviewed. A review of the components with the most failures, however, indicated that the dominant cause of repeat failures was incorrect diagnosis of failure cause (e.g., a packing leak that was repaired six times before a bent valve stem was fixed). This review, as well as more detailed studies,[7,8] indicates that MOV performance is dependent upon maintenance effectiveness (among other factors) and is not generally predictable as a function of valve age.

### 3.1.2 Testing Requirements and Effectiveness

The intent of IST as required by the ASME Code for pumps and valves is to demonstrate operability as an indicator of the ability of the component to meet its design requirements at a given point in time. That is, ISTs are by design "go/no-go" performance tests that indicate component functionality; but they are generally not conducive to providing information on component health and yield very little information worth trending. ISTs are not designed, in general, to provide information about true component margin. An outstanding exception is the pump flow/head if measured at reasonable flow rates, but these measurements only address the hydraulic margin for the impeller and diffuser/volute and provide no information about margins or capabilities for other failure sites and modes (such as shaft, bearings, mechanical seals, or packing integrity). ISTs per se do nothing to renew or refurbish the component being tested (unless an unsuccessful test results in successful maintenance actions being performed). In some cases, the test activity may actually alter the component condition or induce failure (i.e., either positive or negative reliability results). For example, simply rotating standby equipment periodically is a well-recognized good practice (to provide lubricant distribution, minimize the likelihood of certain bearing problems, minimize the likelihood of corrosion binding of the rotating to stationary elements). Alternatively, certain testing techniques such as low-flow testing of standby pumps are unquestionably significant stressors because the pumps' hydraulic behaviors can adversely affect their mechanical subcomponents.

**Pumps**

The 1997 ASME OM Code[16] requires IST on certain centrifugal and positive displacement pumps that have an emergency power source. There are two main classes of pumps: *Group A* pumps are operated continuously or routinely during normal operation, and *Group B* pumps are *not* operated routinely. The testing requirements depend on whether the pumps fall into Group A or Group B, and testing for both is performed on a quarterly basis. Using instrumentation generally having a ±2% accuracy (±5% for vibration), IST is performed on Groups A and B pumps according to specified procedures. The results of these tests are compared to reference values obtained during preservice testing, which is also described in the Code.

**Table 3.1 Prediction capabilities of a preventive maintenance program (Palo Verde)**

| Technology | Failure prediction | Imminent failure prediction |
|---|---|---|
| Vibration | Detects normal wear bearing failures with up to 5% remaining bearing life at about a 90% confidence level. | Imminent failures (<1% of life) predicted with 99% confidence. |
| Lube oil analysis | Detects normal wear bearing failures with up to 10% remaining bearing life at about a 90% confidence level. | Imminent failures (<1% of life) predicted with 90% confidence. |
| Thermography | Detects electrical conditions that will lead to premature failure 75% of the time. | Detects imminent electrical failures with 90% confidence; imminent bearing failures 25% of the time. |

Group A testing requires hydraulic performance data to be recorded and compared to the reference value or reference flow rate value. Broadband vibration (displacement or velocity) data is recorded and compared to both relative and absolute criteria provided in the Code. Pump performance data that shows degradation may result in an "alert" or "required action" status. Group B pumps are tested to determine the differential pressure or flow rate, and these are compared to the reference values. No vibration data is required from Group B pumps. A comprehensive test is performed biennially for both Group A and B pumps. This test is similar to the quarterly Group A test except that no vibration test is required.

Based on a 2-year study (1994-1995),[6] Code testing of pumps revealed a number of failures involving anomalies in the internal pump components/surfaces (affecting hydraulic performance) and a small percentage of degraded or failed bearings as detected by vibration measurements. This data is summarized in Table 3.2. Analysis during a 4-year period (1990–1993)[9] showed that in 92 of 246 (37%) of the significant pump failures the affected part was a pump bearing; in 36 of 78 (46%) of the significant pump motor failures, a motor bearing was the affected part—yet the current regulatory/Code required testing finds very few bearing problems. Additional tests have been optimized since ASME Code testing came into use and are much more effective at detecting and predicting bearing failures. The detection of degradation in the pump motor, circuit breakers, and turbine drive is generally not possible using current ASME Code testing, and no other codes or standards address the testing of these subcomponents.

**MOVs**

Current IST requirements for MOVs at most plants are identified in Section XI of the ASME Boiler and Pressure Vessel Code and/or Subsection ISTC of the ASME OM Code. Code Case OMN-1 identifies alternative testing requirements; however, at this time only one plant has received permission to adopt OMN-1 for its MOV testing. Code Case OMN-1 is discussed in more detail in Sect. 3.1.3.

Current test requirements focus on two areas: stroke time and seat leakage. For valves that must meet maximum leakage requirements, seat leakage can be measured and trended to determine how rapidly a limit is being approached. However, historical failure data shows that seat leakage, which is primarily a function of valve trim degradation, is not the primary cause of MOV unavailability. Rather, an examination of failure data shows about 20% more actuator failures than valve failures.[7]

Stroke time testing does not give a clear indication of actuator degradation for valve actuators with ac motors. A degraded dc motor will run slower than normal, and thus increase the stoke time. However, regardless of the motor type, there are other areas of the actuator where subcomponent failure can cause unavailability. Examination of previous failures indicates that less than 10% of the failures are motor related. Either failure or improper setup of limit switches or torque switches accounted for approximately 30% of all failures. Current IST does not directly require testing of switch integrity, nor does it require verification of correct switch settings. Note that current requirements do not require verification of the motive force necessary to operate an MOV under design-basis conditions. Many of these deficiencies are noted in GL 89-10. ASME Code Case OMN-1 does seek to address these problems; however, use of OMN-1 is not widespread because it is not mandatory at this time.

Historical failure data shows that for MOV failures during 1990–1992, more than 60% of the total failures involved the actuator.[7] Figure 3.1 illustrates the failure distribution during this period by method of detection and failed component area. The data shows that slightly greater than one-half of the total failures were found during some type of testing activity, but nearly 30% of the total failures were discovered only under demand circumstances. Similar results were noted for failures

**Table 3.2 Effectiveness of Code testing of pumps (2-year study)**

| | PWRs | | BWRs | | PWRs and BWRs | |
|---|---|---|---|---|---|---|
| Affected area | Number of failures | Percentage of failures detected by Code-required testing | Number of failures | Percentage of failures detected by Code-required testing | Number of failures | Percentage of failures detected by Code-required testing |
| Internals | 26 | 76.5 | 9 | 64 | 35 | 73 |
| Bearing | 4 | 18 | 1 | 14 | 5 | 17 |
| Shaft/coupling/keys | 2 | 20 | 0 | 0 | 2 | 20 |

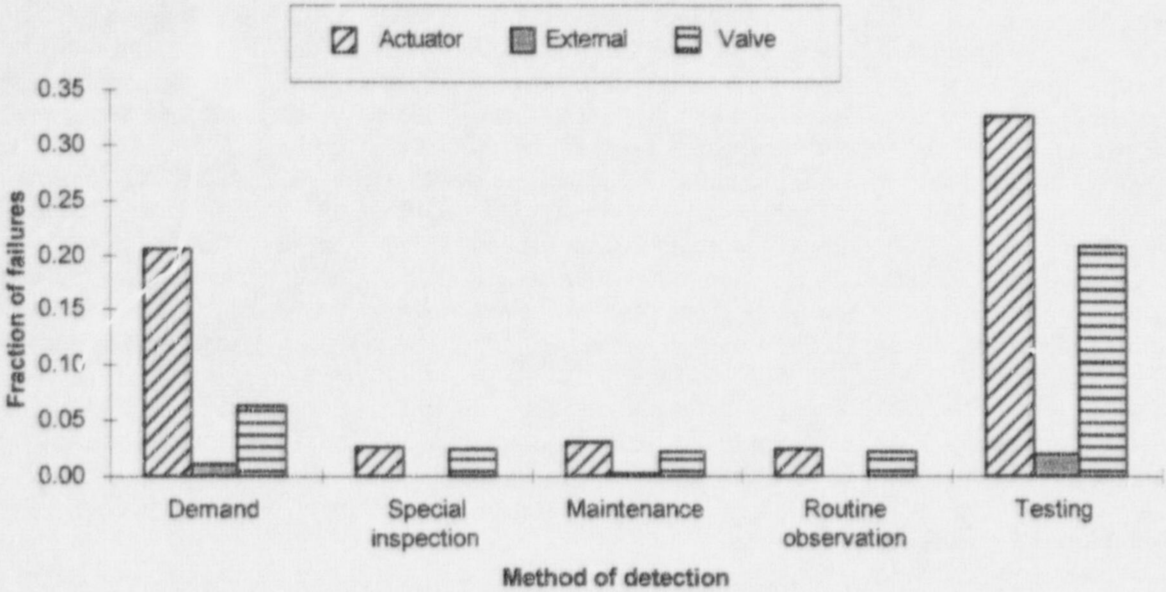



**Figure 3.1 MOV failure distribution by method of detection and failed component area for 1990-1992**

during the 1993 – 1995 analysis period.[8] Failures during the later period were analyzed by examining valves and actuators separately. For both valves and actuators during this period, about one-half of the failures were discovered during testing. Less than 30% of the valve failures were discovered under demand conditions, while more than 40% of the actuator failures went undetected until a demand situation revealed them.

**Regulatory issues related to MOV testing**

Past failures of MOVs have resulted in significant maintenance efforts and, on occasion, have led to the loss of operational readiness of safety-related systems. Since 1979, numerous NRC Information Notices (INs) and Inspection and Enforcement (IE) Bulletins have been issued and are indicative of MOV problems that have occurred during this period and the NRC's continued interest in identifying and solving these problems.

One MOV-related event, in particular, reinforced the NRC position that MOV failures can lead to a loss of critical safety system functions in a nuclear power plant. The event, described in IN 85-50, was aggravated by two motor-operated AFW gate valves that failed to reopen on demand after they were inadvertently closed.[17] This event and other related concerns prompted the NRC to issue IE Bulletin 85-03 in November 1985.[18] This bulletin required that utilities develop and implement a program to ensure that switch settings for MOVs in certain safety-related systems are selected, set, and maintained so that the MOVs will operate under design-basis conditions for the life of the plant.

In 1986, the NRC Office for Analysis and Evaluation of Operational Data (AEOD) published findings from their review of approximately 1200 MOV events that occurred from 1981 to mid-1985 and that were identified from Licensee Event Reports and NPRDS failure records. As a result of this study, AEOD concluded that

> current methods and procedures at many operating plants are not adequate to assure that valves will operate when needed. Furthermore, the deficiencies would generally not be detected by existing plant procedures intended to assure operability, such as surveillance testing (plant Technical Specifications and ASME Boiler and Pressure Vessel Code, Section XI, Inservice Testing) or plant operator observations.[19]

In February 1989, the ASME Board of Nuclear Codes and Standards decided to transfer the IST program responsibilities from Section XI to the ASME OM Committee. Valve testing requirements (defined in the ASME OM Code- Part 10, and more recently by Subsection ISTC) continue to be updated as MOV operational characteristics become more well understood. Current requirements include exercising the valve to verify obturator (e.g., disc or gate) travel to the positions required to fulfill its safety function. Confirmation of obturator movement may be by visual observation, a position indicator (if available), observation of relevant pressures in the system, or other positive means. Certain valves (e.g., those used for containment isolation) are also required to be leak tested.

All of these required tests help to demonstrate MOV operability under the prescribed conditions; however, they do not necessarily ensure valve actuation as required under other anticipated operating conditions. In addition, these tests are generally recognized to be inadequate for timely detection and trending of degradation. This understanding in part prompted the NRC to issue GL 89-10,[1] "Safety-Related Motor-Operated Valve Testing and Surveillance," which superseded the recommendations in IE Bulletin 85-03 and its supplement (issued in April 1988).[20] GL 89-10, issued in June 1989, and its seven supplements extended the scope of IE Bulletin 85-03 to include all safety-related MOVs as well as all position-changeable MOVs (capable of being mispositioned) in safety-related systems. In GL 89-10, the NRC requested that licensees ensure the capability of MOVs in safety-related systems to perform their intended functions by reviewing MOV design bases, verifying MOV switch settings initially and periodically, testing MOVs under design-basis conditions where practicable, improving evaluations of MOV failures and necessary corrective action, and trending MOV problems. The NRC requested that licensees complete the GL 89-10 program within approximately three refueling outages or five years from the issuance of the GL.

GL 89-10 lists 33 common MOV deficiencies, misadjustments, and degraded conditions discovered by utilities from their MOV testing experiences, including their efforts to comply with IE Bulletin 85-03:

1. Incorrect torque switch bypass setting
2. Incorrect torque switch setting
3. Unbalanced torque switch
4. Spring pack gap or incorrect spring pack preload
5. Incorrect stem packing tightness
6. Excessive inertia
7. Loose or tight stem-nut locknut
8. Incorrect limit switch settings
9. Stem wear
10. Bent or broken stem
11. Worn or broken gears
12. Grease problems (hardening, migration into spring pack, lack of grease, excessive grease, contamination, non-specified grease)
13. Motor insulation or rotor degradation
14. Incorrect wire size or degraded wiring
15. Disc/seat binding (includes thermal binding)
16. Water in internal parts or deterioration therefrom
17. Motor undersized (for degraded voltage conditions or other conditions)
18. Incorrect valve position indication
19. Misadjustment or failure of handwheel declutch mechanism
20. Relay problems (incorrect relays, dirt in relays, deteriorated relays, miswired relays)
21. Incorrect thermal overload switch settings
22. Worn or broken bearings
23. Broken or cracked limit switch and torque switch components
24. Missing or modified torque switch limiter plate
25. Improperly sized actuators
26. Hydraulic lockup
27. Incorrect metallic materials for gears, keys, bolts, shafts, etc.
28. Degraded voltage (within design basis)
29. Defective motor control logic
30. Excessive seating or backseating force application
31. Incorrect reassembly or adjustment after maintenance and/or testing
32. Unauthorized modifications or adjustments
33. Torque switch or limit switch binding

The majority of MOV degradations and failures identified in GL 89-10 are related to aging and service wear and inappropriate maintenance actions. Most licensees have now completed the engineering and field validation efforts recommended by GL 89-10.

In September 1996, the NRC issued GL 96-05, "Periodic Verification of Design-Basis Capability of Safety-Related Motor-Operated Valves," which requested that licensees establish programs or modify existing programs to periodically verify that safety-related MOVs can perform their intended safety function.[2] Because GL 89-10 (and its supplements) only provided limited guidance regarding periodic verification and the measures appropriate to assure preservation of MOV design-basis capability, GL 96-05 was issued to provide more complete guidance. GL 96-05 therefore superseded GL 89-10 and its supplements with regard to MOV periodic verification. Although this guidance could have been provided in a supplement to GL 89-10, the NRC prepared a new GL to allow closure of its review of licensee GL 89-10 programs as promptly as possible.

In addition to the long-term regulatory initiated efforts, an industry initiative led by the joint BWR, Westinghouse, and Combustion Engineering owners' groups is currently under way. This Joint Owners Group (JOG) has identified a relatively small number of MOVs at multiple plants that would serve as a control group for all MOVs. Instead of performing dynamic (full-flow) testing on all MOVs that can be tested, in accordance with GL 89-10 and GL 96-05, JOG recommends that dynamic testing be performed only on the small number of selected MOVs. It has been estimated that this approach would reduce the time required to full-flow test MOVs by more than 90%. The primary objective of the JOG effort is to determine how MOV stem factors change over time. Results of this study are not yet available.

### 3.1.3 ASME Code Case OMN-1

To further assess the effectiveness of MOV monitoring methods, their application requirements need to be understood. Rules for preservice and inservice testing of MOVs are contained in ASME OM Code-1995, Subsection ISTC. Recently, ASME published OM Code Case OMN-1 in a response to requests for alternative rules to assess the operational readiness of certain MOVs. The NRC has accepted OMN-1 in lieu of Subsection ISTC, other than leakage rate testing, with the stipulation that the adequacy of test intervals for every MOV be evaluated (and adjusted as necessary) during the first five years of use of this Code Case or three refueling outages, whichever is longer. OMN-1 addresses the following MOV test issues:

- test methods,
- test intervals,
- parameters to be measured and evaluated,
- acceptance criteria,
- corrective actions, and
- records requirements.

Various MOV-related measurements and calculations are specified in this Code Case. To understand these specifications requires an understanding of several terms and definitions. As these terms are first used in the following discussion, they are italicized and defined.

The focus of OMN-1 is the requirement that MOVs be tested to determine their *functional margin*. Functional margin is defined by OMN-1 as "the increment by which an MOV's available capability exceeds the capability required to operate the MOV under design-basis conditions."[15] To determine the functional margin, Section 6.4 of OMN-1 requires that "the Owner shall demonstrate that adequate margin exists between the required torque and the available torque." In this case, the torque referred to is the motor operator output torque. For a rising-stem MOV, this torque is applied to a rotating, but otherwise constrained stem nut, which in turn raises or lowers the valve stem. For the remaining discussions, monitoring methods will be discussed as they relate to this type of MOV.

The *required torque* is the motor operator output torque (stem nut torque, or "stem torque") needed to operate the valve under design-basis conditions. For a rising-stem MOV, the valve internals are repositioned by stem thrust. The conversion of stem nut torque to stem thrust is achieved by the stem nut at an efficiency determined by the thread design, stem lubrication condition, and other factors. The conversion factor between stem torque and stem thrust is called the *stem factor*. Thus,

Stem torque = (stem thrust) × (stem factor).

The *design-basis stem factor* is defined by OMN-1 as "the greatest value for stem factor expected during design-basis operation of an MOV." This value should take into account the possibility of degraded lubrication conditions that can significantly change the relationship between stem torque and stem thrust.[21]

OMN-1 provides a flowchart and an illustration of how functional margin should be determined for a rising-stem MOV. The illustration is redrawn below as Fig. 3.2. This figure shows that, according to OMN-1, the calculation of functional margin requires the following four measurements and calculations:

1. *Operator torque at design-basis motor torque* – the estimated torque that is available from the motor operator based on the motor and gear train capabilities at the design-basis conditions. OMN-1 specifies that this calculation consider several factors including rated motor start torque, minimum voltage conditions, elevated ambient temperature conditions, operator efficiency, and "other appropriate factors."

2. Available stem torque – the operator output torque measured at torque switch trip.

3. Design-basis stem factor – (see definition above).

4. Required stem torque – (see definition above).

A careful examination of Fig. 3.2 shows that three of the four required parameters are constants that have been pre-determined either through testing or by calculations (the operator torque at design-basis motor torque, the design-basis stem factor, and the required stem torque) and only one parameter is an up-to-date measurement (the available stem torque that is measured at torque switch trip).

As previously mentioned, a rising-stem valve is actuated by stem force, not stem torque. Because by definition, the functional margin is the increment by which an MOV's available capability exceeds the capability required to operate the MOV under design-basis conditions, it stands to reason that the valve actuation requirements should be defined and measured in units of stem thrust, not stem torque.

By relying on torque measurements (converted to thrust via the design-basis stem factor) rather than thrust measurements directly, OMN-1 functional margin is always verified under the assumption that the actual stem factor never exceeds the design-basis stem factor. If torque and thrust are not both simultaneously measured, the actual stem factor cannot be determined to prove that it is not greater than the design-basis stem factor. The possibility therefore exists that if the actual stem factor were greater than the design-basis stem factor, insufficient thrust would be delivered to the valve under design-basis conditions, even though the torque-based functional margin was acceptable.

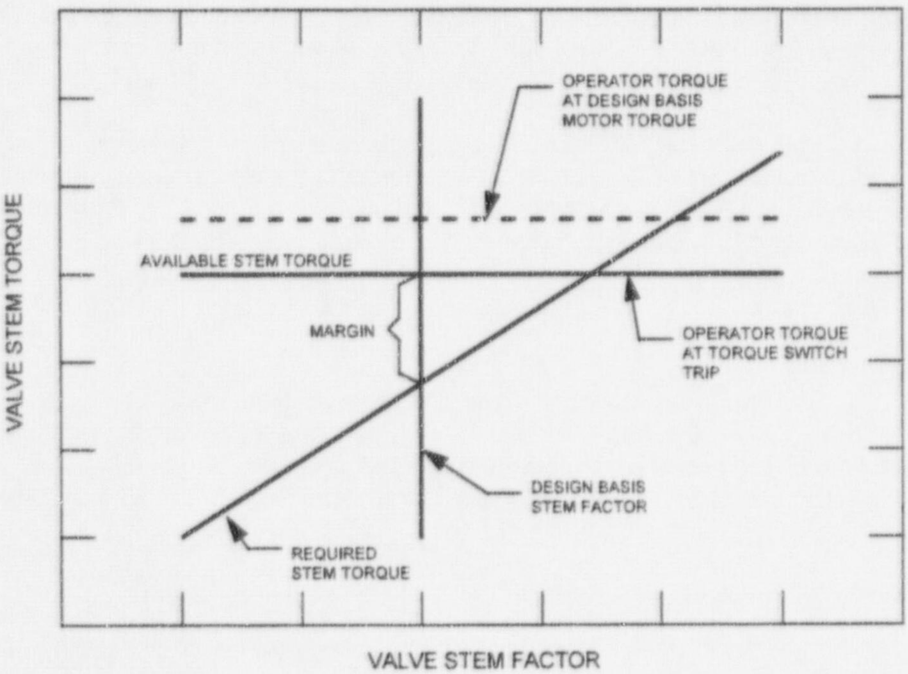



**Figure 3.2 OMN-1 recommendation for calculating functional margin for a rising stem MOV.** Redrawn from ASME Code Case OMN-1 (Fig. 6.4-2). *Reprinted from ASME OM Code-1995, by permission of the American Society of Mechanical Engineers. All rights reserved.*

While OMN-1 primarily specifies how MOVs are to be performance tested, it recognizes that time-related changes in performance may occur. Two illustrations are provided in OMN-1 to show how functional margin can decrease as a result of one or more of the following changes:

1. A decrease in the operator torque at design-basis motor torque
2. A decrease in the available stem torque
3. An increase in the design-basis stem factor
4. An increase in the required stem torque

These illustrations have been redrawn for this document and are shown in Figs. 3.3 and 3.4. Figure 3.4 shows how the margin vs time curve can be extrapolated to predict when the margin would fall below the acceptable limit. This approach may be too simplistic and does not take into account the sudden loss in margin and MOV functionality due to degradations that do not directly impact the OMN-1 margin measurement. Table 3.3 includes the GL 89-10 list of MOV concerns and indicates whether each item can directly affect the available stem torque during valve closure. As shown in this table, degradation in at least 13 of these items could go undetected if only the available stem torque were measured.

These observations suggest that the MOV performance tests as prescribed by OMN-1 should be supplemented by additional diagnostic testing and, if necessary, visual inspections to provide assurance that *all* MOV drivetrain elements (motor, gears, linkages, etc.) are in good condition. Diagnostic tests should be designed to provide data that can be directly related to subcomponent condition and trended over time to identify and address potential problems in their early stages before they threaten the operability of the MOV.

Section 3.1.4.1 of this report provides a discussion of true engineering margin as defined for pumps and MOVs.

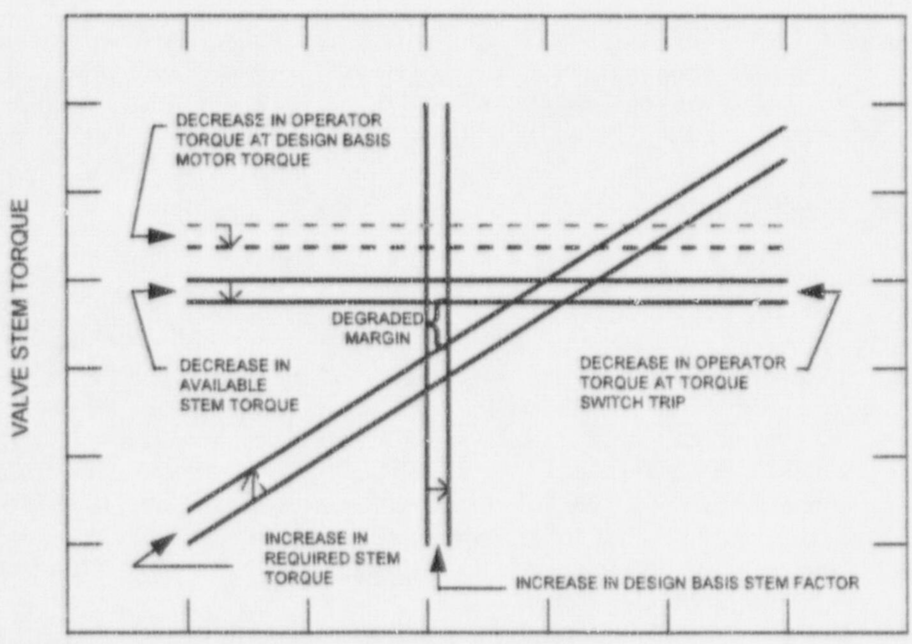



**Figure 3.3** **OMN-1 decrease in functional margin for a rising stem MOV.** Redrawn from ASME Code Case OMN-1 (Fig. 6.4-3). *Reprinted from ASME OM Code-1995, by permission of the American Society of Mechanical Engineers. All rights reserved.*

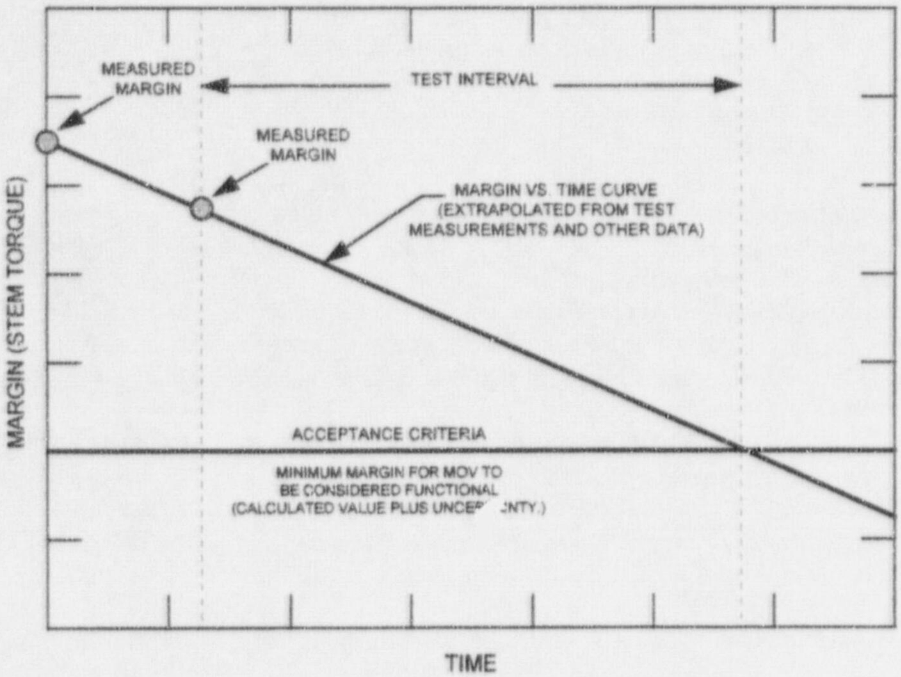



**Figure 3.4** **Determination of test intervals for maintaining MOV functional margin according to OMN-1.** Redrawn from ASME Code Case OMN-1 (Fig. 6.6-4). *Reprinted from ASME OM Code-1995, by permission of the American Society of Mechanical Engineers. All rights reserved*

## 3.1.4 Component Margin Analysis

### 3.1.4.1 Definition and Measurement of Margin for Pumps and MOVs

The *true engineering margin* for any component can be defined in terms of capability (the level of performance that the component can achieve) and requirement (the minimum acceptable level of performance). Figure 3.5 shows this relationship in the form of a difference (the margin is shown as the difference between capability and requirement). If a functional failure is defined as the inability of a component to fulfill a function to a desired acceptance criterion, then in terms of the component's margin, a functional failure has occurred when the capability drops below the requirement (margin is less than zero). This definition does not mean that a complete loss of function has necessarily occurred (such as if a component were completely unable to operate), but that the desired level of performance cannot be achieved. Margin may also be defined as the ratio of the capability to the requirement; in this case, a functional failure has occurred when this ratio becomes unity.

To understand true component margin, the parameters that define capability, such as valve stem thrust, need to be measurable. The functional requirement needs to be known (measured or calculated) and either assumed or known to remain unchanged. It is also important that design-basis margin adequacy issues (e.g., that a valve is capable of developing a required level of output thrust or torque to meet some design-basis criterion) and component operability issues (e.g., component condition) not be confused. The requirement to verify the design basis of a pump or valve is to assure the functional operation of the component up to the design basis at that time and is not directly intended to assess the effects of future time, service, or environment on the progressive deterioration of the component. Also, the parameters monitored to indicate the design-basis performance may not necessarily be the same as those best suited to monitor progressive deterioration of performance. Typically, there is not the intent in design-basis performance testing to derive information about future performance (condition).

Table 3.3 MOV concerns from GL 89-10 and their impact on functional margin as defined by OMN-1

| Concern | Impacts the available stem torque? |
|---|---|
| Incorrect torque switch bypass setting | No |
| Too little or too much seating force | Maybe – Too little or too much seating force may result from an incorrect torque switch setting and thus would affect the available stem torque; however, if the stem thrust discrepancy results from a change in the stem factor, the stem torque is not affected. |
| Too much backseating force due to incorrect torque switch setting | No |
| Unbalanced torque switch | Yes |
| Spring pack gap or incorrect spring pack preload | Yes |
| Incorrect stem packing tightness | No |
| Excessive inertia | Yes |
| Loose stem nut locknut | Maybe – may allow premature torque switch trip on opening. |
| Incorrect limit switch settings | Maybe – If the limit switch rather than the torque switch is wired to trip the motor, any variation in the switch setting would change the stem torque. |
| Stem wear | No |
| Bent or broken stem | No |
| Worn or broken gears | Maybe – Assuming that the gears are just worn (degraded MOV), and not broken (failed MOV), excessive loads may be sensed by the motor due to the worn gears and not sensed by the torque switch. This condition may lead to the motor stalling before the torque switch trips. |

Table 3.3 MOV concerns from GL 89-10 and their impact on functional margin as defined by OMN-1 (continued)

| Concern | Impacts the available stem torque |
|---|---|
| Grease problems (hardening, migration into spring pack, lack of grease, excessive grease, contamination, non-specified grease) | Maybe – Grease migration into the spring pack can affect the stem torque. Absence of lubrication in the worm-to-worm gear interface can result in excessive motor loads (also see "Worn or broken gears.") |
| Motor insulation or rotor degradation | No |
| Incorrect wire size or degraded wiring | Yes, for dc motors. Maybe, for ac motors (could degrade voltage or increase current to compensate for voltage drop, and trip breakers). |
| Disc/seat binding (includes thermal binding) | No |
| Valve seat degradation | No |
| Water in internal parts or deterioration therefrom | Maybe – Water may affect the torque switch operation. |
| Motor undersized (for degraded voltage conditions or other conditions) | Yes – Assuming that this condition is recognized. |
| Incorrect valve position indication | No |
| Misadjustment or failure of handwheel declutch mechanism | Maybe[a] |
| Relay problems (incorrect relays, dirt in relays, deteriorated relays, miswired relays) | Maybe[a] |
| Incorrect thermal overload switch settings | Maybe[a] |
| Worn or broken bearings | Maybe – If the drive sleeve bearings are damaged, the stem torque can be affected. |
| Broken or cracked limit switch and torque switch components | Maybe[a] |

Table 3.3 MOV concerns from GL 89-10 and their impact on functional margin as defined by GMN-1 (continued)

| Concern | Impacts the available stem torque? |
|---|---|
| Missing or modified torque switch limiter plate (resulting in incorrect torque switch setting) | Yes |
| Improperly sized actuators | Yes – Assuming that this condition is recognized. |
| Hydraulic lockup | No |
| Incorrect metallic materials for gears, keys, bolts, shafts, etc. | No – This would not be detected unless a failure of this item has occurred. |
| Degraded voltage (within design basis) | No – This would not be detected unless the motor has stalled before the torque switch has tripped. |
| Defective motor control logic | Maybe[a] |
| Change in system mechanical clearances | Maybe – The location(s) of the changed clearances will dictate whether the stem torque would be affected. |
| Incorrect reassembly or adjustment after maintenance and/or testing | Maybe – The location(s) of the incorrectly assembled part(s) will dictate whether the stem torque would be affected. |
| Unauthorized modifications or adjustments | Maybe – The location(s) of the modifications or adjustments will dictate whether the stem torque would be affected. |
| Torque switch or limit switch binding | Yes |
| Stem taper in packing region | No |

[a] Stem torque would be affected only if the MOV fails to operate because of a complete failure of this item.

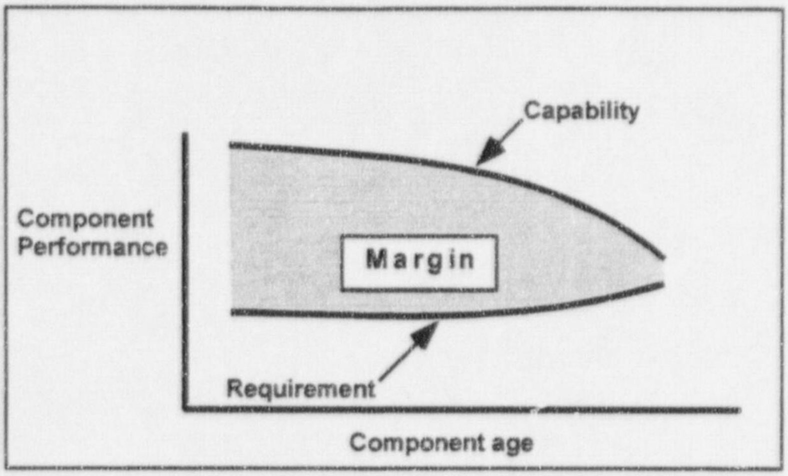



**Figure 3.5 General definition of component margin**

**Pumps**

In determining margins for pumps, the capability can be determined by measuring pressure and flow (i.e., hydraulic performance). This is measured along with vibration data in the periodic ASME Code testing of pumps. The pump hydraulic *requirement* would be defined specifically for each pump application. If significant pipe lengths are involved, the test should attempt to encompass more of the pump system (assembly) by making hydraulic measurements (pressure) that encompass as much of the fluid system as possible. The pump performance requirement used in determining margin can be derived from the design-basis requirement for the pump. If there is no such requirement, the standard design requirement may be used. The hydraulic requirement generally will closely match the actual capability of the pump (i.e., small margin). In cases where the margin of a pump system is low, the resolution of the margin may be compromised (because of difficulties in resolving a performance point of capability within such a small band). The measurement should be precise so that a pump does not fail the test because of the inaccuracies of the test instrumentation. The testing of hydraulic capability may be performed during ASME Code testing of the pump or in an IST performed especially for that purpose. Hydraulic performance does have potential for trending because pump performance can gradually deteriorate as a result of many causes, including (1) the accumulation of foreign deposits on the impeller and other internal surfaces, (2) abrasion of the wear ring with increased recirculating flow, and (3) rotating and stationary part erosion/fractures.

In a limited sense, vibration data collected during surveillance testing may be useful in assessing remaining bearing life because high levels of vibration, from whatever cause, are known to shorten life. However, bearing life analysis would not be related to the testing of margins because the capability and requirement of the bearing cannot be established/measured, and elevated vibration levels should not impair the pump capability or performance in any definable way. Further, the current Code requirements for vibration monitoring are simply for overall vibration amplitude; critical bearing indicators normally account for only a very small part of the overall amplitude. Because very effective monitoring technologies and programs for testing and predicting bearing life have been fully demonstrated in predictive maintenance programs, state-of-the-art monitoring is highly preferable to any attempt to apply the concept of margins to bearing life analysis.

The potential for obtaining useful and trendable margin data for pump motors is deemed to be low. The greatest potential (considering trending and not margin), based on the more frequent types of motor failures, includes deterioration of stator insulation and/or shorting of stator windings. Historically, stator failures have been considered to be sudden occurrences; however, this observation or perception may be caused by a lack of diagnostic testing or monitoring. As discussed in a recent ORNL pump diagnostics report,[10] the use of stator tests such as inductive imbalance, insulation resistance (megger tests), polarization index, and high potential tests may make trending possible. However, margin analysis would require a motor *requirement* for operating the pump and a measurement of motor *capability*. The shorting of a few stator windings may be the only measurable and trendable degradation that might affect motor capability and thus margin. Because this degradation comprises undoubtedly a small percentage of motor failures, it is not a promising application for margin analysis.

The pump turbine drive has a requirement to drive the pump under design-basis event conditions. Although it might be practical to formally establish such a requirement for each turbine drive application, it would be difficult to justify testing the turbine drives for capability. The configuration for testing over a wide range of pumping conditions would be difficult or impossible to attain in many system applications, and the potential benefits would not be clear. The benefits are in doubt because certain age-induced degradation in turbines is *due* to repeated testing. Moreover, many types of degradation in turbine components are not manifested by compromised performance of the turbine. Generally the turbine will either perform as required (i.e., with worn or otherwise degraded components), or it will not; this has been adequately demonstrated in surveillance testing apart from margin analysis or trending studies. Discovering gradually degraded capability would be the exception (i.e., infrequent and isolated cases). Data studies show that a worn linkage, a loose screw, a marginal adjustment, or a certain level of corrosion in the governor either will not impair operation significantly, or it will cause gross operational problems (e.g., wildly fluctuating speed, overspeed, a trip).

Circuit breakers, like turbine drives, fail due to diverse problems involving a wide range of components, and failures tend to be severe (70% are classified as severe based on 1994 and 1995 data).[6] Margin measurement may not be practical because, in assessing capability, there cannot be partial closings, partial charging of springs, partial failures to trip, or partially spurious trips. Almost all essential functions in circuit breakers are discrete, sudden, and well-defined operations. If there is any opportunity for margin testing, it would involve timing certain operations (e.g., spring charging) or making certain electrical measurements (e.g., current to relays, solenoids, and the motor) to determine if current during certain operations is changing significantly. Monitoring voltage to certain contacts and switches may identify arcing. These operations relate more closely to condition monitoring than to margin because the *capability* of the circuit breaker would not be compromised in the normal sense.

In summary, pump system margin may be determined by several diverse parameters, especially if proper emphasis is given to encompassing as much of the total pump system as possible and if innovative methodologies are developed to relate certain qualitative observations and indirect performance measures to the assessment of capability. Degraded motor operation (i.e., reduced torque/speed), incorrect turbine speed (for turbine-driven pumps), and failure of the breaker to operate may be encountered in the testing, and these types of problems will generally either prevent the test or so severely threaten continued pump operation that a total loss of capability should be assumed. The key requirement, whether it be flow, head, or some combination of the two, should be tested for, and the appropriate data collected to facilitate the calculation of margin. The margin test report should record pertinent test conditions and include known maintenance activities or other special conditions that may have affected the test results.

**MOVs**

For MOVs, capability should be defined as the ability of the actuator to move the valve obturator (disc, plug, etc.) to the safety-related position when required. For valves for which the closure element moves linearly (e.g., gate or globe), capability should be measured in pounds of thrust. For valves for which the closure element rotates to isolate flow, such as butterfly or plug valves, the capability should be measured in terms of torque. Valves that require linear travel for closure comprise the largest portion of the population. Note that capability should include more than the creation of output torque at the actuator. Valve actuators produce torque, not thrust, as is the case for air-operated valves. For gate and globe valves there should be a conversion of torque to thrust, and any discussion of capability should also consider the losses during that conversion. Figure 3.6 shows those areas of the valve where losses may change and thus affect margin. Previous studies provide a more detailed description of valve actuator operation.[21,22]

Time dependent changes in margin (aging) may occur in the drivetrain of MOVs. The ability to apply force to the valve stem to open or close a valve quite often degrades with time due to wear of drivetrain components. The components directly involved with the production of motive force, either torque or thrust, include the motor, gear train, stem, and stem nut. If the motor degrades to the point that output torque is reduced, or frictional losses are increased in either the gear train or stem-to-stem-nut connection, then margin may be reduced. However, margin is not the only component to be considered when addressing component availability relative to time dependent degradation of components. Limit switches and torque switches play a critical role in the function of MOVs; however, failure of these components is typically not gradual or trendable. While the wear that contributes to switch failure may be time dependent, the resulting failure may be immediate and unexpected because the condition of the switch itself is not monitored.

As previously discussed, MOVs are actually small assemblies or systems of subcomponents, each with their own failure characteristics. In addition to the valve and actuator, the availability of electrical power to operate the MOV is also critical to availability. Supply power is typically interrupted either through circuit breakers, thermal overloads, or motor starters. All of these components are external to the MOV and are not usually subject to margin testing. Performance of all subcomponents, therefore, is not necessarily trended.

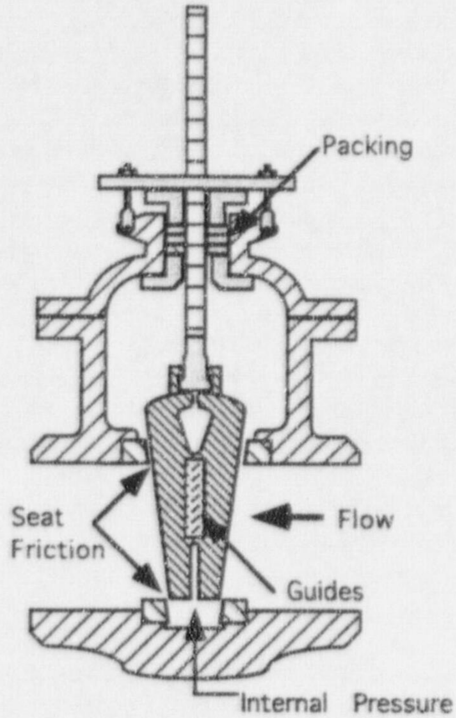



**Figure 3.6 Valve interfaces that can affect margin**

In general terms, a successful performance test cannot by itself guarantee that significant equipment degradation is not present (i.e., the presence of "margin" does not necessarily ensure availability). If the location of the degradation is such that it does not impact the performance parameter being measured, the degradation may go undetected by the performance test and may subsequently lead to an unexpected functional failure. For example, a successful margin test, as prescribed by OMN-1 (see Sect. 3.1.3) can confirm that the MOV motor and gear train can together deliver the desired torque to the stem nut, but it cannot identify degradation in these areas, as long as sufficient torque is still delivered to trip the torque switch. In this case, the true MOV capability is limited (hidden) by the torque switch. If the degradation has increased to the point where not enough torque is delivered to the stem nut and the torque switch does not trip the motor, the motor may stall and is at risk of failing catastrophically (if not adequately protected by a thermal overload device). This case is illustrated graphically in Fig. 3.7.

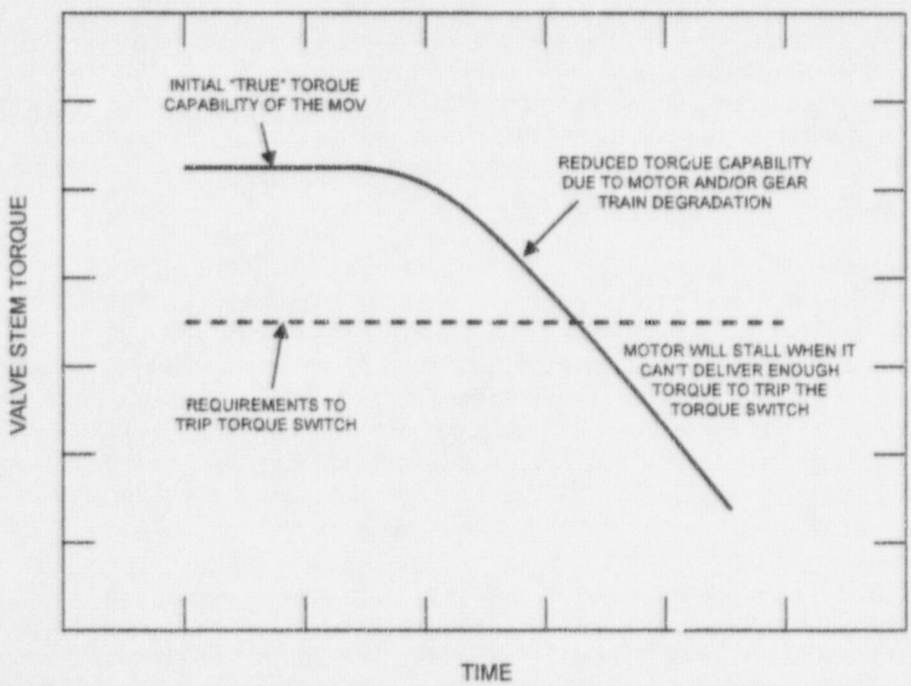



**Figure 3.7 Potential MOV degradation not necessarily evident from a successful margin test**

As applied to MOVs, margin analysis is both necessary yet incomplete in predicting the availability of the component for safety-related service. Even if adequate torque or thrust is provided, a failure of the limit switch, torque switch, or circuit breaker could still render the component unavailable. Because some subcomponents can fail without warning, the presence of "adequate" margin is not necessarily indicative of reliable operation. True component margin should not be confused with margin as determined by the comparison of torque switch trip measurement with other predetermined constants (i.e., the operator torque at design-basis motor torque, the design-basis stem factor, and the required stem torque) as outlined in ASME Code Case OMN-1. Trending data obtained in this fashion provides very little information on actual changes that may be occurring with true component margin other than those possibly related to the condition of the torque switch itself.

#### 3.1.4.2 Maintenance Effects on Margin Trending

**Pumps**

Maintenance and operations activities can affect margin testing of pumps to varying degrees. Obvious examples are actual servicing of the pump (e.g., clean/replace impeller, replace wear rings, remove deposits from internal surfaces) or replacement of bearings. Although the test engineer should be aware of these activities, the following are other less obvious activities that may affect margin trending:

- Changes made to suction and/or discharge piping or valves. For example, a change that does little more than change the binding force transmitted by the piping to the pump could change the shaft alignment and vibration levels.
- Shaft realignment, loosening and tightening mounting bolt, adjusting coupler/key, etc.
- Cleaning of suction screen.

**MOVs**

Maintenance and operations activities can also affect margin testing of MOVs in a variety of ways. Because the actuator stem nut is the interface at which actuator torque is translated to valve stem thrust, the quality of stem lubrication can have a significant impact on delivered thrust. Stroking the valve before testing can redistribute stem lubrication in a manner that may degrade lubrication; however, this may also break the adhesion of valve packing to the valve stem, making subsequent valve strokes easier. Likewise, maintenance actions such as spring pack replacement, torque switch adjustment, and stem lubrication can affect the outcome of margin testing.

## 3.2 Diagnostic and Monitoring Techniques

### 3.2.1 Background

Equipment condition can often be inferred from a careful measurement and analysis of electrical signals from transducers that detect changes in equipment behavior, once the relationship between these signals and actual equipment condition is known. Likewise, equipment performance can be measured by various means and compared against predetermined acceptance criteria. To effectively monitor equipment condition and performance, test parameters should be established based on a thorough understanding of the objective(s) of the tests, the capabilities and limitations of the chosen monitoring method(s), and the skill of the individuals acquiring and analyzing the test data.

The ultimate capabilities of a particular monitoring method are determined by the interaction of many factors such as sensor type and placement, signal conditioning parameters (e.g., amplification and filtering), and the capabilities of the data acquisition system (e.g., measurement precision and sample rate). The data analysis methodologies should be well understood, proven, and compatible with the data acquired. Also, all monitoring methods have inherent limitations that should be observed to prevent the extrapolation of test results beyond the method's capabilities.

### 3.2.2 Diagnostic Testing vs Performance Testing

Important differences exist between diagnostic testing (e.g., condition monitoring ) and performance testing (e.g., ISTs and margin tests). The objectives of a performance test are usually based on a need to verify that equipment operations are "within specification" and/or within acceptable limits. A successful performance test verifies that the tested equipment can meet the required performance levels. An unsuccessful outcome demonstrates that the equipment in its present state cannot perform up to expectations (i.e., has experienced functional failure).

The primary purpose of a diagnostic test is to gather information that, if correctly interpreted, can help to diagnose the general condition of the monitored equipment. When performing a diagnostic test, one or more equipment parameters are monitored, using sensitive transducers located at key points on the equipment. Using a variety of techniques, specific features (condition indicators) can be identified in the transducer signals that reflect the operational characteristics of the monitored equipment. For example, a time waveform (signal magnitude vs time) and a frequency spectrum (signal magnitude vs frequency) are two types of "signatures" that contain important equipment condition indicators that can be relatively easy to interpret.

While an unsuccessful performance test can identify equipment that is not set up correctly (e.g., incorrect limit or torque switch settings on an MOV or high vibration due to pump shaft misalignment), it may also provide strong indications that the equipment is operating in a degraded state and is in need of maintenance or replacement. Unfortunately, even a successful performance test cannot by itself guarantee that significant equipment degradation is not present. If the location of the degradation is such that it does not impact the performance parameter being measured, the degradation may go undetected by the performance test and may subsequently lead to an unexpected functional failure.

To illustrate this point, imagine that it is important to determine an automobile's performance from the standpoint of how well it transports a person to work and back home every day. To determine this, certain measurements can be made such as the automobile's top speed on the highway and the travel time to and from work. These measurements can be affected by several factors such as the road conditions, the number of cars traveling on the same highway, the traffic light sequences, and the delays due to other vehicle accidents. If the travel time is measured every trip, an average time can be computed and used as a measure of performance. For example, assume that the average commute takes 30 minutes. Furthermore, assume that, even under the worst road conditions and traffic, a one-way trip should never exceed 45 minutes. Since the travel time has not yet reached or exceeded this "worst case" time, the driver has concluded that the commute will always take less than 45 minutes and feels secure in scheduling early morning events based on this record.

One day on the way to work to an important early morning meeting, the right front tire, which had not been inspected for more than 2 years, suddenly and catastrophically blew out, due to poor tread condition. Unfortunately, the spare tire had been equally neglected and had lost all its air pressure due to a slow valve stem leak. The trip to work ultimately took much longer than 45 minutes due to the unexpected failures, and the meeting was missed. In this hypothetical example, the performance parameter (travel time) did not provide the sensitivity needed to detect and monitor the condition of a vital subcomponent (the tires); that failure ultimately triggered the functional failure of the automobile.

This illustration underscores the importance of identifying potential failure modes and monitoring the condition of key subcomponents that can degrade over time and prevent the equipment from functioning. In retrospect, if the condition of the automobile's tires (including the spare tire) had been periodically checked, the sudden, unexpected failure of the automobile could have been prevented.

### 3.2.3 MOV Monitoring Techniques

ORNL has prepared two reports that together provide a comprehensive assessment of MOV monitoring methods.[21,22] These reports describe a variety of techniques sensitive to MOV degradations and defects that can adversely affect MOV performance and operational readiness. In addition to illustrating how these methods can detect service wear and switch mis-settings, these reports also discuss the importance of MOV data acquisition in general, with emphasis on data acquisition parameters such as signal conditioning, data precision, and sample rate. Review of these reports is encouraged to develop an understanding and an appreciation for the many elements of MOV performance and diagnostic testing. Appendix A of this report contains a detailed discussion of a component diagnostic technique known as signature analysis. Specific examples of this technique applied to MOVs are included, and the capabilities of signature analysis in detecting several MOV abnormalities are discussed.

An MOV is often thought of as a single component, but it should more realistically be treated as a small-scale assembly or system with controls that govern its performance. The MOV torque switch ultimately controls the maximum torque output of the motor operator. It "senses" the resistance to turning the worm gear and thus "feels" the worm gear, drive sleeve, stem nut, stem, stem packing, and valve loads associated with their operation. The reaction of the torque switch to these loads is restrained by the spring pack; due to its preloaded state, it prevents the torque switch from responding until the running loads transmitted to the torque switch exceed the preload. After the preload is exceeded, the torque switch becomes a sensitive transducer for monitoring the mechanical running loads in the areas described above. However, due to its position in the drivetrain, it cannot sense normal or abnormal running loads present within the motor operator between the motor and the worm gear. Degradation in this region can go undetected by a performance test based on operator torque and/or stem thrust measurements. Fortunately, running loads in this region and throughout the MOV can be sensed by many techniques. For example, MOV seating and unseating transients can usually be measured using time waveforms derived from motor current, spring pack compression, and valve stem thrust signals. More subtle periodic events such as gear meshing and motor speed are better suited for detection and monitoring using the frequency spectra of motor current and actuator vibration signals.

The condition of various subcomponents within an MOV can be directly determined through a careful measurement of one or more relevant signature features (e.g., magnitude, frequency, time of occurrence) as long as there are established relationships between each feature and the condition of the specific subcomponent.

In June 1989, the NRC issued GL 89-10, "Safety-Related Motor-Operated Valve Testing and Surveillance."[1] Included in this GL was a list of 33 common MOV deficiencies, misadjustments, and degraded conditions that had been discovered by utilities. Table 3.4 lists these concerns and indicates whether they may be aging-related. In addition, measurable parameters are identified that are sensitive to these problems, and their effectiveness is assessed. The effectiveness ratings shown in Table 3.4 are most often shown as ranges because the magnitude (severity) and specific location of several MOV concerns are not clearly defined. For example, "worn or broken gears" may be detectable using vibration and/or motor current/power data, but how well it can be detected will be largely determined by how worn the gears are and what gears are involved.

A thorough understanding of the inherit strengths and weaknesses of MOV monitoring methods is essential to assure that they are utilized within their inherent limitations. Commercially available diagnostic systems employ sensors that can detect changes in one or more measurable parameters and display the results in several ways, including time traces, frequency displays, and other graphs that facilitate data analysis. Several parameters are available for monitoring, each of which may be trended over time. While a detailed discussion of MOV monitoring methods is beyond the scope of this document, a short description of available techniques is provided in the following. Previous ORNL reports may provide additional information.[21-23]

MOV measurable parameters include

- valve stem thrust;
- switch continuity (limit, torque, torque bypass);
- motor current, voltage, and power;
- spring pack compression, torque switch shaft angular position;
- valve stem position; and
- vibration.

Valve stem thrust may be sensed by a strain gage mounted on the valve yoke, in a mounting bolt, or on the stem itself. Depending on where the strain gage is installed, the parameter measured may directly reflect the stem thrust or may measure the reaction force between mechanically connected structures. For example, when the valve stem is in compression during valve seating, the reaction forces in the yoke and in mounting bolts will be in the opposite sense (tension). When measuring stem thrust via strain gages installed in locations other than the valve stem, the distribution of the reaction forces should be clearly understood. For example, if the reaction loads are not equally distributed on every support bolt, a stem thrust measurement from a single strain-gage bolt may provide misleading results.

Switch continuity can be easily monitored via clip-on resistance (impedance) measurement systems. A completed circuit should produce a low impedance measurement, while an open circuit should produce an extremely large (infinite) impedance. For some MOVs, control switch (limit, torque, torque bypass) status can be indirectly inferred remotely from the MOV indicator lamp status.

Motor current, voltage, and power can be monitored remotely from the MOV at the motor control center (MCC) using clamp-on or clip-on sensors. The motor inherently acts as a preinstalled MOV sensor that provides the sensitivity and selectivity necessary to detect electrical and mechanical characteristics of an operating MOV. Because of the remote monitoring capability and sensitivity to operational characteristics throughout the entire MOV, motor electrical parameter monitoring can be useful in periodically verifying the operational condition of a MOV. Quantitative results are possible (in units of amps, volts, watts), and they can also be trended over time. Because the MOV sensor is the motor, no inconsistencies can arise from sensor installation or placement as in other MOV-mounted sensors. Motor electrical

**Table 3.4 Motor-operated gate valve concerns from GL 89-10 and the estimated effectiveness of testing parameters**

| GL 89-10 concern | Related to aging<br>* - see comments | Testing parameters[a] | Estimated effectiveness[b] | Comments |
|---|---|---|---|---|
| Incorrect torque switch bypass setting | No | AB,CB,DB | High | |
| Incorrect torque switch setting | Yes* | ABD | High | Valve and/or operator aging (degradation) may result in the MOV requiring a change in the torque switch setting. |
| Unbalanced torque switch | Yes | AD | Medium-High | |
| Spring pack gap or incorrect spring pack preload | Yes | AD | Medium-High | |
| Incorrect stem packing tightness | Yes* | A,C,D | Medium-High | Over time, external leakage caused by packing deterioration or wear may require adjustments in packing tightness. |
| Excessive inertia | No | AC,AB | High | |
| Loose or tight stem nut locknut | Yes | A,C,D | Medium-High | |
| Incorrect limit switch settings | No | BE | High | |
| Stem wear | Yes | A,C,D | Medium-High | |
| Bent or broken stem | Yes | A,C,D | Medium-High | |
| Worn or broken gears | Yes | C,F | Medium-High | |
| Grease problems (hardening, migration into spring pack, lack of grease, excessive grease, contamination, non-specified grease) | Yes | A,C,D,F | Low-High | |

Table 3.4 Motor-operated gate valve concerns from GL 89-10 and the estimated effectiveness of testing parameters (continued)

| GL 89-10 concern | Related to aging<br>* - see comments | Testing parameters[a] | Estimated effectiveness[b] | Comments |
|---|---|---|---|---|
| Motor insulation or rotor degradation | Yes | C | Medium-High | |
| Incorrect wire size or degraded wiring | Yes* | C | Low-Medium | Wiring may degrade over time. |
| Disc/seat binding (includes thermal binding) | Yes | A,C,D | Medium-High | |
| Water in internal parts or deterioration therefrom | Yes | C,F | Low-Medium | |
| Motor undersized (for degraded voltage conditions or other conditions) | Yes* | AC | Medium-High | Motor degradation can result in reduced torque output capabilities, which can effectively "undersize" the motor relative to its expected output. |
| Incorrect valve position indication | Yes* | E | High | Over time, valve position indicator gearing may degrade as all gears can. |
| Misadjustment or failure of handwheel declutch mechanism | Yes* | -- | -- | Over time, the handwheel declutch mechanism can wear with continued use. |
| Relay problems (incorrect relays, dirt in relays, deteriorated relays, miswired relays) | Yes* | C | Low-High | Relays may deteriorate over time. |
| Incorrect thermal overload switch settings | No | C | Low-High | |
| Worn or broken bearings | Yes | F,FC | Medium-High | |

Table 3.4 Motor-operated gate valve concerns from GL 89-10 and the estimated effectiveness of testing parameters (continued)

| GL 89-10 concern | Related to aging<br>* - see comments | Testing parameters[a] | Estimated effectiveness[b] | Comments |
|---|---|---|---|---|
| Broken or cracked limit switch and torque switch components | Yes | -- | -- | |
| Missing or modified torque switch limiter plate | No | DB | Medium-High | |
| Improperly sized actuators | No | ABD | Medium-High | |
| Hydraulic lockup | No | AE,CE | Medium-High | |
| Incorrect metallic materials for gears, keys, bolts, shafts, etc. | No | -- | -- | |
| Degraded voltage (within design basis) | Yes | C | High | |
| Defective motor control logic | No | C | Low-High | |
| Excessive seating or backseating force application | No | A | High | |
| Incorrect reassembly or adjustment after maintenance and/or testing | No | (all) | Low-High | |
| Unauthorized modifications or adjustments | No | (all) | Low-High | |
| Torque switch or limit switch binding | Yes | AB,AD,CB,CD | Medium-High | |

**Table 3.4 Motor-operated gate valve concerns from GL 89-10 and the estimated effectiveness of testing parameters (continued)**

[a] Testing parameters include:

A – Valve stem thrust (e.g., via yoke strain, torque/thrust cell, instrumented stem)
B – Switch continuity (limit, torque, torque bypass)
C – Motor current, voltage, power (including off-line motor testing)
D – Spring pack compression, torque switch shaft angular position (for loads exceeding preload)
E – Valve stem position measurement or observation
F – Vibration (e.g., via accelerometer)

Two parameters (both required) (e.g., AB)
Two parameters (one or the other) (e.g., A, C)
No parameters available (e.g., visual inspection required--)

[b] Ranges are given to reflect the uncertainty of the magnitude (severity) of the problem and/or the difficulty in interpreting the diagnostic data correctly.

measurements can supplement but not replace measurements of stem thrust or torque due to the potential inconsistencies in the drivetrain, which result from gear wear, and lubrication deficiencies.

Spring pack compression (or torque switch shaft angular position) measurements can provide a relative indicator of the output torque of the motor operator. These measurements are valid as long as the running and seating loads exceed the preload of the torque switch. Because valve seating loads are largely controlled by the torque switch setting, these measurements may not provide adequate sensitivity for detecting many possible motor and gear train degradations. Because the motor operator output torque is converted into stem thrust at the stem nut/valve stem interface, the stem thrust can be indirectly monitored using spring pack compression measurements; however, due to the potential inconsistency in stem lubrication and condition that can adversely affect stem factor, this approach is not recommended.

Valve stem position can be an important parameter to acquire when measured in conjunction with other parameters such as stem thrust or torque . By converting a time waveform (e.g., stem thrust vs time) into a position waveform (e.g., stem thrust vs stem position), defects in the stem and valve guide rails can be referenced to valve position, which can be useful in locating the defect for future maintenance.

Vibration monitoring can provide a means of detecting gear train wear and other degradation at an early stage before it threatens the operability of the MOV. Vibration analysis has been refined over several decades on rotating machinery and can be applied to MOV (especially motor operator) condition monitoring through the use of accelerometers and frequency spectrum analyzers.

### 3.2.4 Pump Monitoring Techniques

The application of diagnostic and monitoring technology and practices in the nuclear pump system is not new. Testing of pump bearing lubrication, motor stator megger (insulation resistance) tests, turbine drive speed regulation monitoring, maintenance/testing of circuit breakers per manufacturer's specifications and, of course, regulatory/Code testing of pump vibration and hydraulic performance have been performed in the nuclear industry since its beginning. Newer technologies such as pump motor current signature analysis have also seen limited use at certain plants.

Some of the conventional testing and monitoring that has been used historically has been of less than optimal design. These are tests that should be upgraded to most effectively support IST. For instance, the Code-specified vibration tests that are performed on pumps as part of the surveillance testing program are essentially ineffective in detecting bearing problems. Vibration spectral analysis, if performed correctly, *is* effective in the detection of bearing problems and other anomalies as well.

Monitoring of pump degradation has been discussed in much detail.[24] Review of the discussion of ESA and vibration spectral analysis is encouraged.

Historically, the most common monitoring techniques have been vibration, pump head and flow, bearing temperatures, and lube oil condition. ASME Code testing of the pump has required that pump head, flow, and vibration be monitored periodically. The vibration monitoring requirement is for a broadband, unfiltered (i.e., nonspectral) amplitude over the frequency range of one-third pump minimum shaft rotating speed to at least 1 kHz.

Special test programs have also used pressure pulsation measurement. Sensing of pressure pulsations is performed at the pump suction, discharge, and selected casing locations.

Many promising monitoring techniques have not been applied with any significant frequency. Also, applications of currently available monitoring techniques are not commonly pursued, such as the use of vibration monitoring in detecting and analyzing hydraulically induced vibration. An AFW system pump study[25] indicated that vibration of this type, caused by low-flow related forces, can contribute to pump degradation. Other effective techniques include

- using vibration and acoustic spectra analysis with established frequency and acceleration limits to assess bearing degradation (this is widely accepted in many industries other than nuclear),
- applying motor ESA (i.e., motor current and power analysis) to monitor shaft alignment, motor rotor condition, and flow instability, and

- recent innovations[26] in selected lube analyses, vibration, and thermography techniques to accurately predict remaining life in bearings.

The pump circuit breaker and turbine drives present special problems for diagnostic monitoring. Because of the relatively large number of circuit breaker components (mechanical and electrical), their complexity in terms of alignment and moving parts (e.g., cam, linkages, switches), and the wide variety of failure types involving numerous components, conventional approaches to monitoring may not be practical. Timed response analysis can be used for the monitoring of a variety of circuit breaker and turbine drive components. The idea behind this monitoring approach is that if sensors are installed in the correct locations in the circuit breaker and turbine drive, it would be possible to monitor the timing of voltages and the current amplitudes and trend the data. If it is apparent that certain switching and/or mechanical operations are beginning to take longer, it may indicate a lack of adjustment or that certain parts (e.g., linkages, cams) are beginning to bind or need lubrication. If certain current levels (e.g., spring charging motor current) become higher over time, it may indicate problems such as degraded hardware/lubrication (i.e., the driven mechanism) or possibly that the motor itself has become damaged. These approaches require the installation of sensors (i.e., hard wiring) at various locations in the breaker. However, when considering the failures commonly encountered in circuit breakers (e.g., loose parts, misalignment, defective switches, open or shorted coils), it becomes clear that other alternatives should be considered in addition to conventional condition monitoring. One alternative would be to design and implement an innovative and aggressive preventive maintenance program that seeks to discover these hardware and electrical problems in a "hands-on" approach before they occur. Because many designs of larger circuit breakers are especially difficult to perform preventive maintenance on, other alternatives should be considered, including

- retrofits,
- improved lubrication,
- upgrades,
- increasing design margins (e.g., electrical coils),
- redesign,
- improved fasteners, and
- replacement of older, more difficult-to-maintain circuit breakers.

The turbine drive has many of the problematic monitoring aspects of circuit breakers, but in this case it involves primarily the governor, speed regulation/trip hardware, trip and throttle valve (TTV), and the governor valve (GV). Complicating the situation further, few turbine drives are in use relative to motor drives. This increases the cost of implementing many of the changes previously described for circuit breakers; however, safety considerations during station blackouts add to the importance of the turbine drive. Certainly the alternative of designing and implementing an innovative and aggressive preventive maintenance program that seeks out degradation in known problem areas is applicable to turbine drives. Retrofits and upgrades should also be considered.

The GV in the turbine drive experiences a high failure rate and a failure mechanism that would suggest that this subcomponent would be a strong candidate for monitoring. However, this is not practical because it is a design- and application-related corrosion problem that needs corrective action more than diagnostics. Furthermore, the problem does not lend itself well to detection before complete failure (i.e., the shaft becoming pitted and stuck where it enters the packing). Because of the infrequent operation of the turbine drives in nuclear industry service, the valve stem exists in a corrosive environment that is not encountered in applications in other industries. In nuclear service, the valve may be exposed to hot steam for 15 minutes and then cool temperatures for an extended period (e.g., a month) before exposure to hot steam for another 15 minutes and so on. The valve stem and packing were not designed for such low duty cycles, and an effective correction has not been identified or implemented to date.

A 1997 pump diagnostic study[10] identified a number of monitoring and diagnostic technologies that are applicable to the pump assembly. Table 3.5 summarizes, qualitatively, the types of tests and/or parameters that could be integral to a condition monitoring program for pump assemblies.

The parameters and monitoring tools listed for the pump and pump motor are fairly standard and have at least some application in plants today. However, the parameters and monitoring tools listed for the circuit breaker and turbine drive are not yet standard.

The parameters to be monitored consist of some that are attainable during both operation and shutdown (e.g., integrity of the motor stator); however, most parameters should be measured during operation. Because of the variety of mechanical and

**Table 3.5 Condition indicator tests and parameters for pump assemblies**

| Component | Parameter | Technology/monitoring tool |
|---|---|---|
| *Pumps* | | |
| Pump internals | Hydraulic performance | Standard flow and pressure instrumentation and spectral analysis |
| Pump mechanical dynamics | Vibration | Accelerometers, amplifiers, and spectral analysis |
| Pump bearing lube | Condition/purity of lubricant | Wide range of lubrication tests available |
| Pump bearing | Vibration | Accelerometers, amplifiers, and spectral analysis |
| Pump bearing | Wear | Thermography to detect heating in bearing |
| Pump shaft/coupling | Vibration/torque modulation | Accelerometers; ESA |
| *Pump Motor* | | |
| Motor stator insulation | Insulating properties/integrity | Megger test, polarization index, potential tests, partial discharge tests |
| Motor bearing | Wear | (See bearing information under pumps/lube) |
| *Circuit breaker* | | |
| Circuit breaker hardware | Physical integrity and position | Inspection, servicing, timed response analysis, and thermography |
| Circuit breaker relays/solenoids | Electrical integrity of winding | Voltage/current sensors, timed response analysis, current monitoring, and thermography |
| Circuit breaker miscellaneous electrical | "Clean" energizing and deenergizing of components in precise sequence/timing | Voltage sensors installed in breaker, transitional waveforms, timed response analysis |
| *Turbine drive* | | |
| Turbine drive trip-related hardware | Functionality of hardware | Turbine response (timed) to transients, monitor operation to ensure no trips occur |
| Turbine drive governor | Speed regulation | Standard speed sensors and recording |

electrical problems that can and do occur in the circuit breaker and turbine drive, it is difficult to devise a cost-effective system of monitoring the many components that are involved in these failures. Little has been done to pursue the types of monitoring proposed in the table for circuit breakers and turbine drives. Generally, a well-designed and managed preventive maintenance program should be the first step in improving the reliability and availability of these two components. Supplementation with carefully selected monitoring schemes should be a valuable addition to the maintenance program.

## 3.2.5 Data Acquisition and Trending for Pumps and MOVs

### 3.2.5.1 Trendable Parameters

**Pumps**

The pump assembly has certain measurable parameters that may be trended over time to assess degradation and predict failures. Commercially available sensors as common as pressure transducers, thermocouples, and accelerometers are required to provide the necessary data. A condition monitoring program for the pump and pump motor could be planned and based, in part, on the many diagnostic and monitoring technologies and tools available.[24] This could be further enhanced to encompass the turbine drive and circuit breaker if concepts from another recent ORNL study[10] were considered.

Trendable parameters for the pump assembly include

- pump head and flow;
- pump/motor vibration overall amplitude;
- pump/motor vibration amplitude in specific frequency zones (spectral analysis);

- thermography data – bearings, packing, coupling, and motor casing;
- motor stator insulation test data;
- motor ESA;
- circuit breaker response times;
- circuit breaker current levels for selected components;
- turbine drive speed regulation data; and
- oil/lube laboratory analysis results.

The effectiveness of these parameters for detecting common pump assembly problems is discussed in Sect. 3.2.4. Trending of these parameters and appropriate action should have the following positive results :

- successful avoidance of most unscheduled bearing maintenance,
- increased pump availability (i.e., without complete loss of pump margin),
- fewer packing failures (e.g., in turbine drive valves),
- increased pump motor availability,
- increased availability of the circuit breaker mechanism/electrical components, and
- fewer turbine drive speed regulation problems requiring unscheduled maintenance.

**MOVs**

There are also many measurable parameters for MOVs, each of which may be trended over time. Commercially available diagnostic systems generally employ sensors that can measure changes in one or more of these parameters and use the measured values in several ways, including time traces, frequency displays, and other graphs that facilitate the analysis of these measurements. While a detailed discussion of these parameters is beyond the scope of this document, previously issued ORNL reports may provide additional information.[21,22]

Trendable parameters for the MOV assembly include

- valve stem thrust (e.g., via yoke strain, torque/thrust cell, instrumented stem);
- switch continuity (limit, torque, torque bypass);
- motor current, voltage, and power;
- spring pack compression, torque switch shaft angular position;
- valve stem position; and
- vibration.

A thorough understanding of the inherent strengths and weaknesses of these parameters is essential to ensure that they are utilized within their limitations. It is equally important to consider the characteristics (e.g., principal of operation, sensitivity, range, etc.) of the sensors used to measure these parameters.

The effectiveness of these parameters for sensing common MOV assembly deficiencies, misadjustments, and degraded conditions is discussed in Sect. 3.2.3.

### 3.2.5.2 Diagnostic Technologies

Measurable parameters for pumps and MOVs are available for detection, acquisition, analysis, and trending by numerous diagnostic technologies. For example, current to the MOV or pump motor may be detected nonintrusively by a clamp-on current probe. Valve stem thrust may be sensed by a strain gage mounted on the valve yoke, in a mounting bolt, or on the stem itself. Actuator and valve vibration or vibration in the pump and pump motor may be detected using an accelerometer. Appendix A contains a detailed discussion of signature analysis as a component condition diagnostic technique. Regardless of the measurable parameter detected and the sensor used, acquiring trendable data involves several steps that need to be carried out carefully and consistently. Figure 3.8 illustrates a "general data flowchart" that identifies each step. A short description of factors that should be considered for each step follows:

1. *Measurable parameter*—An understanding of what each parameter is capable of responding to is critical. For example, MOV stem nut torque and valve stem thrust would not be parameters of choice for monitoring motor degradation.

2. *Sensor*—Sensor type and placement should obviously be considered. In some cases (e.g., for certain accelerometers) cable lengths should also be kept short.

3. *Signal conditioning*—Signal conditioning electronics are usually required in coordination with sensor sensitivity and frequency response and with data acquisition parameters (especially sample rate).[21]

4. *Data acquisition*—Data acquisition parameters, such as sample rate, data precision, and sample size (block size), should be correctly selected according to the time and frequency ranges desired, the data acquisition system limitations, and the sensor limitations.

5. *Data analysis*—Many methods for analyzing data are available. Care should be taken to avoid diagnosing component condition (either good or bad) based on limited data. Because many component parameters are available for monitoring, it is recommended that several be employed that offer complementary, but also confirmatory information.

6. *Data archiving and trending*—Data should be stored in a manner that can be retrieved quickly for comparison with data acquired at different times. Each stored data set should be documented so that, even years from its acquisition, the stored data can be completely understood (e.g., when it was acquired, where it was acquired, what component was tested, what sensor was used, and what data acquisition parameters were used).

#### 3.2.5.3 Data Trending Guidelines

As described in Sect. 3.2.5.2, data trending can be accomplished only if data acquisition and analysis specifications are selected carefully and then consistently maintained. These specifications include

- sensor type and placement (even small position changes for certain sensors can produce unwanted changes in sensitivities to monitored degradations),
- sensor calibration (should be recently verified),
- signal conditioning attributes (e.g., gain, filter response),
- data acquisition parameters (e.g., analog-to-digital precision, sample rate , number of points analyzed);
- data analysis methods (waveform analysis, frequency spectrum analysis). Care should be taken in the selection of windows and frequency bands for Fast Fourier Transform (FFT) analysis. Most sensors require that their raw outputs (normally voltage or current) be converted to the correct engineering units (e.g., pounds of thrust, foot-pounds of torque). These conversion factors should be verified through recent calibrations.
- data archiving and trending (store data in a consistent format with appropriate documentation so that it can be retrieved quickly for comparison with data acquired at different times).

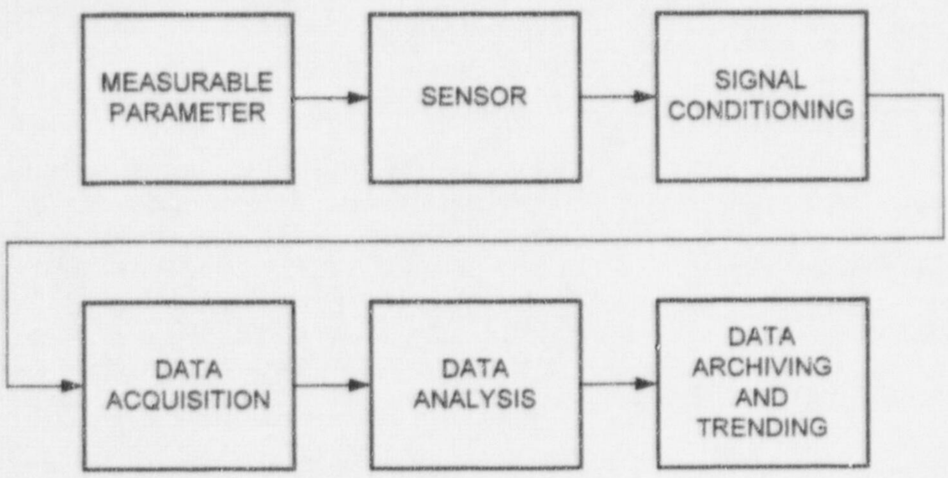



**Figure 3.8 General data flowchart**

Maintaining consistent test conditions (when practical) can be as important as the data acquisition specifications. For example, line voltage, process pressures, and ambient temperatures, should be recorded and repeated for each test if practical. The sensitivity of the measured parameter(s) to changes in the ambient test conditions should be recognized and accounted for. Personnel should be trained in data acquisition and interpretation for each diagnostic technology employed.

Figure 3.9 illustrates a hypothetical trend plot for three similar components (e.g., MOVs or pumps). In this case the "Condition Indicator" for each component is obtained as part of the analysis of a diagnostic signal that is sensitive to the level of degradation (e.g., the lower the measured number, the better the condition). All three components exhibit acceptable performance because all test readings are below the level that would require a disassembly and inspection.

The most recent test on each component (test 9) shows component 3 to be slightly more degraded than component 2, which is slightly more degraded than component 1. If the test data is not trended, the fact that components 1 and 2 are degrading at a more rapid rate than component 3 is lost. It may be seen from this plot that component 1 will probably require disassembly and inspection after the next scheduled test and that component 3 will probably test acceptable. Thus, the degradation dynamics (e.g., rate of change in condition) can be more important than a single reading.

It may also be concluded from Fig. 3.9 that component 1 may need to be tested at an earlier date (e.g., before the next scheduled test) if unacceptable performance is to be detected at the earliest time. Component 3, due to its consistently acceptable performance, may not need to be tested at the next test period, but it may be tested according to a longer test interval (e.g., double the test interval).

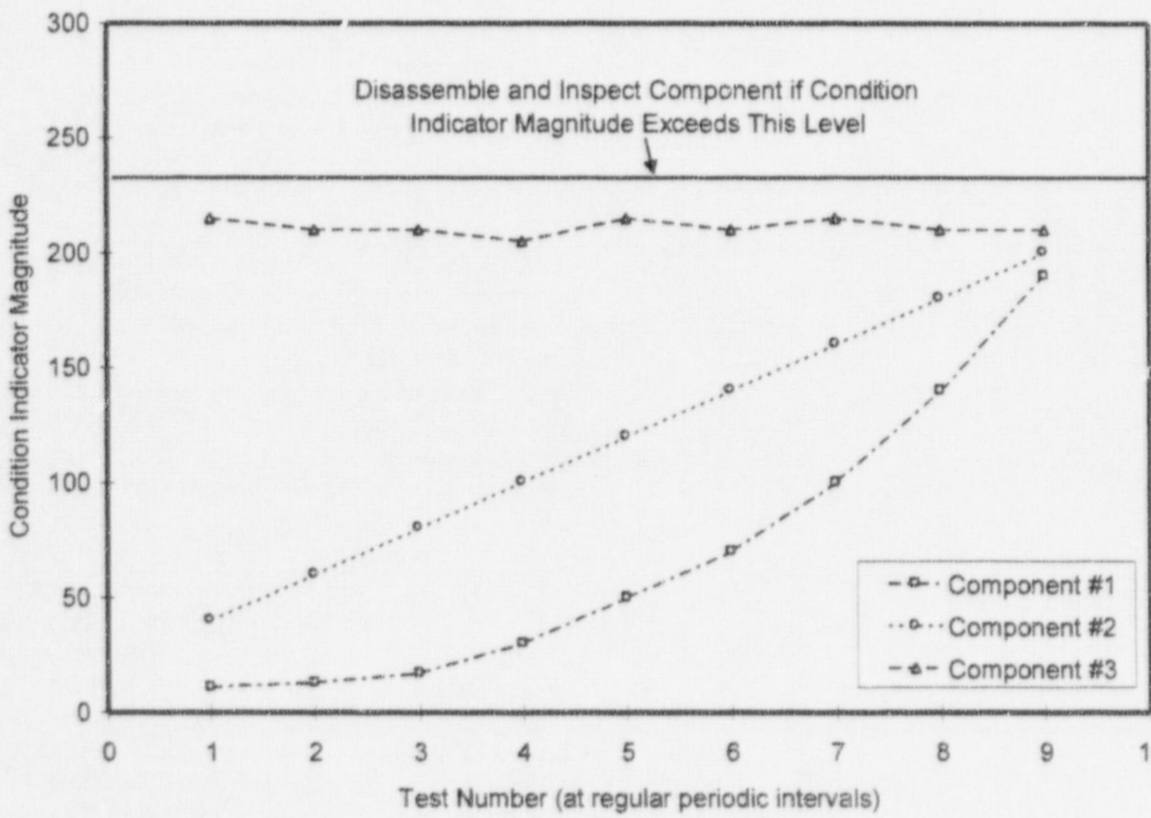



**Figure 3.9 Hypothetical trend plot for three similar components**

## 3.3 Summary

Table 3.6 Summarizes key points and important results from Chap. 3

**Table 3.6 Summary of key points and results**

| Section | Key points and results |
|---|---|
| Preventive, predictive, and corrective maintenance and testing | ❑ Maintenance and testing play critical roles in ensuring component operability.<br>❑ There are important differences between diagnostic and performance testing:<br>▪ Diagnostic tests collect information to provide indication of component health or condition.<br>▪ Performance tests verify that a functional failure has not occurred |
| Current pump testing | ❑ Current regulatory/code required testing finds very few pump and pump motor bearing failures.<br>❑ Detection of degradation in the pump motor, circuit breakers, and turbine drives is generally not possible using current ASME Code testing, and other standards and codes do not address these subcomponents. |
| Current MOV testing | ❑ Data has shown that there are about 20% more MOV *actuator* failures than there are *valve* failures.<br>❑ About 30–40% of the valve and actuator failures were discovered under demand conditions during a recent study period. |
| ASME Code Case OMN-1 | ❑ By relying on torque measurements rather than thrust measurements, OMN-1 margin is always verified under the assumption that the actual stem factor never exceeds the design-basis stem factor.<br>❑ Degradations can occur that do not directly affect the OMN-1 margin measurement.<br>❑ Performance tests as prescribed by OMN-1 should be supplemented with additional diagnostic testing and, if necessary, visual examination. |
| Component margin analysis | ❑ Differences exist between true component margin and margin as defined in Code Case OMN-1 (which is limited by switch settings).<br>❑ Inservice tests are not generally designed to provide information on true component margin.<br>❑ A successful margin test does not necessarily ensure that significant equipment degradation is not present.<br>❑ Margin tests are useful indicators of component functionality. |

**Table 3.6 Summary of key points and results (continued)**

| Section | Key points and results |
|---|---|
| MOV monitoring techniques | ❑ No individual diagnostic method is currently capable of monitoring for all potential MOV degradation mechanisms.<br>▪ Because performance varies with multiple parameters, failure and degradation modes will vary with component groupings.<br>▪ The most common failure and degradation modes should be identified for each grouping.<br>▪ The diagnostic and performance testing methods selected should be effective in detecting and trending the most common failure and degradation modes for each component group.<br>❑ Measurable parameters (condition indicators) are available to assess/trend MOV condition, depending on the area of interest.<br>▪ Table 3.4 correlates testing parameters with GL 89-10 concerns. |
| Pump monitoring techniques | ❑ No individual diagnostic method is currently capable of monitoring for all potential pump degradation mechanisms.<br>▪ Since performance varies with multiple parameters, failure and degradation modes will vary with component groupings.<br>▪ The most common failure and degradation modes should be identified for each grouping.<br>▪ The diagnostic and performance testing methods selected should be effective in detecting and trending the most common failure and degradation modes for each component group.<br>❑ Measurable parameters (condition indicators) are available to assess/trend pump condition, depending on the area of interest.<br>▪ Table 3.5 correlates pump parameters with monitoring tools. |
| Data acquisition and trending | ❑ Trendable parameters for the pump and MOV assemblies are listed in Sect. 3.2.5.<br>❑ Data must be acquired and trended in a consistent manner to be meaningful.<br>❑ Personnel should be trained in data acquisition and interpretation for each technology utilized within a licensee program. |

# 4 Guidelines for Evaluating Effects of Changes to IST Programs on Pump and MOV Operability—An Integrated Approach

Issues regarding verification of the design and operability of safety-related MOVs, combined with requests for changes to traditional IST programs for pumps and valves, have resulted in the need for an improved understanding of degradation effects on performance. Proposed changes to traditional IST programs have resulted in relief requests for extended pump and MOV test interval allowances. For example, licensees have requested changes from traditional, relatively short, IST intervals (usually quarterly) to intervals of up to 5 to 10 years. Because component operability may be impacted by undetected degradation or failure, an enhanced understanding of methods for mitigating/detecting potential significant component degradation or failure is important. The effects of changes to IST programs on component operability therefore need to be evaluated to assess the appropriateness of proposed test intervals. These evaluations should focus on the engineering and programmatic aspects of licensee activities as well as on specific test intervals. The guidelines presented here for performing such evaluations are designed to be used in conjunction with supporting engineering information from Chaps. 2 and 3 and the analytical methods described in Chap. 5.*

The NRC has identified an iterative approach for licensees to follow in *proposing* risk-informed licensing basis changes given the principles of risk-informed decision making outlined in Regulatory Guide 1.174 (see Fig. 1.1). This approach consists of four elements, depicted graphically in Fig. 4.1. The process for *evaluating* changes to IST programs on pump and MOV operability outlined herein is consistent with this approach and may also be used for assessing other (nonrisk-informed) relief requests to extend IST intervals and/or for issues related to component margin testing. The general evaluation process consists of three elements as shown in Fig. 4.2.

It is not the intent of this chapter to estimate specific test, inspection, or maintenance intervals. These estimates should be plant-specific and should be included as part of individual change request submittals. The guidelines provided here support an integrated regulatory evaluation of proposed changes to IST programs – that is, assessment of the technical bases for such changes, overall operability assurance programs (testing, monitoring, maintenance, and trending and feedback programs), and test intervals. Determination of what constitutes an appropriate test interval may change as experience is gained and additional information becomes available from trending and feedback programs.

Sections 4.1 and 4.2 provide general guidelines for evaluation of licensee change requests such as those associated with IST interval extension. Attributes of well-founded, balanced engineering analyses (including component groupings and failure rate estimation) and operability programs (including maintenance, condition monitoring, performance testing, and trending and feedback) are provided for evaluation of licensee submittals. Section 4.3 provides recommendations for minimum extension request content and the technical evaluation of such requests for pumps and MOVs. Section 4.4 contains general information on considerations for test interval extension.

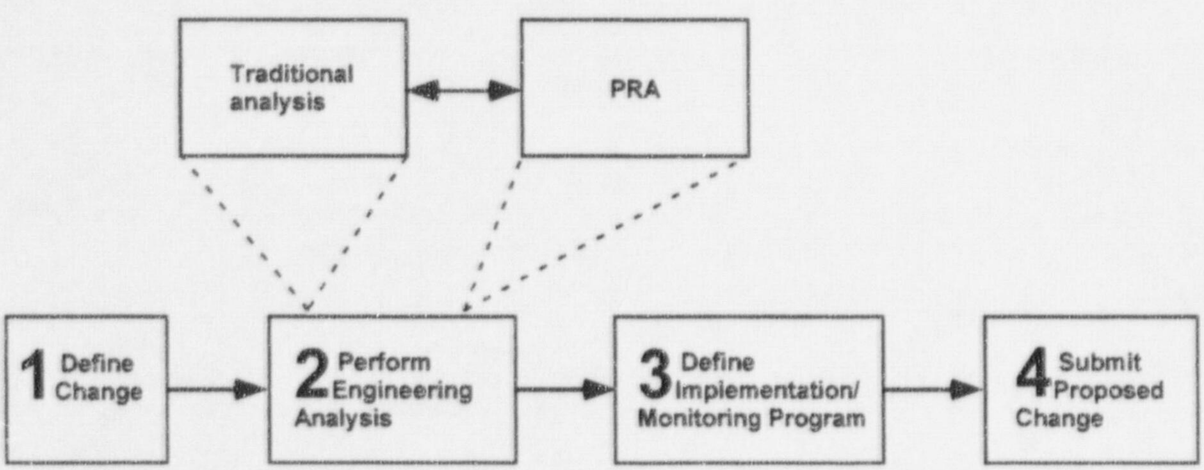



**Figure 4.1 Principal elements of risk-informed, plant-specific decision making.** *Source:* Redrawn from Regulatory Guide 1.174 (Fig. 2).

* Although beyond the scope of this report, an evaluation of unavailability and risk analyses and their implications should also be considered as part of the movement toward risk-informed ISTs.

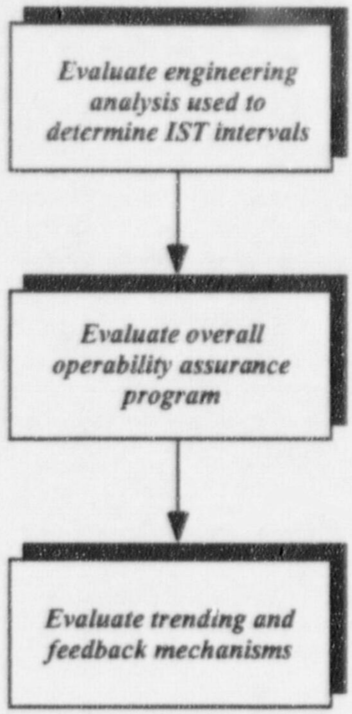



**Figure 4.2 Steps in change request evaluation process**

## 4.1 Engineering Analysis Evaluation

The scope and quality of the engineering analyses presented as a basis for proposed change requests such as IST interval extensions should be appropriate for the nature and scope of the changes. The appropriateness of qualitative and quantitative analyses, as well as analyses using traditional engineering approaches and PRA approaches should be considered.[5] The following elements should be included in the evaluation of a licensee's engineering basis for changes to pump and/or MOV IST programs:*

- Component groupings. Groupings should take into account desired reliability and the parameters that have been shown to correlate with component performance. (Sects. 2.1.2, 2.1.3, 2.1.4, 4.1.1, 4.1.2)
- Historical plant and industry experience. Failure rates for groupings of components based on plant-specific and nuclear industry data are preferable to those taken from generic reference sources. (Sects. 2.1.2, 2.1.3, 2.1.4)
- Consequences of component failure (safety/operational).
- Component functions, failure criteria, and critical failure modes. (Sects. 2.1.3, 2.1.4) Critical failure modes are the failure modes most likely to occur and that would result in the most undesirable consequences.
- Unavailability and risk implications. (Chap. 5)
- Behavior models and failure rates should be based on actual data if analytical approaches are employed. The methodology in Chap. 5 may be used to provide bounding estimates within the limitations of the assumptions. (Chap. 5)
- Analytical analyses (including PRA) should be supplemented with deterministic evaluations. (Chaps. 2,3,5)
- Component specialists should be included in panel composition if an expert panel is used.

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* Related sections in this document are identified in parentheses after each bullet.

### 4.1.1 Component Groupings

Just as it is intuitively illogical to discuss specific performance expectations for a large inhomogeneous group of items, such as "all motor vehicles," it is also unreasonable to do so for "all MOVs" or "all pumps." For example, a 6-in. pump from manufacturer "A" in continuous service in a service water system would probably exhibit different performance characteristics (and failure rate expectations) than a 12-in. RHR pump from manufacturer "B" required to operate only during shutdown conditions. To establish valid measures of component performance, logical "groupings" should be established based on the *parameters with which their performance has been shown to correlate*. In this way, a more homogeneous population may be established and used to determine probabilities of failure, maintenance programs, and test plans.

Some of the component parameters available from the NPRDS and/or Equipment Performance and Information Exchange (EPIX) databases (for both engineering and failure records) are presented in Table 4.1. Example data is representative of data that should be available for MOVs.

If determination of the performance characteristics for "MOVs" is desired, it is clear that a more specific definition of MOVs is necessary. Table 4.1 provides information on a variety of parameters that might be considered by a licensee to group the broader category of MOVs into more meaningful subsets. For example, it might be more useful to select smaller, more homogeneous populations such as "all MOVs from Manufacturer A391 less than 8-in. in size," or "all MOVs in the CCW system," or "all MOVs that have experienced stuck open failures," such that the components included in each grouping share the technical characteristics most likely to affect the performance measure of interest.

Table 4.2 is a checklist for component grouping determinations/evaluations. Section 2.1.4 identifies some of the performance-affecting variables for pumps and MOVs.

### 4.1.2 Failure Rate Estimation

Information needed to estimate failure rates is available from a number of sources, including industry databases (NPRDS, EPIX), plant maintenance and failure records, component manufacturers, industry users groups, national laboratories, and NRC and Electric Power Research Institute (EPRI) reports.[7-9] Data obtained from trending component performance (e.g., data obtained from nonintrusive diagnostic tests) might be especially useful, particularly if it were possible to determine some kind of wear rate for failure modes known to be age-related. The important point to consider is that valid failure rates should be based on the parameters with which component performance is likely to correlate (e.g., "How likely is it that pump model "X" from manufacturer "Y" used in the CVCS system during intermittent service will fail to pump the required head due to impeller wear?"). Although these calculations can never be completely accurate, enough information should be generally available to provide an estimate for most components. Chapter 2 includes selected results of studies of pump and MOV performance and indicates relative failure rates based on certain parameters. More detailed analyses may be found in Refs. 3-6.

**Table 4.1 Example NPRDS/EPIX data for MOVs**

| Component ID | Type | Size | System | Manufacturer | Model | Age | Failure mode | Failure cause |
|---|---|---|---|---|---|---|---|---|
| CC-931 | Gate | 6 | CCW | A391 | 21454-H | 2 | Internal leakage | Debris |
| Q2P17V087 | Globe | 16 | RHR | P305 | 828-A | 10 | Stuck open | Bad limit switch |
| CCW-2-656 | Ball | 6 | ESW | D243 | FVL16D | 7 | Stuck closed | Human error |
| 750A | Gate | 2 | CVCS | A391 | E3339-1 | 14 | Circuit breaker failure | Unknown |

**Table 4.2 Potential component grouping characteristics**

| |
|---|
| Component type (e.g., motor-operated gate valve, centrifugal pump) |
| Component design:<br>- Unusual design features<br>- External penetration (e.g., valve stem)<br>- Ready availability of spare parts<br>- Actuating, control, or peripheral devices related to the component to comprise the "component assembly" |
| Component application/normal service function(s) (e.g., safety-injection pump) |
| Normal operating context (stand-alone, duty, standby) |
| Normal flow rate |
| Component age (since installation/since last refurbishment) |
| Materials of construction (including internals parts and subcomponents, as relevant) |
| Normal system temperature and pressure |
| System fluid |
| System cleanliness characteristics |
| Normal system operating status (normally operating; shutdown support; standby/testing) |
| Component size/capacity |
| Component manufacturer; model/drawing number; manufacturers/model numbers for associated actuators, motors, if relevant to component performance |
| Component orientation (i.e., horizontal or vertical) |
| Upstream disturbances in close proximity (e.g., pump, elbow); if so, number of pipe diameters between the component and the upstream disturbance, and any associated abnormal stress on the component |
| Other factors that could result in abnormal operational stresses on the component |
| Desired availability of the component |
| Risk significance |

## 4.2 Overall Operability Assurance Program Evaluation (Including Trending and Feedback Mechanisms)

An effective program to assure component operability should be integrated; that is, it should consider operation, testing, monitoring, maintenance, and trending and feedback. Figure 4.3 identifies a process that a licensee might follow to develop an integrated operability assurance program. Some of the activities identified in Fig. 4.3 are proactive (intended to prevent failures), others are intended to discover concealed failures, and still others can only deal with failures after they occur. In general, proactive activities designed to prevent failures should take precedence over those that can only detect or correct them, but an appropriate operability assurance strategy for most components should usually consist of a combination of these activities. Trendable diagnostic and performance data that may provide information about component condition or likelihood of failure should be recorded and periodically assessed for trends. Feedback mechanisms should be in place to adjust maintenance, testing, and monitoring activities and intervals as necessary based on data trends. The following elements should be considered in the evaluation of a licensee's overall operability assurance program:

**Operability assurance programs**

*Programmatic*

- An integrated operability assurance program should be in place that considers maintenance, diagnostics, performance assessment, operation, and trending and feedback. The program scope should be clearly defined.

- The integrated operability assurance program should be applied rationally across component groups; that is, the greatest attention should be paid to the components that represent the greatest contributions to overall risk. The program should be focused on detection of the failure modes that are most likely to occur and that would result in the greatest undesirable consequences (critical failure modes).

- For component groupings within the program, maintenance/testing activities should be linked to critical failure modes. (Sect. 4.2.1)

*Maintenance program*

- Both preventive and corrective maintenance programs should be in place. Maintenance activities that are based on component condition are preferable to those that are periodically scheduled based on calendar time. (Sect. 4.2.1).

- The maintenance program should distinguish between age-related and nonage-related failures. (Sect. 4.2.1)

- Appropriate preventive measures should be taken to preclude age-related failures. (Sect. 4.2.1)

- The preventive maintenance program should discriminate by service conditions (i.e., consider appropriate groupings).

- For preventive and corrective activities, measures should be implemented to ensure that components are left in operable condition following maintenance. (Sect. 4.2.1)

*Performance testing program (including IST, margin testing, and other testing)*

- Performance testing programs should be in place to detect functional failure (failure to meet performance criteria). (Sect. 4.2.2)

- Performance testing activities should be designed to detect failure of any part of the component assembly. (Sect. 4.2.2)

- Performance tests should be used as supplements to, not replacements for, other types of diagnostic tests.

- Distinction should be made between trendable and nontrendable test data. Data that is trendable and may provide information about component condition or likelihood of failure should be trended and feedback mechanisms identified. (Sect. 3.2.5)

*Diagnostic testing program*

- A diagnostic testing program should be in place to provide information on component condition. The program should be designed to minimize the number of unexpected failures, as evident from historical performance data. (Sect. 4.2.2)

- Diagnostic tests should be designed to detect degradation or failure related to critical failure modes.

- Personnel involved in diagnostic testing should be trained in operation, fundamental capabilities, and limitations of the diagnostic equipment as well as data acquisition, signal processing, and data analysis. (Sect. 3.2.5)

**Trending and feedback mechanisms**

*Maintenance*

- Preventive maintenance programs should have a feedback link with corrective maintenance programs.

- Unplanned maintenance activities should be periodically assessed for trends.

*Test data and failure trending*

- Programs should be in place to trend diagnostic and performance testing data that is trendable and that may provide information about component condition or likelihood of failure. (Sects. 3.2.5, 4.4.1)

*Reevaluation of test intervals*

- Feedback mechanisms should be in place that allow for modification of diagnostic and performance test intervals. (Sect. 4.4.1)

- Reevaluations should consider plant-specific and industry failure experience, maintenance records, and trends in test data. (Sect. 4.4.1)

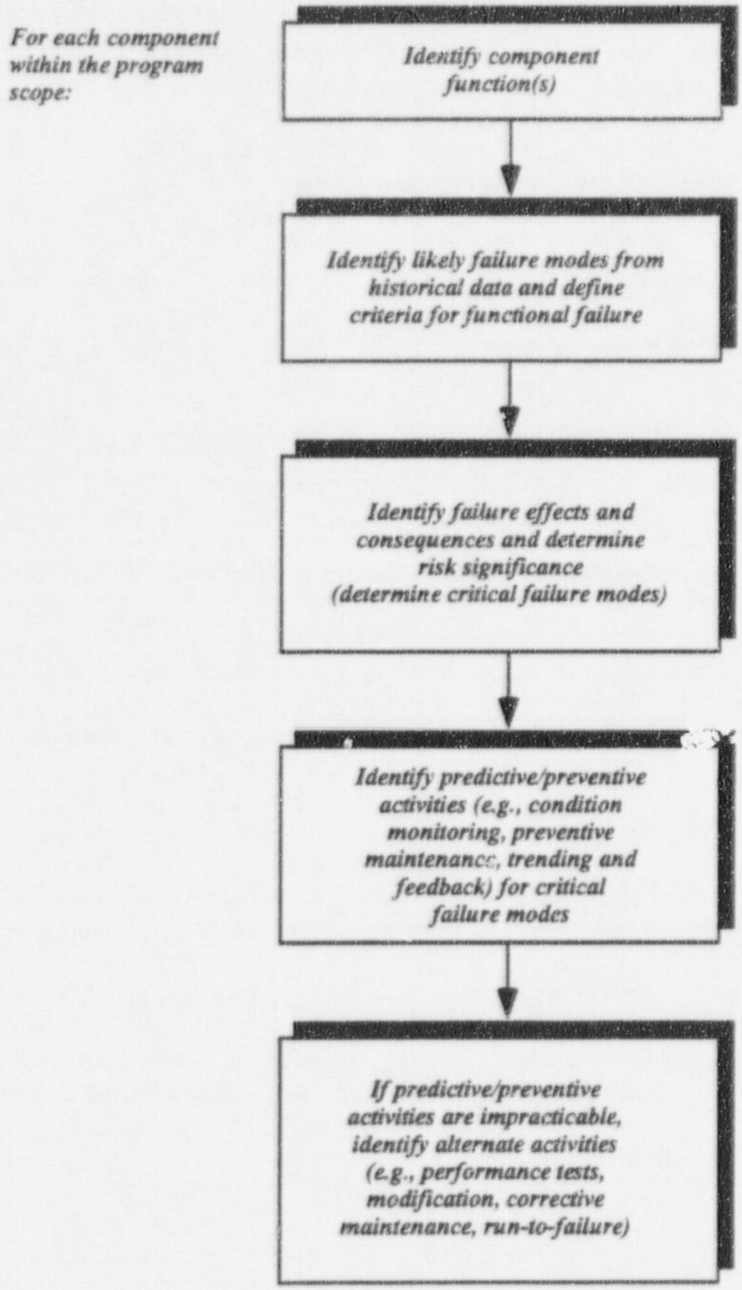


**Figure 4.3 Steps for establishment of an integrated operability assurance program**

### 4.2.1 Maintenance Programs

The way in which components are maintained has a significant influence on their availability and reliability. Maintenance can be divided into two general categories: (1) proactive measures that try to prevent failure; and (2) alternate or default measures that are reactive and deal with the failed state. Proactive measures are undertaken before occurrence of a failure, with intentions of preventing it. Preventive and predictive maintenance and condition monitoring activities would be included in this category. Alternate or default actions are those that actually deal with the failed state and should be chosen when it is impracticable to identify an effective proactive measure.[13] Included within this category would be modification or redesign, performance tests (failure detection tasks such as ISTs), corrective maintenance, and run-to-failure.

*A maintenance program hierarchy of condition monitoring, predictive/preventive activities, performance tests, corrective maintenance, and run-to-failure might be considered the most effective. It should be considered, also, that a maintenance strategy for any component might include a combination of these categories, depending on how each failure mode is handled.*

#### 4.2.1.1 Age-related failures and maintenance

As discussed in Sect. 2.1.2, failures such as those caused by normal wear, corrosion, and erosion, may be related to the service time or operating age of the component under consideration. That is, components are subjected to operating stresses that, over time, cause a corresponding decrease in resistance to stress. (A direct relationship between failure probability and component age assumes that deterioration is directly proportional to applied stress, that the stress is applied consistently, and that the "operating age" can be accurately determined; Sect. 2.1.2 explains why this is often not true in practice.) Figure 2.12 and pattern 1 in Fig. 2.13 are indicative of age-related failures. For failure modes that can be shown to be age-related (e.g., pump impeller wear) and where it is possible to determine an age at which action may be taken to prevent failure, preventive maintenance actions such as refurbishment and/or parts replacement may be warranted. For preventive-based refurbishment or parts replacement to be practical (1) there should be an identifiable age at which the component exhibits a rapid increase in failure probability (or for slowly progressing failures, the failure probability pattern should be understood and some "action level" should be assigned); (2) the component is likely to survive to that age; (3) refurbishment should restore the component to its original resistance to failure; and (4) the refurbishment per se should not increase the probability of failure (e.g., from reassembly errors). Frequency of these activities should be governed by the age at which the failure probability can be shown to begin increasing.

#### 4.2.1.2 Nonage-related failures and maintenance

For many failure modes, deterioration is not always directly proportional to applied stress, and stress is not always applied consistently. Many failures are caused by increases in applied stress, which may result from system transients, incorrect operation, poor maintenance, external damage, etc. Failures may also be caused by manufacturing defects, design weaknesses, maintenance/human error, and other unknown causes for which age-related degradation may be eliminated as a cause. In all of these cases, there is little or no relationship between overall component operating age and failure probability, and failures may therefore occur at any time during the component's operating life. The combination of variable stress, erratic response to stress, and component complexity results in a significant fraction of failures that cannot be characterized as strictly age-related, with the resulting failure patterns such as patterns 2 and 3 in Fig. 2.13. Therefore, from a maintenance viewpoint, the concept of a fixed wear-out age does not apply to these types of failures, so the idea of restoration or replacement activities at periodically scheduled intervals based on calendar time cannot apply. This does not mean, however, that nothing can be done to prevent failure. Although no direct relationship between component operating age and failure probability can be determined, for most failure modes some early indication of failure is usually available. Therefore, a lead-time-to-failure period exists (i.e., the period of time between the point when an identifiable condition indicates a functional failure is either about to occur or is in the process of occurring and the functional failure occurrence).[13] Some combination of predictive or condition monitoring techniques (possibly combined with certain default actions, such as performance tests) can usually be identified that will allow for failure detection during this period, thereby effectively reducing the likelihood of a failure during a demand situation.

It is important to distinguish between age-dependent failure modes and those that have no relationship to operational age so that maintenance (and also test/inspection/monitoring) activities can be planned to provide the most benefit while inflicting the least interruption to the component. Accordingly, it needs to be understood that while proper maintenance is necessary to ensure that components remain in good condition and do not experience wear-out, the assumption that intrusive maintenance or testing activities always reduce the likelihood of component failure is false. In some cases, these activities may actually increase the likelihood of failure.

### 4.2.2 Condition Monitoring, Predictive/Preventive Activities, and Performance Tests

#### 4.2.2.1 Condition monitoring (diagnostic testing)

Even though many failure modes are not strictly a function of the length of time that a component has been in service (its "operating age"), most components do give some warning that they are in the process of failing prior to actual functional failure. For example, a motor rotor bar might be cracked and on the verge of failure, but by using certain diagnostic techniques such as vibration monitoring or motor current signature analysis, some evidence of degradation or impending failure might be evident in the spectral data. A potential failure is defined as an identifiable condition that indicates when a functional failure is either about to occur or is in the process of occurring.[13] It may be possible to develop an approximate range of the interval between the identification of the potential failure and its decay into a functional failure (i.e., the lead-time-to-failure interval). For many failure modes, it is possible to identify suitable condition monitoring (diagnostic testing) activities that are effective at detecting potential failures so that action may be taken to prevent the functional failure. To be effective in assuring the operational readiness of a component, the condition monitoring activities should be done at intervals less than the lead-time-to-failure interval. This interval may be measured in time or cycles and is dependent on the failure mode that it is intended to detect. These measures are proactive and are designed to ensure that a component does not fail, as opposed to alternate or default activities such as performance testing that are reactive and are intended to find out if the component has already failed.

Scheduled condition monitoring activities are technically feasible if

- it is possible to define a clear potential failure condition,
- the lead-time-to-failure interval is reasonably consistent,
- it is practical to monitor the component at intervals less than the lead-time-to-failure interval, and
- the period between failure detection and actual functional failure is long enough so that some preventive action can be taken.

Condition monitoring may be applied both to age-related and nonage-related failure modes because usually in both cases, functional failures are preceded by some kind of warning (the warning period may vary depending on the failure mode and operating conditions). Understanding of the deterioration mechanisms and rates is needed to determine the length of the monitoring interval. Where the final stages of deterioration are linear (usually an age-related failure), a rate of deterioration or aging can usually be determined and a corresponding lead-time-to-failure interval calculated.* For failures that are not age-related, engineering judgement, experience, and/or trend data need to be relied on to estimate the time interval between failure detection and functional failure. (In cases where this is impossible, alternate activities such as preventive maintenance or failure detection should be employed.) Only one failure mode at a time should be considered when defining appropriate condition monitoring intervals because (1) not all technologies can detect all failure modes and (2) different failure modes exhibit different characteristics and occur on different time frames. The final monitoring program should, of course, be based on the technologies available, the failure modes that can be detected, and the most efficient use of resources. Multiple failure modes may also be tested during the same test. Figure 4.4 provides guidelines for determination of condition monitoring intervals. Trending of test data should be incorporated into a feedback mechanism that allows for adjustment of test intervals, if necessary.

#### 4.2.2.2 Condition monitoring for pumps and MOVs

Guidelines for the development or evaluation of a condition monitoring program for pumps and valves in nuclear service are identified in Table 4.3. As a minimum, a condition monitoring program should consider component application, operating experience, safety, "as low as reasonably achievable" (ALARA) assessments, and test/monitoring activities and frequencies. Table 4.3 provides a checklist for each component (or component group) to be included in a condition monitoring program. Specific information for pumps and MOVs (e.g., potential failure modes) is provided in Chaps. 2 and 3 of this report.

#### 4.2.2.3 Predictive/preventive activities

Condition monitoring, refurbishment, and parts replacement at scheduled intervals can all be considered proactive in nature. In order of preference, condition monitoring should generally be given first consideration, followed by refurbishment and parts replacement. This is because nonintrusive activities usually have a lower probability of upsetting a system that was otherwise functioning properly. In many practical cases, however, a combination of activities may be necessary to provide the most effective proactive maintenance program.

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* Although the final stages of failure for wear- or aging-related failures may remain linear, it is possible that the probability of failure during the final stages may be nonlinear. That is, the probability of an on-demand failure may increase with age as the system is subject to wear at a constant linear rate because the system capability to resist failure is decreasing. For example, a gate valve obturator might exhibit a relatively constant linear wear rate (with time or number of actuations), but as the extent of wear increases the misalignment, the likelihood of the obturator sticking or jamming into the guides increases.

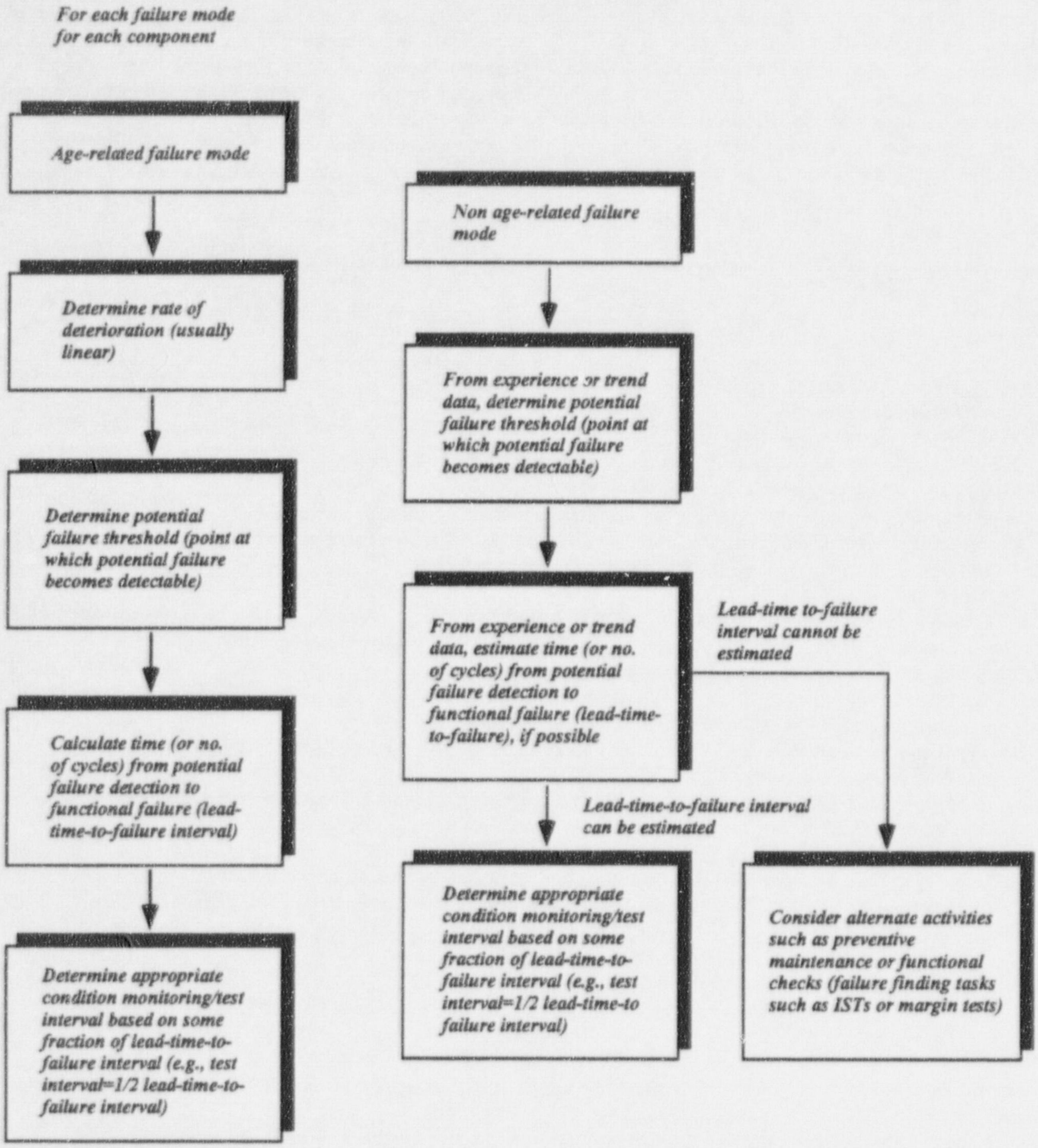


**Figure 4.4 Condition monitoring interval determination**

Diagnostic activities that provide some measure of actual component condition should usually be considered first because, by their nature, they can be performed in situ without being invasive. This means that, for most techniques, component and/or system operation is unaffected. These diagnostic techniques also have the benefit that specific potential failure conditions can be identified prior to failure so that corrective measures can be planned before failure actually occurs (and the consequences of failure can be avoided). An additional benefit is that needless replacement and/or refurbishment are avoided, resulting in decreased costs, increased operating life, and reduced opportunity for human-induced error. Section 3.2 provides a detailed discussion of monitoring techniques for pumps and MOVs.

Component refurbishment (or renewal) and/or parts replacement at scheduled intervals may be chosen when appropriate activities cannot be identified that would provide information on component condition. To be effective, these tasks should be performed at some age when degradation is likely to occur, but prior to actual failure. For this reason, refurbishment or replacement is usually effective on age-related failures only. Problems with these activities include their effect on operation (some component and/or system downtime is almost always necessary); the tasks are done at scheduled intervals so that sometimes it may be unnecessary and sometimes it may be too late (deterioration or failure has already started to occur); and they provide the opportunity for maintenance-induced failure. Scheduled parts replacement also has the disadvantage that some parts not scheduled for replacement may also be degraded, but are overlooked (where presumably, complete renewal would offer increased assurance that the component was restored to its original resistance to all failure modes).

**Table 4.3 Checklist for component condition monitoring program**

## I. Component Application*

*A. Identify Design and Operating Characteristics*

What is the component type (e.g., motor-operated gate valve, centrifugal pump)?
Describe the component design:
- Are there any unusual design features?
- Does the component have an external penetration (e.g., valve stem)?
- Are spare parts readily available?
- What actuating, control, or peripheral devices are related to the component to comprise the "component system?"

What is the component application/normal service function(s) (e.g., safety-injection pump)?
What is the normal operating context (stand-alone, duty, standby)?
What is the normal flow rate?
What is the component age (since installation/since last refurbishment)?
What are the materials of construction (including internals parts and subcomponents, as relevant)?
What is the normal system temperature and pressure?
What is the system fluid?
What are the system cleanliness characteristics?
What is the normal system operating status (normally operating; shutdown support; standby/testing)?
What is the component size/capacity?
Who is the component manufacturer? What is the model/drawing number? Identify manufacturers/model numbers for associated actuators, motors, or other drive mechanisms, if relevant to component performance.
What is the component orientation (i.e., horizontal or vertical)?
Are there any upstream disturbances in close proximity (e.g., pump, elbow)? If so, how many pipe diameters are between the component and the upstream disturbance? Does the disturbance result in abnormal stress on the component?
Are there other factors that could result in abnormal operational stresses on the component?
What is the desired availability of the component?
What is the risk significance of the component?

*B. Identify Failure Effects*

What constitutes a functional failure (e.g., failure of a pump to supply adequate flow; failure of a valve to completely close = partial loss of function; failure to operate at all = total loss of function)?
What are the potential failure modes (e.g., broken motor rotor bar, circuit breaker fails to trip)?
Which failure modes are significant to safety or environment and/or plant/system availability?
What are the potential failure causes (e.g., corrosion, abnormal stress, human error)?
What are the system/plant operational consequences of failure?
Does a failure (of any part of the component system) manifest itself under normal operating conditions, or could it remain hidden until a demand situation occurs (dependent upon failure mode)?

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* The term "component" is intended to apply either to a single component (e.g., pump or valve) or to a group of similar components. The grouping of components is assumed to be based on the design and operating characteristics in Sect. I.A., which have been determined by the user to correlate with component performance and reliability. Throughout the report the term "component" is assumed to include the complete pump or valve assembly. For pumps, this would include the pump itself, motor or turbine drive, and related circuit breaker. The MOV assembly includes the valve, actuator, motor starter, circuit breaker, and switches.

**Table 4.3 Checklist for component condition monitoring program (continued)**

**II. Operating Experience**

*A. Identify Plant Operating Experience*

What is the maintenance history?
What is the test/inspection history?
What trend data exists?
What failure data exists (e.g., from databases, operators, manufacturers)?
Has the particular component or a similar component used in a similar application ever failed or been discovered to be in a degraded condition?
 If so, what was the failure mode?
 If so, what was the failure cause? Was the failure time-related?
 If so, what was the failure area?
 If so, what was the discovery method?
Has this component or a similar component in a similar application experienced repetitive failures?
Has this component or a similar component in a similar application ever been changed out or modified? If so, why?
Can failure rates be estimated based on available data/experience for the parameters of interest (e.g., for a 10-in. feedwater pump Model Y from Manufacturer X)?

*B. Identify Industry Operating Experience*

What failure data exists (e.g., from databases, manufacturers, users groups)?
Has the particular component or a similar component used in a similar application ever failed or been discovered in a degraded condition?
 If so, what was the failure mode?
 If so, what was the failure cause? Was the failure time-related?
 If so, what was the failure area?
 If so, what was the discovery method?
Has this component or a similar component in a similar application experienced repetitive failures?
Has this component or a similar component in a similar application ever been changed out or modified? If so, why?
Can failure rates be estimated based on available data/experience for the parameters of interest (e.g., for a 10-in. feedwater pump Model Y from Manufacturer X)?

**III. Safety Assessment**

What is the risk significance of the component?
 What is the component's safety function?
 What are the component's potential failure modes?
 Which failure modes are safety significant?
 What is the likelihood that the component will fail in a safety significant failure mode (see Sect. II)?
 What are the safety/environmental consequences of failure?
Under what operating conditions can the test(s) be performed?

**IV. ALARA Considerations**

Under what operating conditions can the test(s) be performed?
What is the potential for personnel/environmental exposure (see Sect. V)?

**Table 4.3 Checklist for component condition monitoring program (continued)**

| |
|---|
| **V. Test /Monitoring Considerations** |
| What tests/monitoring activities can be performed? |
| Is the component easily isolable? |
| Is the component easily disassembled/reassembled? |
| Is the likelihood of failure increased by disassembly/reassembly? |
| What postactivity measures are available to ensure that the component was not left in a failed state? |
| What diagnostic techniques are available? Which techniques are nonintrusive? |
| Are diagnostic techniques available that provide information about the condition of the component, or do they simply identify that the component has failed? |
| Can the potential test or technique identify precursors to the failure modes of interest (i.e., what is the estimated test effectiveness)? |
| Can the potential test or technique provide information on condition or state (i.e., failed or not failed) of the entire component assembly? |
| What is the accuracy, repeatability, range, and sensitivity of the test equipment? |
| What is the experience and training of test personnel? |
| Under what operating conditions can the test or technique be performed? |
| Is the test equipment compatible with the component (e.g., materials of construction)? |
| Is the test equipment compatible with the system operating conditions (e.g., temperature/pressure)? |
| What characteristics/test data can be trended? |
| What other tests can be performed (e.g., leak rate test, margin)? |
| Do other available tests provide information on the component condition or simply identify that it has failed? |
| Do other available tests provide information on the condition or state (i.e., failed or not failed) of the entire component system? |
| Is the likelihood of failure increased by performance of the test itself? |
| What postactivity measures are available to ensure that the component was not left in a failed state? |
| Monitoring frequency |
| What is the minimum level of degradation that the test/monitoring technique can detect (i.e., how long before failure can the failure be predicted)? |
| What is the historical reliability of the component? What is the risk significance of the component? What is the desired availability of the component? Is component failure acceptable? What preventive maintenance activities are being/can be performed? |

#### 4.2.2.4 Performance testing

Another key element in an effective operability assurance program is that of periodic performance tests. These activities, which are essentially failure detection tasks, are intended to detect, rather than predict or prevent failures. Included within this category are margin tests, minimum flow tests, and ISTs. Generally, these are "go/no-go" tests that seek to determine whether a component meets some performance criteria. If it is desirable for a component to have a very high level of availability, these tasks should be considered supplemental to, not replacements for, the other proactive measures already discussed.

To be effective, performance tests should be able to determine whether any part of a component assembly (i.e., the pump or valve and all its associated subcomponents and auxiliary equipment) has failed. For example, a performance test on an MOV should be able to detect a failure in the control system, electrical circuitry, actuator, and/or valve itself. Of equal importance is that the process of checking for functional failure or performance acceptance not induce failure or degradation. This might occur because of the stresses imposed on the system during the test or from invasive activities that create the opportunity for human-induced failure. Analyses of NPRDS failure data has suggested that in some cases, performance testing could be the cause of increased failure rates in PWR pumps (caused by Code-required minimum flow tests).[9,27] The possibility that the component might be left in the failed state because of the test should also be considered.

## 4.3 Evaluation of Change Requests for Pumps and MOVs

This section presents guidelines for the evaluation of proposed change requests for test interval extension for pumps and MOVs. Recommendations for minimum change request content and the technical evaluation of such requests are provided. The approaches proposed in these guidelines are designed to allow evaluations to proceed through a broad range of possible scenarios because variations in test interval extension proposals, available performance data, applicable components, and service conditions should be accommodated. These guidelines, to be as versatile as possible, allow the reviewer to consider both mature and new technologies as they become available in industry. These guidelines may be used to supplement risk-informed regulatory guides and risk-informed standard review plans but are not limited to risk-informed change requests. They provide a focused technical perspective and methodology for use in the technical review of test interval extension requests. The guidelines describe several elements that should be included in the licensee change requests and the various bases on which the requests should be evaluated and scored. Although the guidelines are presented as specific to evaluation of IST interval extension requests, they are also applicable to evaluation of requests for changes to margin testing programs and for the application of condition monitoring strategies as an alternative to traditional predetermined IST intervals.

It is recommended that evaluations of requests for IST interval extensions for pumps and MOVs should generally follow the technical review process described in this section. Higher tier or program-level descriptions of the evaluation process and basic activities that should be included in the process are presented in Sect. 4.2.

The guidelines presented in this section follow the general process discussed in Fig. 4.2, that is, the evaluation of requests for IST extensions should include three basic elements:

- evaluation of the licensee's engineering analysis used to determine IST interval allowances,
- evaluation of the licensee's overall program to assure component operability, and
- evaluation of the licensee's trending and feedback mechanisms that ensure that test intervals are reevaluated and updated as necessary.

### 4.3.1 Evaluation of Proposed IST Interval Extensions for Pumps

#### 4.3.1.1 Minimum IST Extension Request Content for Pumps

The evaluation should determine if the following elements as a minimum are included in the IST interval extension request for pumps:

- Pump sy[illegible] identification of the system(s) in which the pump(s) operate.
- Specific pump application(s) – description of the service conditions, type and condition of fluid, and general type of application for each pump. If pumps are characterized as either low safety significant components (LSSCs) or high safety significant components (HSSCs), a description of how the characterization was made should be included.
- Type of pump driver – engineering information regarding the motor or turbine drive(s).
- Failure modes – description of the way in which a component is likely to fail (e.g., failure to pump sufficient fluid because of impeller wear). This will typically be determined from analysis of historical data.
- Proposed interval extension(s) – identification of the past and proposed frequency of ISTs.
- Detailed justification for the extension – technical basis that ensures safety while increasing test intervals.
- Performance data for pump and driver – description of failure and engineering data (such as that available from NPRDS or EPIX) specifically for the pump(s) and driver(s) to which the interval extension would apply (both plant-specific and industry data should be included, as available). This data may also include excerpt, citation, or reference to published failure data and characterization studies. A description of the data obtained through diagnostic testing activities (condition indicators) should also be included.
- Maintenance, IST, monitoring, and diagnostics – description of historic maintenance, testing, and monitoring/diagnostic programs that have been used to detect and control the rate of degradation/failure in the pump(s) and driver(s). Proposed programs to improve maintenance, testing, and/or monitoring/diagnostics to be employed during extended IST intervals should also be identified. Information on proposed IST technologies and their potential usefulness in detecting significant failure modes of interest should be included.

- Trending and feedback mechanisms – description of activities that ensure that data trending will be performed as a means of gaining advanced awareness of approaching failures or increasing rates of degradation. Feedback mechanisms that ensure necessary maintenance responses are initiated and any necessary changes in testing or preventive actions should be included.

### 4.3.1.2 Technical Evaluation of IST Extension Requests for Pumps

The technical evaluation should focus primarily on the following elements of the IST interval extension request for pumps and should encompass the following criteria/considerations:

**Evaluation of Engineering Analysis**

- Specific pump application(s) – Special service conditions (e.g., abrasives, high temperature) should be fully described whenever applicable. Component groupings for the purpose of reliability assessment and the basis for selecting these groupings should be identified. The basis for assigning pumps to LSSC and HSSC categories (if applicable) should also be evaluated.

- Performance data – This data should clearly indicate what degradation is taking place in the pump groupings considered for IST interval extension and therefore what maintenance, testing, and monitoring/diagnostics are needed to preclude or reduce the frequency of the critical failure modes. Both plant-specific and industry data should be included. The pump population on which the data is founded must not be overly broad to include pumps in diverse service conditions and duty requirements. If a very narrow population is presented that includes just the applicable pumps at the plant for which interval extension is sought, the total service time in pump-years should be considered. If the total service is <250 pump-years (approximately), the data should be supplemented with a larger body (preferably >500 pump-years) of data for pumps in similar service and/or application.

  Pump motor reliability is generally high; however, the application under study should not represent an exception. An estimate of motor life (readily available from the licensee and/or motor manufacturer) should be compared to the proposed testing interval.

- Failure modes – In general, the failure modes of greatest importance will be significant failures of the bearings, pump internals, seal/packing, shaft/coupling, and possibly other areas. These failure modes are defined by the plant-specific and industry performance data. This information should be used to evaluate the suitability and completeness of the proposed maintenance, IST, monitoring, and diagnostics activities. The bases by which the failure modes can be correlated to maintenance, IST, monitoring, and diagnostics include (1) information supplied in the test interval extension submission, (2) this report, and (3) published documents.[6,9,10,28]

  For turbine drives, the failure rate in the nuclear industry is relatively high, and the number of possible failure areas is much higher than for the pump or pump motor.[6] A similar situation exists for pump-related circuit breakers (which are not included in the IST program). Therefore, unless unusual circumstances exist and a sound technical argument is provided, it is unlikely that justification can be found for extending test intervals or diminishing any type of test or maintenance activity for turbine drives and pump-related circuit breakers. Moreover, the addition or improvement of diagnostics and monitoring for these items should be encouraged as an important means of improving availability in the pump assemblies (i.e., including essential auxiliary equipment).

- Detailed justification for the extension – This guide is based on the assumption that a regulatory evaluation of the request for IST interval extension will be performed in addition to that found in the actual engineering analysis submitted by the licensee. Nevertheless, the submitted analysis should be reviewed to determine how well-conceived the proposed interval extension is and what reliance is placed on supporting performance data, maintenance, and monitoring. Obviously, a well thought-out quantitative and technically sound analysis should be considered more highly than one that is qualitative and vague. The most important consideration in light of the analysis and available data is whether the licensee provides a strong case for satisfactory pump performance during the extended test intervals on a long-term (i.e., multi-interval) basis. Secondly, if the pump degradation becomes severe between tests, will it likely be detected and what adverse consequences may result? Thirdly, what is the likelihood and impact of unscheduled corrective maintenance?

In some cases, the components under study (e.g., pump internals) and the available data may be appropriate for margin analysis (i.e., the determination of the probability of having inadequate margin). If the results of such an analysis will be useful in the determination or justification of test interval extensions, it might be useful for the requests for extensions to make use of the parametric studies described in Chap. 5. Otherwise, a more open scope of technically sound arguments/justifications based on established reliability theory and appropriate component performance data should, of course, be permitted. For instance, it would *not* be possible to use margins in the analysis of pump bearing failures because the margin-related definitions of *requirement* and *capability* do not apply. However, suppose that, in extending the test interval, the submitter prorates the pump bearing failure probability by the new to old test intervals (i.e., assumes a constant failure rate). This can be justified because bearing repairs involve replacement (i.e., full renewal) and an almost random in-service date distribution exists for bearings in typical plants (see discussion on the randomization of failures in Sect. 2.1.2). The conservatism of this approach is even more apparent as additional aspects of the enhanced testing program are considered, such as staggered testing programs using advanced diagnostic and monitoring technologies/techniques that, in the case of bearings, can provide accurate predictions of remaining life.

**Evaluation of Overall Operability Assurance Program**

- Maintenance – The maintenance program should be a mature program that has proven to be adequate for long-term control of the pump failure rate. The preventive maintenance program should be carefully designed to consider logical pump groupings, their corresponding failure rates, specific stressors, and the most vulnerable piece-parts.

- IST effectiveness – A sound technical basis should provide assurance that IST will be effective in assessing the availability of the pump (of course, this assurance is essentially limited to the time of testing). In general, the primary consideration will be how realistic the test conditions are (e.g., flow and pressure).

- Monitoring and diagnostics – Tools and methods now exist to predict remaining bearing life (see Sect. 3.2.4). The extension request should include an accurate method of bearing life prediction in instances where the pump is accessible and the method practical for the pump application/location. This can be accomplished today using technologies such as vibration analysis, spectral acoustic analysis, thermography, and lubrication analysis. Nonintrusive monitoring of the pump hydraulic performance should also be included, if practical. This can be accomplished using technologies such as ESA, spectral vibration analysis, standard root-mean-square vibration analysis, and acoustic signature. ESA and standard vibration analysis are also useful in monitoring the condition of the shafts and coupling.

  Motor testing should include bearing and megger tests as necessary based on the estimated reliability of the motor. Other useful motor tests include polarization index and inductive imbalance (several additional tests are currently under development). Combinations of these diagnostic and monitoring technologies and techniques will add significantly to the assurance of satisfactory long-term operation. The implementation of an improved testing/monitoring program is generally needed to justify an extension of testing intervals.

**Evaluation of Trending and Feedback Mechanisms**

- Trending and feedback – Mechanisms should be in place that allow for trending of maintenance, monitoring, and test data as well as information on functional failures. These may include, but are not limited to, trending of spectral bearing vibration data, overall vibration data, and ESA data. Trending of available data should be used to periodically reevaluate IST, maintenance, and monitoring intervals. Failure rates for groupings should compare well to those of pumps in similar applications (both plant-specific and elsewhere in industry), and no significant year-to-year increase in failure rate should be observed. Similarly, no trend showing an increase in failure rate relative to pump age groups should be evident.

#### 4.3.1.3 Interval Extension and Quantification

Licensee requests for IST interval extension should have sound technical bases for there to be adequate assurance that extended test intervals will not increase the likelihood of component degradation or failure. Furthermore, a consideration of the adverse consequences that could result from IST interval extension relates to failure risk (i.e., the combination of failure probability and consequence). Clearly, in the more critical pump applications where a loss could result in adverse safety implications, the standards for interval extension should be carefully considered.

Figure 4.5 is a sample form that might be adopted and refined for use in evaluating IST interval extensions for pumps. The form incorporates a scoring system that would quantify the process and help to make evaluations more consistent. The form helps to ensure that the evaluation weighs risk, failure rate, quality of data, applicability of data, maintenance, monitoring and diagnostics activities, and trending and feedback to reach a technically sound decision for IST interval extension rejection or approval.

## 4.3.2 Evaluation of Proposed IST Interval Extensions for MOVs

### 4.3.2.1 Minimum IST Extension Request Content for MOVs

The evaluation should determine if the following elements as a minimum are included in the IST interval extension request for MOVs:

- MOV system(s) – identification of the system(s) in which the MOV(s) operate.
- Specific MOV application(s) – description of the service conditions (including external environment), type and condition of fluid, and general application for each MOV. The application should include whether the service being considered is isolation or modulation and the position that the valve is required to achieve to fulfill the safety function (open or closed). Application should also consider stresses incurred when the valve is used as part of a test for other components and the frequency of operation. If MOVs are characterized as either LSSCs or HSSCs, a description of how the characterization was made should be included.
- MOV type – engineering information regarding the motor type (ac or dc), whether the valve is position- or torque-seated, and the valve type (gate, globe, butterfly).
- Failure modes – description of the way in which a component is likely to fail (e.g., failure to stroke for the actuator or failure to isolate flow for the valve). This will typically be determined from analysis of historical data.
- Proposed interval extension(s) – identification of the past and proposed frequency of ISTs.
- Detailed justification for the extension – technical basis that ensures safety while increasing test intervals.
- Performance data for MOV – description of failure and engineering data (such as that available from NPRDS or EPIX) specifically for the MOV(s) to which the interval extension would apply (both plant-specific and industry data should be considered, as available). This data may also include excerpt, citation, or reference to published failure data and characterization studies. A description of the data obtained through diagnostic testing activities (condition indicators) should also be included.
- Maintenance, IST, monitoring, and diagnostics – description of historic maintenance, testing, and monitoring/diagnostic programs that have been used to detect and control the rate of degradation/ failure in the MOV(s). Proposed programs to improve maintenance, testing, and/or monitoring/diagnostics to be employed during extended IST intervals should be identified. Information on proposed IST technologies and their potential usefulness in detecting significant degradation and failure modes of interest should be included. This section should also identify maintenance performed for compliance to other regulations, such as 10 Code of Federal Regulations (CFR) 50.49.
- Trending and feedback mechanisms – description of activities that ensure that data trending will be performed as a means of gaining advanced awareness of approaching failures or increasing rates of degradation. Feedback mechanisms that ensure that necessary maintenance responses are initiated and any necessary changes in testing or preventive actions should be included.

Reviewer: Date:

Description of applicable pumps:

Pump driver description:

In general, was adequate information supplied by submitter?

Omissions in submitter's package:

Performance data (significant findings):

Condition indicator data (significant findings):

Failure data (significant findings):

Description of maintenance program:

Changes to maintenance program, if any:

Description of monitoring/diagnostic program:

Changes to monitoring/diagnostic program, if any:

Description of trending/feedback program:

Changes to trending/feedback program, if any:

Summary of justification:

Strengths of submitter's plan/justification:

Deficiencies in submitter's plan/justification:

**Scoring of test interval extension plan (for each pump grouping)**

**(1 = strongly disagree, 5 = strongly agree)**

1. Failure rates have historically been acceptable, and trend data supports the new test interval. ________
2. Significant failure modes are understood and are detectable prior to failure. ________
3. The maintenance program will support the new test interval. ________
4. The monitoring and diagnostic programs will support the new test interval, and trending and feedback mechanisms are in place to periodically reevaluate test intervals. ________
5. The justification illustrates a strong and well-conceived program. ________

Total: ________

*Minimum passing score:*

*Pump represents a high safety significant component:* 20
*Pump represents a low safety significant component:* 15

**Figure 4.5 IST interval extension request evaluation form for pumps**

#### 4.3.2.2 Technical Evaluation of IST Extension Requests for MOVs

The technical evaluation should focus primarily on the following elements of the IST interval extension request for MOVs and should encompass the following criteria/considerations:

**Evaluation of Engineering Analysis**

- Specific MOV application(s) – Special service conditions (e.g., abrasives, high temperature, degraded voltage, bonnet orientation, potential for thermal binding) should be fully described whenever applicable. Component groupings and the basis for selecting those groupings should be identified. The basis for assigning MOVs to LSSC and HSSC categories (if applicable) should be identified.

- Performance data – This data should clearly indicate what degradation is taking place in the MOV groupings considered for IST interval extension and therefore what maintenance, testing, and monitoring/diagnostics are needed to preclude or reduce the frequency of the critical failure modes. Both plant-specific and industry data should be included. The MOV population on which the data is founded must not be overly broad to include MOVs in diverse service conditions and duty requirements. If a very narrow population is presented that includes just the applicable MOVs at the plant for which interval extension is sought, the total service time in MOV-years should be considered. If the total service is <200 MOV-years (approximately), the data should be supplemented with a larger body (preferably >500 MOV-years) of data for MOVs in similar service and/or application.

- Failure modes – In general, the failure modes of greatest importance will be significant failures of the limit switch, torque switch, disc/seat, stem friction increase from degraded lubrication, motor, geartrain, and possibly other areas. These failure modes are defined by the plant-specific and industry performance data. This information should be used to evaluate the suitability and completeness of the proposed maintenance, IST, monitoring, and diagnostics activities. The bases by which the failure modes can be correlated to maintenance, IST, monitoring, and diagnostics include (1) information supplied in the test interval extension submission, (2) this report, and (3) published documents.[7,8]

- Detailed justification for the extension – This guide is based on the assumption that a regulatory evaluation of the request for IST interval extension will be performed in addition to that found in the actual engineering analysis submitted by the licensee. Nevertheless, the submitted analysis should be reviewed to determine how well-conceived the proposed interval extension is and what reliance is placed on supporting performance data, maintenance, and monitoring. Obviously, a well thought-out quantitative and technically sound analysis should be considered more highly than one that is qualitative and vague. The most important consideration in light of the analysis and available data is whether the licensee provides a strong case for satisfactory MOV performance during the extended test intervals on a long-term (i.e., multi-interval) basis. Secondly, if the MOV degradation becomes severe between tests, will it likely be detected and what adverse consequences may result? Thirdly, what is the likelihood and impact of unscheduled corrective maintenance?

**Evaluation of Overall Operability Assurance Program**

- Maintenance – The maintenance program should be a mature program that has proven to be adequate for long-term control of the MOV failure rate. The preventive maintenance program should be carefully designed to consider logical MOV groupings, their corresponding failure rates, specific stressors, and the most vulnerable piece-parts.

- IST effectiveness – A sound technical basis should provide assurance that IST will be effective in assessing the availability of the MOV (of course, this assurance is essentially limited to the time of testing). In general, the primary consideration will be how realistic the test conditions are (e.g., flow and pressure).

- Monitoring and diagnostics – Technologies now exist to monitor valve and operator condition and to predict delivered thrust. The extension request should include an accurate method of thrust measurement or prediction in instances where the MOV is accessible and the method is practical for the MOV application/location. Direct thrust measurement is preferable to thrust prediction. Thrust verification can be accomplished today using technologies such as direct measurement or analysis of motor electrical signatures (see Appendix A).

**Evaluation of Trending and Feedback Mechanisms**

- Trending and feedback – Mechanisms should be in place that allow trending of maintenance, monitoring, and test data as well as information on functional failures. These may include, but are not limited to, trending of opening and closing stroke data and ESA data. Trending of available data should be used to periodically reevaluate IST, maintenance, and monitoring intervals. Failure rates for groupings should compare well to those of MOVs in similar applications (both plant-specific and elsewhere in industry), and no significant year-to-year increase in failure rate should be observed. Similarly, no trend showing an increase in failure rate relative to MOV age groups should be evident.

#### 4.3.2.3 Interval Extension and Quantification

Licensee requests for IST interval extension should have sound technical bases for there to be adequate assurance that extended test intervals will not increase the likelihood of component degradation or failure. Furthermore, a consideration of the adverse consequences that could result from IST interval extension relates to failure risk (i.e., the combination of failure probability and consequence). Clearly, in the more critical MOV applications where a loss could result in adverse safety implications, the standards for interval extension should be carefully considered.

Figure 4.6 is a sample form that might be adopted and refined for use in evaluating IST interval extensions for MOVs. A scoring system that would quantify the process and help improve the consistency of evaluations is also included.

The analysis should weigh risk, failure rate, quality of data, applicability of data, maintenance, monitoring and diagnostic activities, and trending and feedback to reach a technically sound decision for IST interval extension rejection or approval.

## 4.4 Considerations for Test Interval Extension

The current ASME Code specifies quarterly IST intervals for most components, where practicable. In some cases, however, this frequency may be overly burdensome in terms of economic costs and potential detrimental effects on the components. Because recent industry initiatives such as risk-informed IST and condition monitoring have focused attention on obtaining relief from traditional (relatively short) test intervals for some components, the process for determining appropriate periodic performance test intervals needs to be addressed. As explained throughout this report, the use of generic test intervals for a broad spectrum of components whose design and service parameters (e.g., application, service condition, duty cycle) are diverse is generally inappropriate. Because parameters such as those listed in Table 4.2 have been shown to significantly affect component performance and reliability, logical groupings need to be identified to establish more appropriate test intervals. (This applies to monitoring and maintenance intervals as well.) Groupings are established by identification of the parameters with which component performance is most likely to correlate. This information is usually available from historical performance data (see Chap. 2).

Once logical groupings have been established, the determination of appropriate test intervals can proceed using the grouping parameters as inputs. For example, a calculation for test intervals used in commercial (nonnuclear) process industries as part of an overall reliability centered maintenance (RCM) program can be expressed in terms of the component's allowable unavailability, its reliability (expressed as mean-time-between-failure [MTBF]), and test interval:[13,29,30]

$$\text{Test interval} = 2 \times \text{MTBF} \times \text{Allowable unavailability.}^{*\dagger} \qquad (4.1)$$

This linear relationship is considered to be valid for all unavailabilities < 5%, provided that the component behavior conforms to an exponential survival distribution (failure pattern 2 or random failure in Fig. 2.13). The key point is that the test interval is dependent on the combination of the importance of the component[‡] and its likelihood of failure.

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[*] Unavailability = 1 – availability; MTBF = 1/failure rate.

[†] This calculation does not include any downtime resulting from the test or from required repairs, because the downtime required to perform the test and/or to complete any resulting repairs is likely to be very small compared to any unknown unavailability between tests (and will usually be mathematically negligible). Furthermore, tests and repairs would normally be accomplished with the component declared out-of-service, so that the component would not be called upon to function during the test or repair period.

[‡] The importance of the component is determined by the licensee by, for example, PRA techniques.

Reviewer: Date:

Description of applicable MOVs:

MOV driver description:

In general, was adequate information supplied by submitter?

Omissions in submitter's package:

Performance data (significant findings):

Condition indicator data (significant findings):

Failure data (significant findings):

Description of maintenance program:

Changes to maintenance program, if any:

Description of monitoring/diagnostic program:

Changes to monitoring/diagnostic program, if any:

Description of trending/feedback program:

Changes to trending/feedback program, if any:

Summary of justification:

Strengths of submitter's plan/justification:

Deficiencies in submitter's plan/justification:

**Scoring of test interval extension plan (for each MOV grouping)**

**(1 = strongly disagree, 5 = strongly agree)**

1. Failure rates have historically been acceptable, and trend data supports the new test interval. ______

2. Significant failure modes are understood and are detectable prior to failure. ______

3. The maintenance program will support the new test interval. ______

4. The monitoring and diagnostic programs will support the new test interval, and trending and feedback mechanisms are in place to periodically reevaluate test intervals. ______

5. The justification illustrates a strong and well-conceived program. ______

Total: ______

*Minimum passing score:*

*MOV represents high safety risk:* *20*

*MOV represents low safety risk:* *15*

**Figure 4.6 IST interval extension request evaluation form for MOVs**

This approach to estimation of test intervals is presented for two reasons: (1) it illustrates how other commercial process industries have addressed the issue of test interval determination, and (2) it identifies a relationship among test interval, unavailability, and reliability.

Various methods may be used to calculate component test intervals assuming that the selected method is technically defensible and conservative in the context of the licensee's overall operability assurance program.

Equation 4.1 represents a simplistic approach to test interval calculation that may be appropriate for component groupings found in nuclear industry applications. Other, more rigorous methods for calculation of test intervals may also be useful and can be found in standard RCM and reliability engineering texts. The engineering analysis presented by the licensee as a basis for test interval extension should identify the methodology used to estimate specific test intervals and its associated limitations. The engineering analysis should also validate the methodology's applicability to the components under consideration for interval extension.

Statistical methodologies such as those presented in Chap. 5 may also be used as a basis to estimate test intervals for certain groups of components, provided that the range of applicability and the limitations of the methodologies are appropriate. Chapter 5 provides results of parametric studies performed to assess the effects of test interval and aging on component margin and component unavailability. The parametric studies explore the contributions of varying deterioration rates, statistical parameters, and length of test intervals. These studies are based on mathematical models for component behavior (assuming that age-related failures account for the dominant failure modes) and are presented as bounding case estimates. When using these approaches to test interval determination, the licensee's justification should describe the basis for the behavior model chosen, the historical performance data that validates the behavior model and aging rates used, and the basis for any other inputs to the analysis.

Regardless of how test intervals are initially estimated, they should be periodically reevaluated and adjusted based on appropriate trend data. Trending and feedback mechanisms should be an integral part of operability assurance programs. The purpose of these mechanisms is to adjust all activity intervals (i.e., testing, monitoring, and maintenance) as necessary based on analysis of data acquired from these activities. As experience is gained, the methods used to calculate test intervals can also be reassessed and modified if necessary.

### 4.4.1 Periodic Reevaluation of Test Intervals

Data trending is necessary to validate and, where required, to modify or extend test intervals. Data to be trended may come from periodic diagnostic tests, from performance tests (usually in a limited sense), and from component failures and/or maintenance records. Operational data, including number of cycles, actuations, or operating time, if available, would also be useful. As more data becomes available, the accuracy of failure rate estimations can be improved. A more detailed discussion of data trending for pumps and MOVs is provided in Sect. 3.2.5. Any proposed extension of test intervals should also take into account the factors discussed in Table 4.3 (condition monitoring programs) and should be validated by review of both plant and industry experience with the component(s) under consideration for extension.

## 4.5 Summary

Table 4.4 Summarizes key points and important results from Chap. 4

**Table 4.4 Summary of key points and results**

| Section | Key points and results |
|---|---|
| Process for change request evaluation | ❑ Evaluations should focus on engineering and programmatic aspects of licensee activities as well as on specific test intervals. The evaluation process should consist of<br>▪ review of licensee's engineering analysis<br>▪ review of licensee's overall operability assurance program<br>▪ review of licensee's trending/feedback mechanisms.<br>Test, inspection, and maintenance intervals should be plant-specific and should be included in licensee submittals. |

**Table 4.4 Summary of key points and results (continued)**

| Section | Key points and results |
|---|---|
| Engineering analysis evaluation | ❑ Scope and quality of engineering analysis should be appropriate for requested changes. Analysis should consider<br>▪ component groupings<br>▪ historical plant and industry experience<br>▪ failure consequences<br>▪ functions, failure criteria, critical failure modes<br>▪ unavailability and risk implications.<br>❑ Analytical approaches should be based on actual data and should be supplemented with deterministic evaluations.<br>❑ Component specialists should be included in expert panel composition if an expert panel is used to provide input to the analysis process. |
| Overall operability assurance program evaluation | ❑ Component operability programs should be integrated in nature, considering<br>▪ operation,<br>▪ testing,<br>▪ monitoring,<br>▪ maintenance, and<br>▪ trending and feedback mechanisms.<br>❑ Proactive measures intended to prevent failures are preferable to activities that detect or correct failures.<br>▪ Condition monitoring (diagnostic testing) and preventive maintenance are examples of proactive measures.<br>▪ Performance tests (such as ISTs and margin tests) and corrective maintenance are examples of failure detection and failure correction activities. |
| Trending and feedback program evaluation | ❑ Trendable diagnostic and performance data that may provide information about component condition or likelihood of failure should be recorded and periodically assessed for trends.<br>❑ Feedback mechanisms should be in place to adjust maintenance, testing, and monitoring activities and intervals as necessary based on data trends. |
| Evaluation of change requests for pumps and MOVs | ❑ Minimum contents for change requests:<br>▪ System<br>▪ Application<br>▪ Type of pump driver or type of MOV<br>▪ Failure modes<br>▪ Proposed interval extensions<br>▪ Detailed justification for extension<br>▪ Description of performance data<br>▪ Description of historic and proposed maintenance, IST, monitoring, and diagnostic programs<br>▪ Description of historic and proposed trending and feedback programs<br>❑ Technical evaluation of change requests should consist of<br>▪ Evaluation of engineering analysis<br>▪ Evaluation of overall operability assurance program<br>▪ Evaluation of trending and feedback mechanisms |

**Table 4.4 Summary of key points and results (continued)**

| Section | Key points and results |
|---|---|
| Considerations for test interval extension | ❑ Test intervals should be determined by the importance of the components and their likelihood of failure.<br>❑ Trending and feedback mechanisms are necessary to validate and periodically reevaluate test intervals and the methods used to estimate specific test intervals. |

# 5 Inadequate Margin Failure Mode: Probability of Failure and Unavailability as a Function of Margin and Testing Characteristics

## 5.1 Overview

This chapter presents the bases for the computation of failure probabilities from margin time trends and margin statistics and illustrates how to characterize the inadequate margin failure mode. Existing databases show that failure rates and their distribution functions are far from uniform, varying significantly with the type of component, design, manufacturer, application, and maintenance. Thus, neither the rates and statistical distributions of failures due to inadequate margin alone nor the rates of margin change (RMC) and statistical distributions are expected to be uniform. Missing in existing databases is any information related to how the capability and requirement—or the margin—of components, such as valves and pumps, behave with time. Thus, it is not possible to know how they behave statistically.

Because of this lack of fundamental data it was decided to illustrate a statistical methodology to examine the probability of component failure and unavailability due to inadequate margin by means of parametric studies. A virtual component characterized by an exponential deterioration of margin with age and by lognormal statistics was chosen. Exponential deterioration of margin with age implies that the requirement increases exponentially with time; the capability either remains essentially constant or decreases exponentially with time. The assumption that capability decreases exponentially with time is often debatable, but mathematical tractability and the fact that it covers the no-deterioration in capability case justifies its use here. The choice of the lognormal distribution to describe the statistics of margin is also arbitrary, but it is typical of industrial components. No component used in any nuclear plant is known to behave like this virtual component. Consequently, use of the numbers and illustrations in this chapter is not warranted for purposes other than the intended (i.e., to illustrate a methodology).

Because it is impossible to extract from existing failure data the failure mode component corresponding to inadequate margin, parametric studies are performed with formulae derived for a generic case in which the overall failure rate is presumed to vary exponentially with time. The formulae could be used and the results may be interpreted as corresponding to the particular case of failures due to inadequate margin. The values of the initial failure probability due to inadequate margin and the RMC should be used, where pertinent in the formulae, instead of the overall failure-oriented parameters.

The parametric studies illustrate how RMCs, statistical parameters, and length of testing intervals would affect the failure probability and unavailability of this theoretical component. Strictly, these results could be used for decision making on adequacies of margins, length of test intervals for margin assessment, and impact of changes in the length of IST intervals *only* for this particular theoretical component and this particular failure mode (inadequate margin).

Presently, ISTs generally only test or report the "snapshot" operability of a component, that is, the "go" vs "no-go" status of the component. ISTs do not necessarily test and report the amount of margin available. ASME Code Case OMN-1 does not specify an actual measurement of margin until it reaches a low-threshold value. Consequently, appropriate actions should be taken to ensure that the necessary data is available in the future for a rational application of margin-based techniques to nuclear plant components.

The methodology used in the evaluations of component unavailability vs time interval between tests documented in this chapter could be applied to present ISTs by interpreting the test intervals as IST intervals and by considering that the parameters correspond only to margin-degradation-related operability failures, that is, "go/no-go" failures.

The parametric studies address both initial (time = 0) and time-dependent evaluations of the failure probability of the theoretical component for the inadequate margin failure mode. Unavailabilities as a function of test interval and test downtime, with and without repair maintenance, are also computed. Not considered are the probability of failure added by imperfect maintenance or refurbishment (renewal) and the possibility that refurbishment may not restore the component's original resistance to failure (i.e., "as good as new").

## 5.2 General Methodology for the Development of Capability vs Requirement Models

This section presents the general methodology for determining the failure probability of a component from descriptions of how its capability and requirement vary statistically and with time (i.e., age). The failure probability determined in this section corresponds to the failure mode of inadequate margin, that is, the probability that at a given time the capability is less than the requirement. The mathematical bases are those of standard stress-vs-strength methodologies.

Stress-vs-strength models focus on the study of the probability that the acting capability of a component is less than the action requirement. Stress-vs-strength models are useful when measurable parameters can be directly correlated to single parameters characterizing the component's capability and requirement. For example, the capability of a motor-driven component could be characterized by the torque produced at the motor shaft. It could also be characterized by the torque at a gearbox's output shaft or by the thrust imparted to a valve stem. The requirement, in turn, should be characterized consistently, that is, by either the torque required at the motor or gearbox output shaft or by the force at the stem required for the valve to operate.

The time dependence of the capability of a motor-driven component may be governed by a function incorporating the effects of changes in motor components such as insulation degradation, core losses, and friction and windage losses. The time dependence of the requirement of a valve may be governed by functions describing the effects of changes in gearbox losses, friction, and seating forces with time.

In this study, margin is defined as the ratio of capability to requirement, which is dimensionless. The term "excess capability" is also used in the literature. It refers to the difference between the capability and requirements (see Fig. 5.1). It has the same units as the capability and requirement, but it is not used in this study.

In this section, RMC refers only to the rate of change in margin caused by aging effects that impact the inadequate margin failure mode. The overall component deterioration rate would include the contributions of all failure modes.

The general methodology for determining the failure probability due to inadequate margin is presented in Fig. 5.1; it shows hypothetical curves of capability and requirement vs time for a theoretical component. These curves, when considered to be deterministic, would correspond to the behavior of a particular component. The point F where the two curves intersect

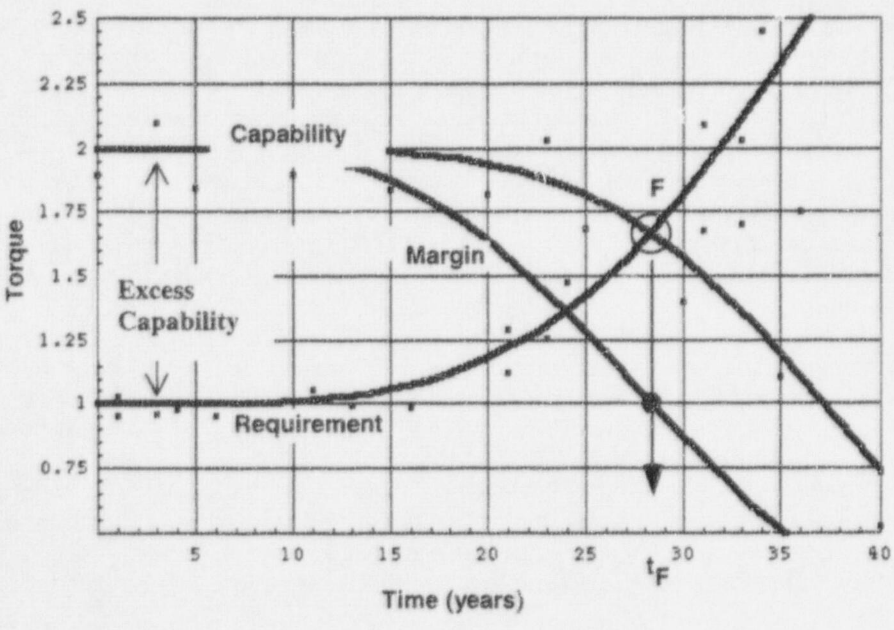


**Figure 5.1 Hypothetical age dependence of capability, requirement, and margin.** (Note that the capability and requirement intersect at F where margin = 1.)

(i.e., margin = 1) would be the point of failure (i.e., $t_F$ = 28.4 years.) When studying the behavior of a large group of similar components, that is, similarly built and loaded, the curves may instead represent the loci of the mean values, median values, or other selected representative measures of sets of data points taken on the group at particular times. Then, the point F in Fig. 5.1 would yield the apparent time of failure. Because of the variability and uncertainty of the values of capability and requirement around each point in time, however, there would be a probability that the component capability is less than the requirement even at times before $t_F$. Similarly, there would be a probability that the capability of a component is higher than the requirement even at times after $t_F$.

The failure probability due to inadequate margin at a certain point in time depends on the degree of overlap between the statistical distributions of capability and requirement at the particular time. In general, it is assumed that the capability and requirement are independent random variables. Then the probability that the capability is less than the requirement is given by the formula:

$$P(c<r)=\int_0^{\infty} f_c(c)\int_c^{\infty} f_r(r)\,dc\,dr \quad , \tag{5.1}$$

where $P(c < r)$ represents the failure probability due to inadequate margin (probability that the value of c is less than the value of r), and the terms $f_c(c)$ and $f_r(r)$ are the probability densi[illegible]ns (PDFs) for the capability (c) and requirement (r), respectively, at a given time. The integrals in Eq. (5.1) are over a[illegible] values of c and r such that $c < r$.

The dimensionless margin is numerically defined as the ratio of the capacity to the requirement:

$$m = c/r \quad , \tag{5.2}$$

where

- $m$ = the margin to carry out the function,
- $c$ = the capability to perform the function,
- $r$ = the requirement to perform the function.

Because the capability decreases and the requirement increases, the margin decreases with age.

Note that, in terms of the margin $m = c/r$, Eq. (5.1) can also be written as

$$P(c<r)=P\left(\frac{c}{r}<1\right) \tag{5.3}$$

$$=P(m<1) \tag{5.4}$$

Thus, Eq. (5.1) also gives the probability that the margin is less than 1. The failure probability due to inadequate margin is thus also equal to the probability that the margin is less than 1.

Figure 5.2 illustrates hypothetical density functions for $f_c(c)$ and $f_r(r)$ at a given time corresponding to the age dependence curves of capability and requirement previously shown in Fig. 5.1. The probability that the capability is less than the requirement, as computed by Eq. (5.1), is shown as the shaded area in Fig. 5.2. Per Eq. (5.1), the shaded area in Fig. 5.2 is the product of the PDF curve for the capability times the cumulative distribution function (CDF) curve of the requirement.

For specific applications, specific distributions need to be substituted for $f_c(c)$ and $f_r(r)$ in Eq. (5.1). Where data is sparse, standard statistical distributions are used for $f_c(c)$ and $f_r(r)$. The lognormal, normal, and Weibull distributions are commonly used. In subsequent sections, values for $P(c < r)$ are computed using parametric values and lognormal distributions.

In specific applications it is also important to consider that the performance of some components can be affected by external conditions, such as voltage, load, and humidity. These should be considered in developing the age-dependent curves of capability and requirement. For instance, in motor-driven components the capability depends on the applied voltage. Figure 5.3 illustrates possible different capability curves as a function of the applied voltage. The apparent time of failure $t_F$ will then be a range as shown in the figure. These effects should be considered in selecting appropriate field data to generate the probability density functions and trend functions.

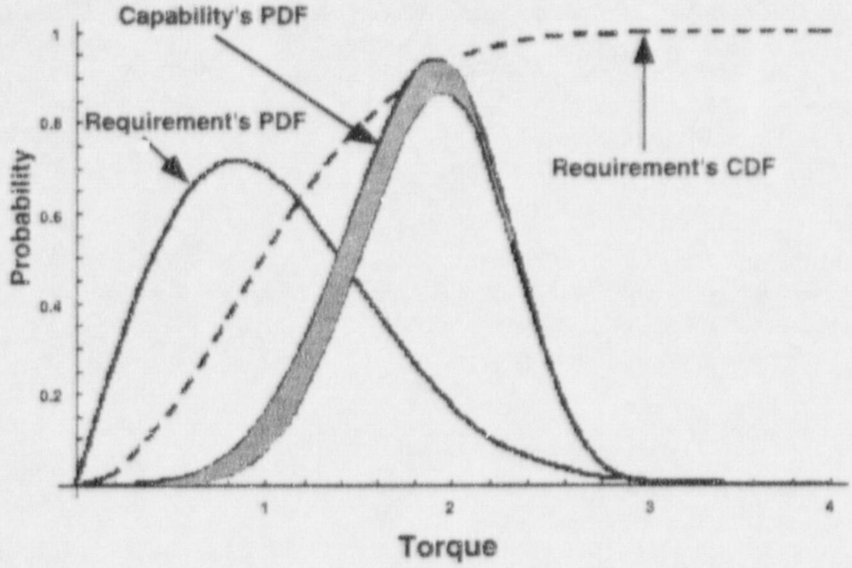


**Figure 5.2 Hypothetical continuous distribution functions for capability and requirement.** (The shaded area is the probability of failure. The monotonic curve is the CDF of the requirement.)

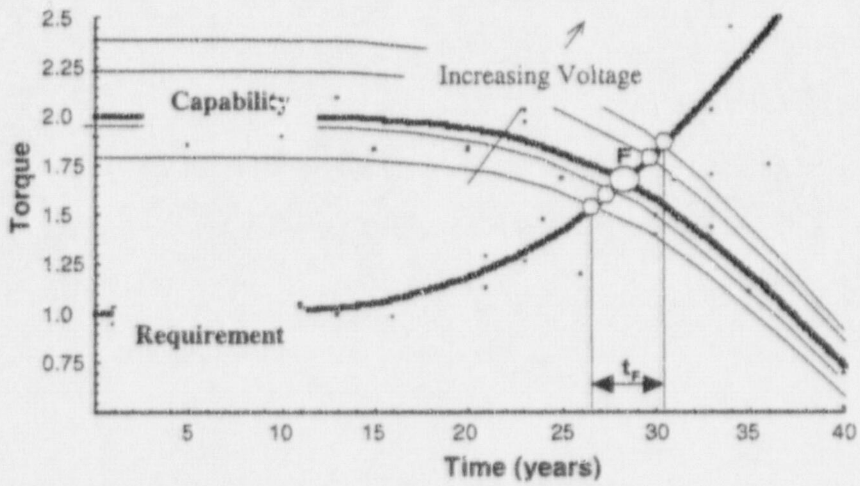


**Figure 5.3 Hypothetical age dependence of requirement and voltage-dependent capability**. (The apparent time of failure is now a range.)

## 5.3 Probability of Inadequate Margin: Selection of Margin Time Dependence and Statistics

As indicated in Sect. 5.2, because of the statistical nature of the component population, the probability of inadequate margin is not zero when the estimated margin is larger than 1 (similarly, the probability of adequate margin is not necessarily zero when the estimated margin is smaller than 1). To study the probability of inadequate margin, the probability distributions of the capability and requirement need to be known. When these probability distributions are not available from measurement data, then standard distribution forms can be assumed and parametric studies carried out. Characteristics that must be supplied for standard distributions usually include the mean and/or the standard deviation. The assumptions behind the chosen distribution should always be checked for reasonability, and alternate distributions should be considered if needed.

In the following, the formulae related to the probability of inadequate margin for the initial margin are derived first with log-normal statistics. Subsequently, an exponential time dependency of the margin is incorporated into the formulae. The results obtained with similarly derived formulae, using statistical distributions and time dependencies representative of the component of interest, could be used to assess test intervals for component margin.

### 5.3.1 Initial Probability of Inadequate Margin for Lognormal Statistics

To define the statistical distributions of capability and requirement, standard probabilistic approaches can be used. As indicated in Sect. 5.2, the normal, lognormal, and Weibull are among the standard distributions typically used in these types of studies. The lognormal distribution is often used for reliability studies and for PRA applications. For the parametric studies in this report, however, the lognormal distribution has been chosen because it seems realistic for the kind of systems involved and it is adequate for the analysis of ratios of random variables. When the capability and requirement are describable by lognormal distributions with independent means and standard deviations, then the distribution of the ratio of the capability to requirement, i.e., the margin, also has a lognormal distribution. This feature allows focusing on the margin directly without having to operate with the capability and requirement separately. The mean and standard deviation of the margin's lognormal distribution are readily determined from the values of the means and standard deviations of the capability and requirement distributions.

To determine the formula for the failure probability F using a lognormal distribution, Eq. (5.4) may be rewritten as

$$F = P(\ln M < 0) \ , \qquad (5.5)$$

where "ln" denotes the natural logarithm, and M is the random variable associated with the margin. Equation (5.5) was obtained from Eq. (5.4) by replacing the deterministic variable m with its corresponding random variable M and by taking the natural logarithms of both sides of the inequality.

When M has a lognormal distribution, then ln M has a normal distribution. Equation (5.5) can thus be written in standard normal form as

$$F = P\left(\frac{\ln M - \mu_0}{\sigma_0} < \frac{-\mu_0}{\sigma_0}\right) \ , \qquad (5.6)$$

where $\mu_0$ and $\sigma_0$ are the mean and standard deviation of ln M. Equation (5.6) is obtained by subtracting $\mu_0$ from both sides of the inequality and dividing by $\sigma_0$.

Equation (5.6) can also be written as

$$F = \Phi\left(\frac{-\mu_0}{\sigma_0}\right) \ , \qquad (5.7)$$

where $\Phi(z)$ is the cumulative distribution function evaluated at z for the normalized standard normal distribution. Using the symmetric properties of $\Phi(z)$, Eq. (5.7) can also be rewritten as

$$F = 1 - \Phi\left(\frac{\mu_0}{\sigma_0}\right) \ . \qquad (5.8)$$

Finally, to calculate F, the mean $\mu_0$ and the standard deviation $\sigma_0$ of the logarithm of the margin ln M need to be related to the mean $m_0$ and standard deviation $s_0$ of the margin M. These relationships are given using the standard formulas for the log-normal distribution:

$$m_0 = e^{\mu_0 + \frac{\sigma_0^2}{2}} \ , \qquad (5.9)$$

$$\frac{s_0}{m_0} = \left(e^{\sigma_0^2} - 1\right)^{\frac{1}{2}} \quad . \tag{5.10}$$

The standard deviation $\sigma_0$ can be determined from Eq. (5.10) above to give

$$\sigma_0 = \left[\ln\left[1 + \left(\frac{s_0}{m_0}\right)^2\right]\right]^{\frac{1}{2}} \quad , \tag{5.11}$$

where the term $s_0/m_0$ is the relative standard deviation of the margin. Note that the expression for $\sigma_0$ simplifies for small relative standard deviations to

$$\sigma_0 \cong \frac{s_0}{m_0} \quad \text{for} \quad \frac{s_0}{m_0} << 1 \quad . \tag{5.12}$$

The value for $\sigma_0$ can be substituted into Eq. (5.9) to determine $\mu_0$:

$$\mu_0 = \ln m_0 - \frac{\sigma_0^2}{2} \quad . \tag{5.13}$$

Thus, Eqs. (5.11) and (5.13) determine $\sigma_0$ and $\mu_0$ from $m_0$ and $s_0/m_0$.

The failure probability F can now be calculated using Eq. (5.8), Eq. (5.11), and Eq. (5.13). Figures 5.4, 5.5, and 5.6 show the values of the failure probability F vs the relative standard deviation, $s_0/m_0$, for margin means $m_0$ of 1.15, 1.25, and 1.5, respectively. For the values of $m_0$ near 1, the figures show that the failure probability is very sensitive to the relative standard deviation of the margin. Thus, to assure a low failure probability F of inadequate margin when the margin is near 1, it is necessary that both the margin and the standard deviation be known with sufficient accuracy. The relative standard deviation $s_0/m_0$ must then be below a minimally acceptable value. This finding is important.

## 5.3.2 Definition of Exponential Age Dependence for the Margin

It is normally assumed that a component's capability c would decrease with age, resulting in a loss of exerted force or energy, while its requirement r would increase because of added resistance. For example, as an MOV ages, the force supplied by the valve actuator may decrease. At the same time, due to corrosion, erosion, and other causes, the resistance provided by the valve may increase and cause the requirement to increase. In a similar manner, the pressure or flow provided by a pump's motor may decrease with age, while the resistance provided by the pump may increase with age and cause the requirement to increase. For pumps and MOVs, the increase in resistance is often assumed to be the dominant aging effect due to the increased friction, corrosion, and wear. Nevertheless, the inadequate margin failure mode is not necessarily the dominant contributor to the overall failure rate of pumps and MOVs.

As discussed in Sect. 5.2, the dimensionless margin is numerically defined to be the ratio of the capability to the requirement [Eq. (5.2)]. Because the capability decreases and the requirement increases, the margin decreases with age.

To quantify the impacts of aging and deterioration on the capability and requirement, various models can be used. As a simple, but still flexible, model, a constant relative rate of change in both the capability and the requirement may be assumed. As shown below, this is equivalent to assuming that the magnitudes of the capability and requirement vary exponentially with time.

By defining $\alpha_c$ as magnitude of the coefficient ruling the change in capability with age and $\alpha_r$ as magnitude of the coefficient ruling the change in requirement with age the deterioration effect on the capability c and requirement r as a function of age t is described by the equations:

$$\frac{1}{c}\frac{dc}{dt} = -\alpha_c \quad , \tag{5.14}$$

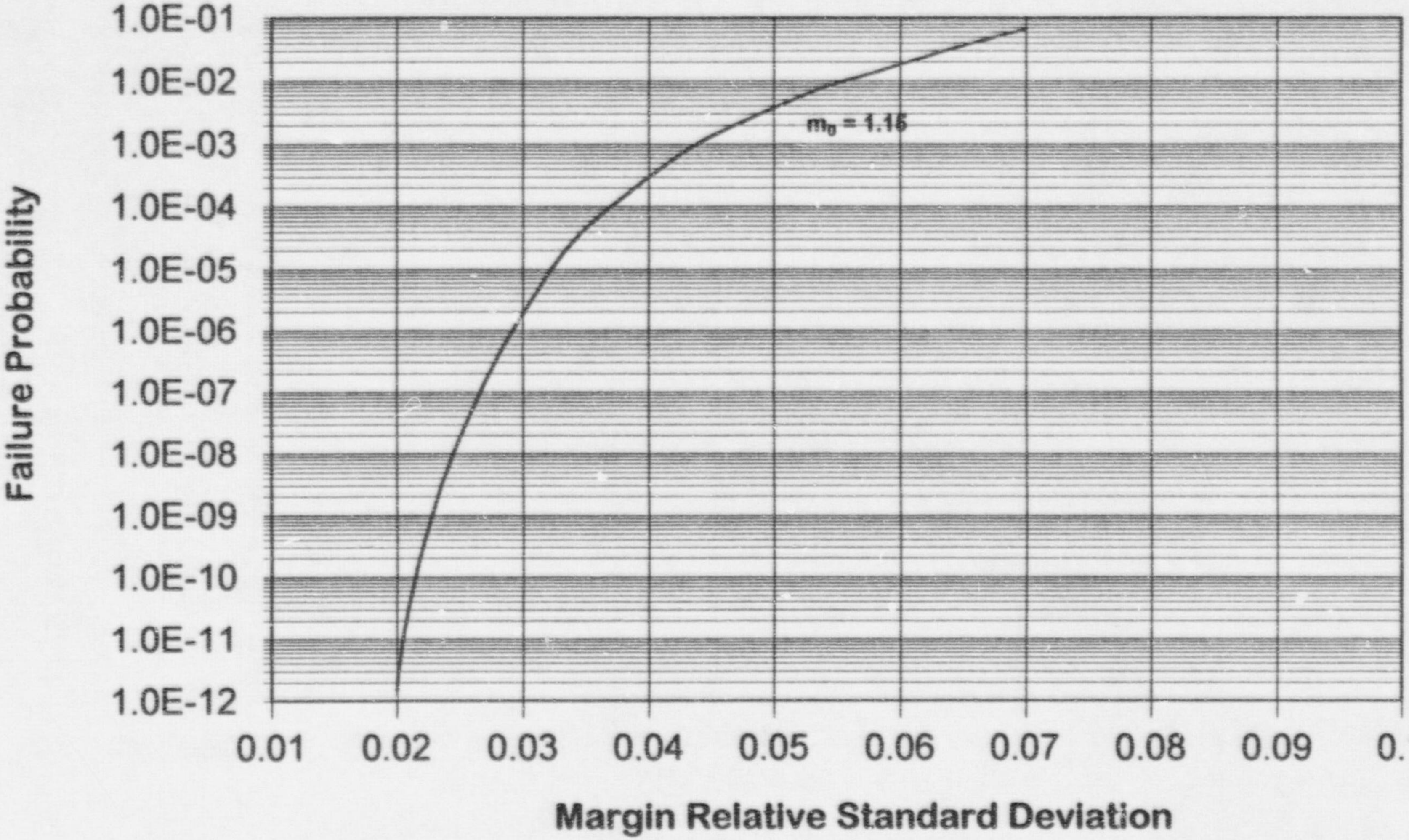


**Figure 5.4** **Functional failure probability vs margin relative standard deviation ($s_0/m_0$): margin mean $m_0$ = 1.15**

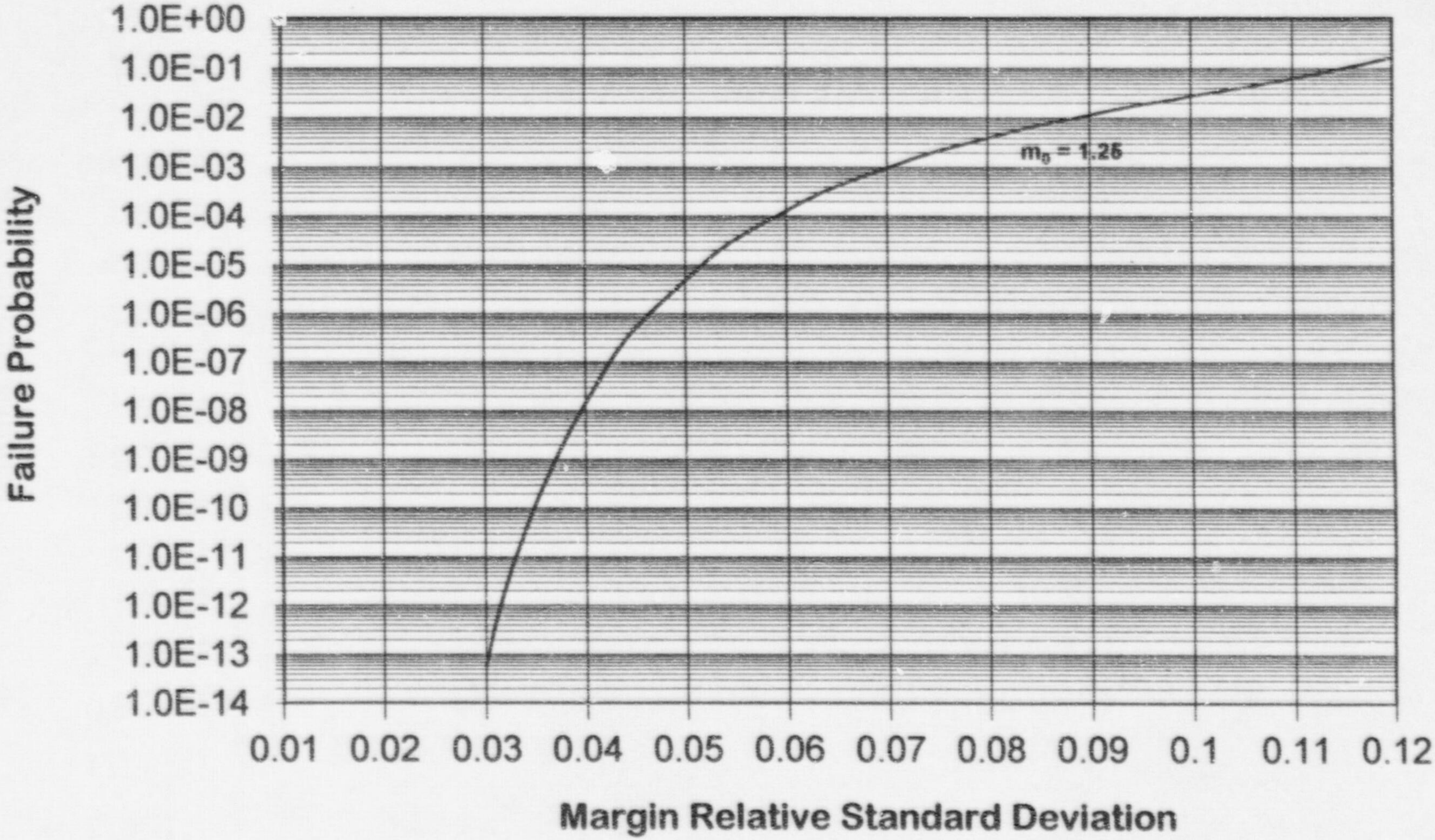


**Figure 5.5** **Functional failure probability vs margin relative standard deviation ($s_0/m_0$): margin mean $m_0$ = 1.25**

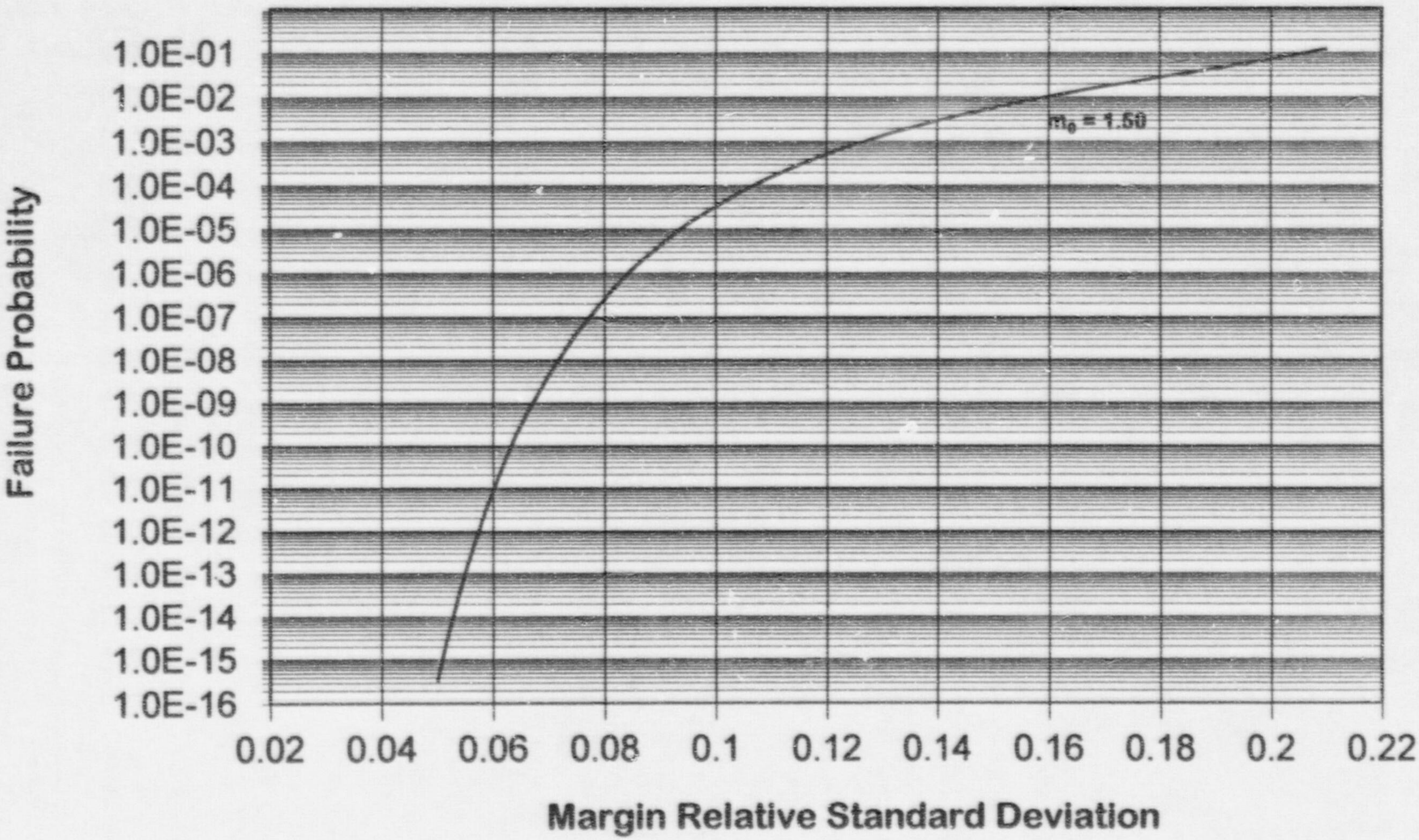


**Figure 5.6** Functional failure probability vs margin relative standard deviation ($s_0/m_0$): margin mean = 1.50

and

$$\frac{1}{r}\frac{dr}{dt} = \alpha_r \quad . \tag{5.15}$$

The minus sign in Eq. (5.14) indicates that the capability is likely to decrease with age.

Solving these equations gives the capability and requirement as a function of the component age t:

$$c = c_0 e^{-\alpha_c t} \quad , \tag{5.16}$$

$$r = r_0 e^{\alpha_r t} \quad , \tag{5.17}$$

where $c_0$ and $r_0$ are the initial capability and requirement at $t = 0$, and $\alpha_c$ and $\alpha_r$ are as defined previously. For example, for a 1% per year rate of change in capability, the coefficient characterizing the change would be $\alpha_c = 0.01$ year$^{-1}$.

The above relative aging models for the capability and requirement can specialize to various types of behavior. For no deterioration, $\alpha_c = 0$, and $\alpha_r = 0$; there is no change in the capability and requirement:

$c = c_0$ : no deterioration, $\alpha_c = 0$;
$r = r_0$ : no deterioration, $\alpha_r = 0$.

For small values of the product of time and change coefficient, the time dependence becomes approximately linear. First-order expansion of the exponential function yields:

$c \cong c_0(1 - \alpha_c t) : \alpha_c t << 1$;
$r = r_0(1 + \alpha_r t) : \alpha_r t << 1$.

Figure 5.7 illustrates an example of the capability and requirement behavior with the component age for a negligible, that is, 0% change in capability ($\alpha_c = 0.0$ year$^{-1}$) and a 3% initial growth rate in requirement ($\alpha_r = 0.03$ year$^{-1}$). The initial capability is taken to be 1.25 times the requirement. For an MOV this corresponds to the case of initial torque 1.25 times larger than the torque required. These values are characteristic of some undocumented MOV values.

Because the margin has been defined as the ratio of the capability to requirement [Eq. (5.2)], then the chosen models of capability and requirement determine its behavior with age t to be

$$m(t) = c/r = \frac{c_0 e^{-(\alpha_c + \alpha_r)t}}{r_0} \quad , \tag{5.18}$$

$$m(t) = m_0 e^{-\alpha_m t} \quad , \tag{5.19}$$

where

$$m_0 = \frac{c_0}{r_0} \quad , \tag{5.20}$$

$$\alpha_m = \alpha_c + \alpha_r \; . \tag{5.21}$$

Thus, in this model, the margin also varies exponentially with time. The initial margin $m_0$ equals the ratio of the initial values of capability and requirement. Its change coefficient $\alpha_m$ is the sum of the capability's $\alpha_c$ and the requirement's $\alpha_r$. This allows focusing on the margin rather than dealing with capability and requirement separately. For no aging of capability and requirement, the margin does not deteriorate and remains unchanged with time, that is, $m(t) = m_0$. For small values of the product of the margin change coefficient and age, the exponential simplifies to a linear function, and the margin linearly decreases with age, that is, $m(t) = m_0(1 - \alpha_m t)$. Because the initial rate of change coincides with the value of the coefficient $\alpha_m$ per Sect. 5.1, $\alpha_m$ is referred to as the RMC for the rest of the chapter. Figure 5.8 shows the associated margin behavior for RMC values $\alpha_m$ from 0 to 0.03 year$^{-1}$.

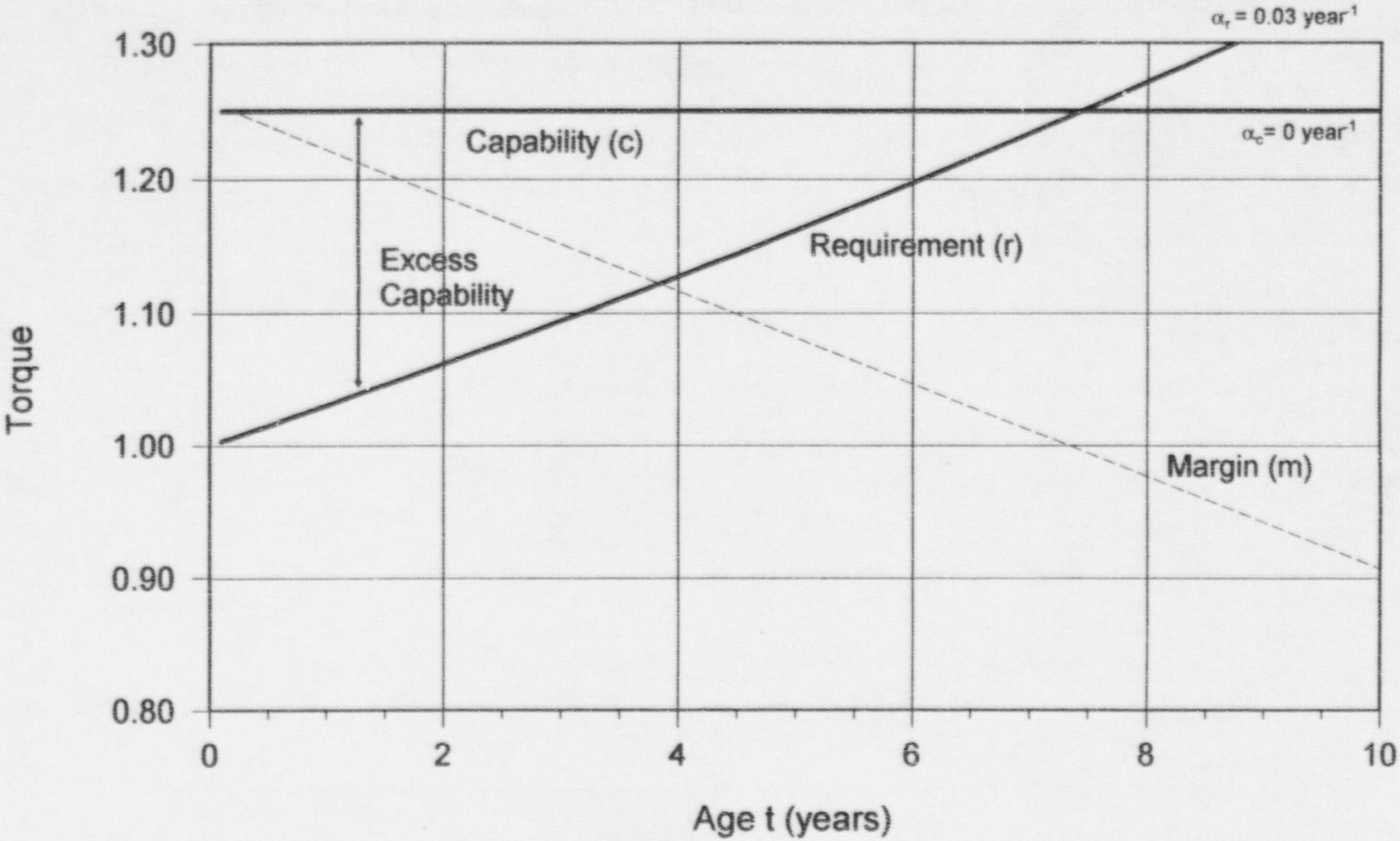


**Figure 5.7** **Functional capability and functional requirement vs age: initial capability = 1.25 x initial requirement; exponential time dependence models: capability's $\alpha_c$= 0.0 year$^{-1}$, requirement's $\alpha_r$ = 0.03 year$^{-1}$**

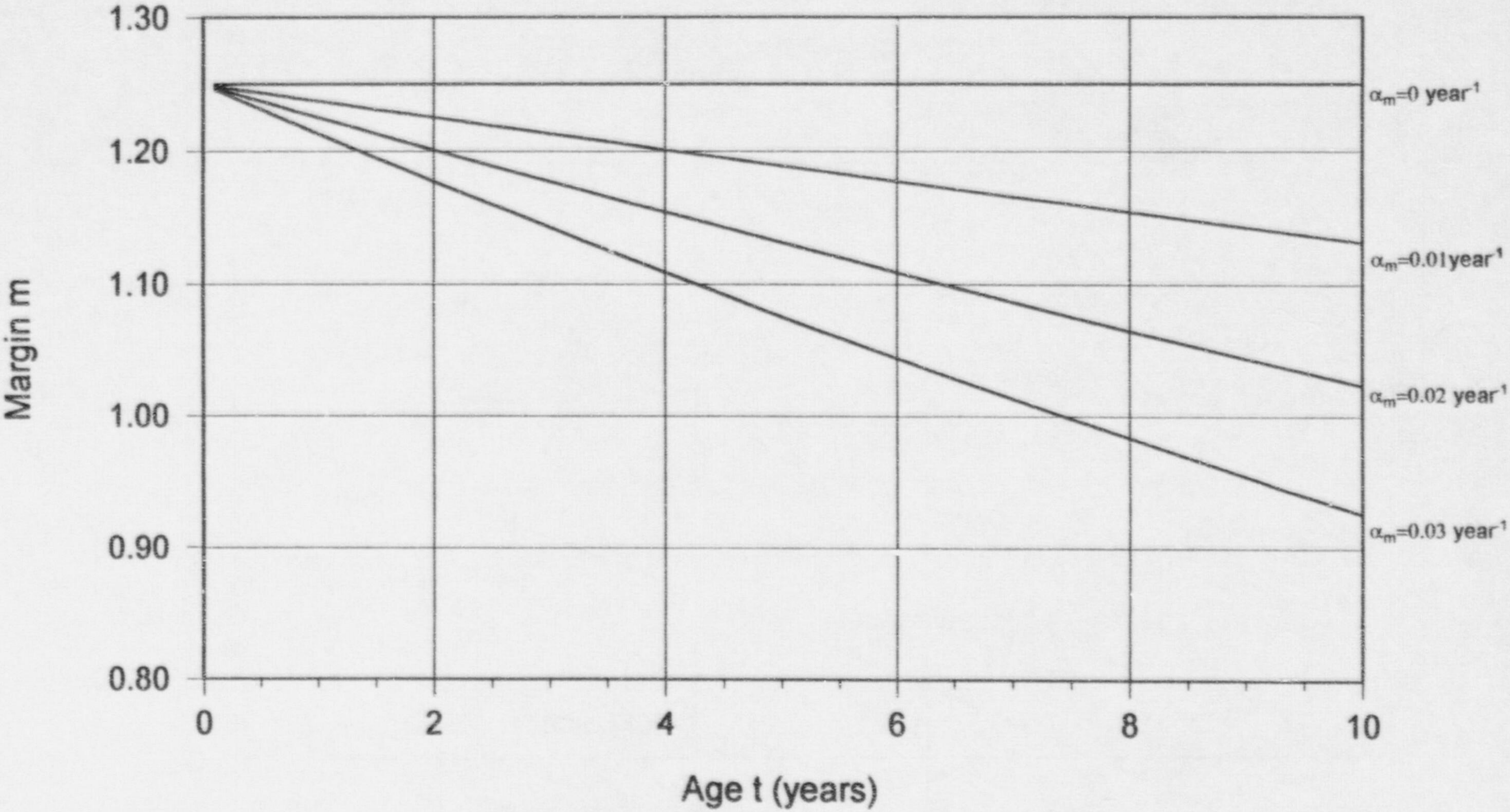


**Figure 5.8** **Functional margin vs age: different rates of margin change ($\alpha_m$) for exponential time dependence models. Initial margin $m_o$ = 1.25.**

Often it is interesting to examine the time dependence of the margin in terms relative to the value of the initial margin. Thus, if the relative margin $\hat{m}$ is defined as the ratio of the margin at a given age t over the initial margin $m_0$:

$$\hat{m}(t) = \frac{m(t)}{m_0} \quad , \tag{5.22}$$

then

$$\hat{m}(t) = e^{-\alpha_m t} \quad . \tag{5.23}$$

The behavior of the margin with time, in relative terms to the initial value, depends solely on the value of the RMC, $\alpha_m$. Figure 5.9 illustrates the behavior of the relative margin as a function for the same RMCs used in Fig. 5.8.

The following equation can be used to determine the age $t_{\hat{m}}$ at which the margin will decrease to a fraction $\hat{m}$ of the initial value:

$$t_{\hat{m}} = -\frac{1}{\alpha_m} \ln \hat{m} \quad . \tag{5.24}$$

Figure 5.10 illustrates values of $t_{\hat{m}}$ for different relative margin thresholds $\hat{m}$ and RMCs. The value of $t_{\hat{m}}$ for a given threshold $\hat{m}$ and RMC can be used to define the time at which margin tests may be conducted.

### 5.3.3 Probability of Inadequate Margin With Lognormal Statistics and Exponential Time Dependence of the Mean

The evaluation in the previous section of the probability of inadequate margin was an initial static evaluation and did not account for any time-dependent component deterioration effects. To incorporate component deterioration effects with age, the exponential model, Eq. (5.19), derived in Sect. 5.3.2, is used to represent the time dependence of the mean values of margin. The time-dependent failure probability F(t) is then given by

$$F(t) = P\left(M_0 e^{-\alpha_m t} < 1\right) \quad . \tag{5.25}$$

Taking the logarithms of both sides of the inequality in Eq. (5.25) above gives

$$F(t) = P\left(\ln M_0 - \alpha_m t < 0\right) \tag{5.26}$$

or

$$F(t) = P\left(\ln M_0 < \alpha_m t\right) \quad . \tag{5.27}$$

This, in turn, can be transformed into a standard normal distribution form by subtracting the mean of $\ln M_0$ from both sides of the inequality and dividing by the standard deviation of $\ln M_0$. This yields

$$F(t) = P\left(\frac{\ln M_0 - \mu_0}{\sigma_0} < \frac{\alpha_m t - \mu_0}{\sigma_0}\right) \quad , \tag{5.28}$$

where, as in the previous section, $\mu_0$ is the mean of $\ln M_0$, and $\sigma_0$ is the corresponding standard deviation.

Thus, F(t) can be written in terms of the standard normal cumulative distribution $\Phi(z)$ as

$$F(t) = \Phi\left(\frac{\alpha_m t - \mu_0}{\sigma_0}\right) \quad , \tag{5.29}$$

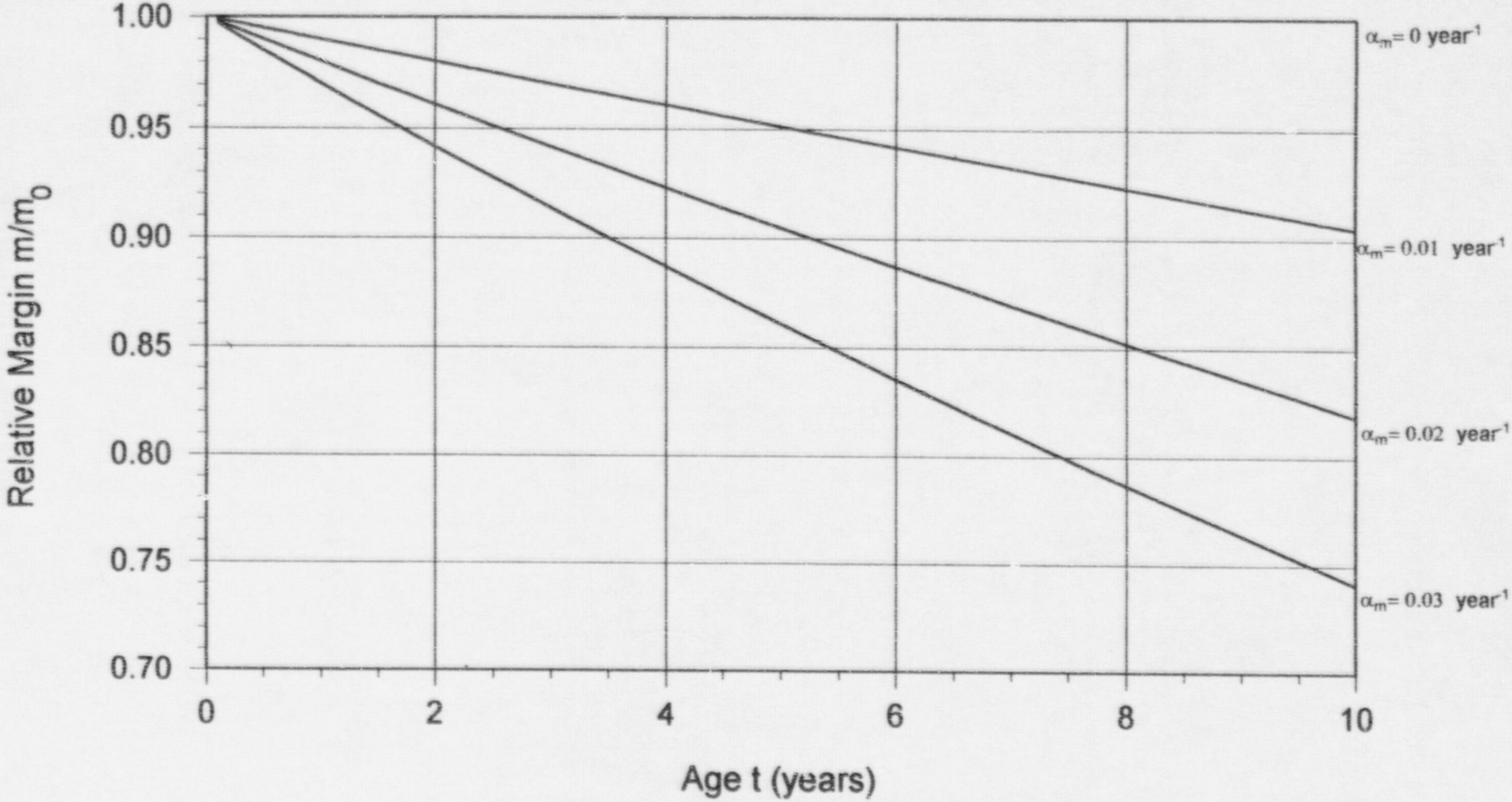


**Figure 5.9** **Relative margin vs age for different rates of margin change ($\alpha_m$): relative margin = margin/initial margin**

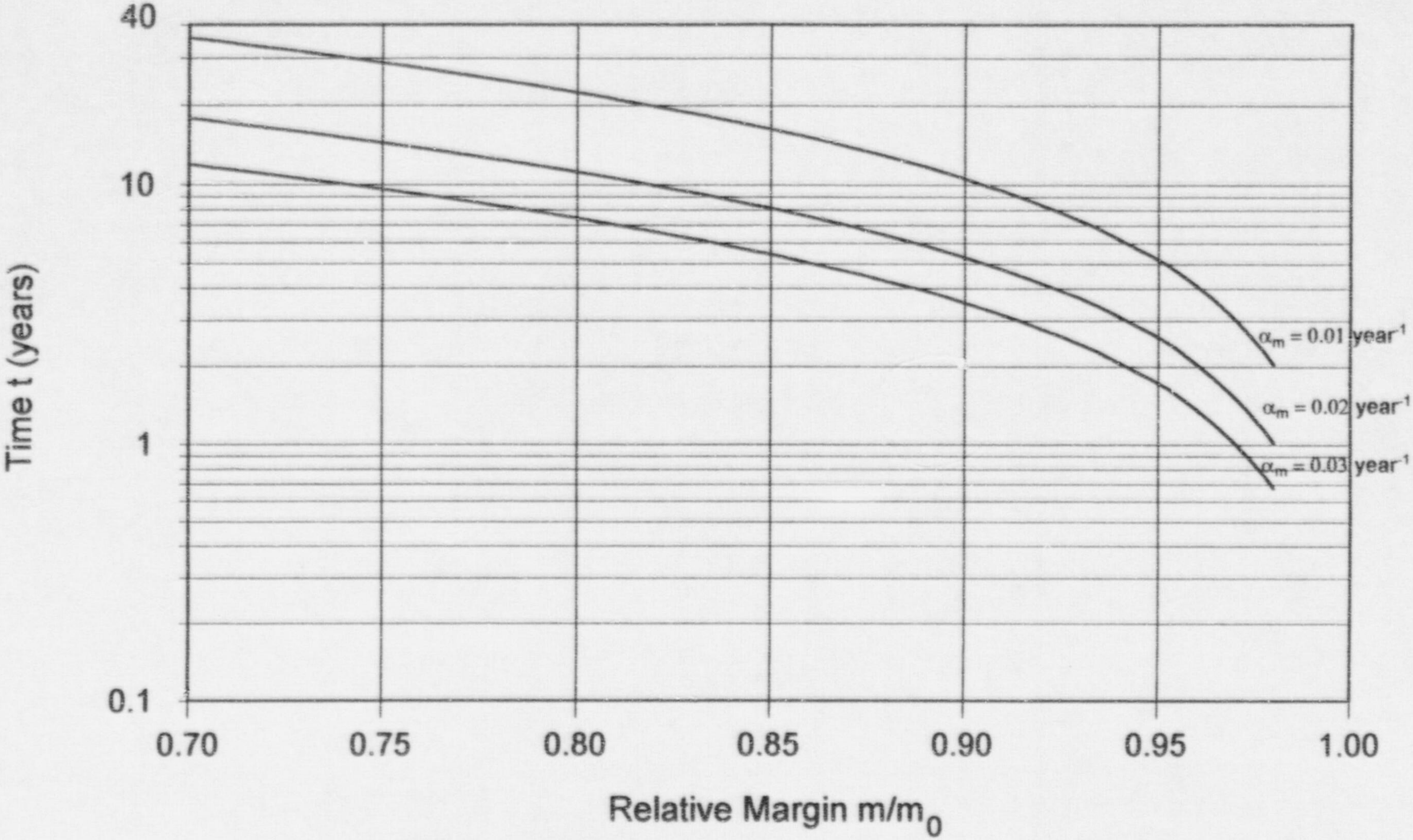


**Figure 5.10** **Time to a given relative margin for different rates of margin change ($\alpha_m$) for exponential time dependence model**

or equivalently, using the symmetry property of $\Phi(z)$,

$$F(t) = 1 - \Phi\left(\frac{\mu_0 - \alpha_m t}{\sigma_0}\right) . \tag{5.30}$$

When t = 0, Eqs. (5.29) and (5.30) reduce to the initial static equations in the previous section, Eqs. (5.7) and (5.8). The equations for relating the mean $m_0$ and standard deviation $s_0$ of a normal distribution to the mean $\mu_0$ and standard deviation $\sigma_0$ of the lognormal derived in the previous section also apply.

### 5.3.4 Unavailability of a Component Tested Periodically for Detection of Inadequate Margin: Parametric Studies

The following sections present parametric studies of the unavailability of a component, subject to periodic testing for detection of inadequate margin, as a function of the time interval between tests. This unavailability is defined in terms of the average failure probability of inadequate margin between margin tests and the probability of the component being called into service while the tests are being performed. This is a standard quantity used in PRAs.

The average failure probability between margin tests may be approximated as the failure probability taken at the midpoint of the interval between tests. This approximation is of sufficient accuracy for the parametric studies carried out for this report. The test downtime contribution accounts for the possibility of the margin test being conducted during operation and having a nonzero test downtime. The effects of margin tests on the unavailability depend on the characteristics of the margin test. The following sections treat bounding cases.

#### 5.3.4.1 Unavailability When Margin Assessment Tests Are Followed by Renewal

In this section, the formula for the unavailability of a component subject to periodic testing for detection of inadequate margin is given as a function of the time interval between tests L, when the tests are followed by renewal of the margin. Renewal of the margin means that if a significant loss of margin is found during the test, then maintenance is performed so that the margin is restored to its initial value. Even if the margin is still deemed to be adequate, all detected losses of margin are corrected. Thus, this assumption of a margin test followed by full renewal represents the best the margin testing can do. Consequently, the resulting unavailability would be the best (lowest) possible if maintenance repairs took zero time.

Let

Q = the unavailability of a component periodically tested for detection of inadequate margin, including test downtime contributions;
$\mu_0$ = the mean value of the logarithm of the initial margin of the component;
$\sigma_0$ = the standard deviation of the logarithm of the initial margin of the component;
$\alpha_m$ = the initial RMC used in the exponential model;
L = the time interval between margin assessment tests and renewal;
d = the average downtime associated with a margin assessment test.

The unavailability Q when the margin tests are followed by full renewal is then given by

$$Q = 1 - \Phi\left(\frac{\mu_0 - \alpha_m \frac{L}{2}}{\sigma_0}\right) + \frac{d}{d + L} , \tag{5.31}$$

where again, $\Phi(z)$ is the standard normal distribution function for argument z. The above formula for Q is simply one minus the failure probability at the midpoint (t = L/2) of the margin test interval plus the test downtime contribution, d/(d + L). When there is no downtime contribution (e.g., the margin test is conducted at shutdown), d = 0.

### 5.3.4.2 Unavailability When Margin Assessment Tests Are Not Followed by Renewal

When a margin assessment test is conducted to simply check for margin adequacy, then the margin is not renewed at each test. The component is repaired only when the margin is found to be inadequate or near inadequate. This case corresponds to assurance testing only.

Let S represent the interval at which preventive maintenance is carried out to restore acute losses in the margin. If no preventive maintenance is carried out, then S is the lifetime of the component. If maintenance is performed at every test interval, then S = L. Consequently, using the same definitions as in the previous section, the nonrenewal case unavailability $Q_{nr}$, as derived in Appendix B, is given by

$$Q_{nr} = 1-\Phi\left(\frac{\mu_0}{\sigma_0}\right)+\Phi\left(\frac{\mu_0}{\sigma_0}\right)\bullet\frac{\Phi\left(\dfrac{\mu_0-\alpha_m\dfrac{S}{2}}{\sigma_0}\right)-\Phi\left[\dfrac{\mu_0-\alpha_m\left(\dfrac{S}{2}+\dfrac{L}{2}\right)}{\sigma_0}\right]}{\Phi\left(\dfrac{\mu_0-\alpha_m\dfrac{S}{2}}{\sigma_0}\right)}+\frac{d}{d+L} \quad (5.32)$$

Equation (5.32) can also be written as

$$Q_{nr} = 1-\Phi\left(\frac{\mu_0}{\sigma_0}\right)+\Phi\left(\frac{\mu_0}{\sigma_0}\right)\bullet\frac{1-\Phi\left[\dfrac{\mu_0-\alpha_m\left(\dfrac{S}{2}+\dfrac{L}{2}\right)}{\sigma_0}\right]-\left[1-\Phi\left(\dfrac{\mu_0-\alpha_m\dfrac{S}{2}}{\sigma_0}\right)\right]}{1-\left[1-\Phi\left(\dfrac{\mu_0-\alpha_m\dfrac{S}{2}}{\sigma_0}\right)\right]}+\frac{d}{d+L} \quad (5.33)$$

Equation (5.33) is useful when expressions are given for $1-\Phi(z)$ in references. The above expressions, which appear complex, can be straightforwardly evaluated using standard tables or expressions for the normal distribution function $\Phi(z)$. Again, if there is no downtime contribution or if only the average failure probability due to inadequate margin is desired, then the term $d/(d+L)$ is omitted.

### 5.3.4.3 Unavailability as a Function of the Time Interval Between Margin Assessment Tests: Parametric Studies

The following sections illustrate applications of the unavailability formulas derived in the previous section. The applications are carried out using an initial margin mean $m_0$ value of 1.25 and a relative standard deviation $s_0/m_0$ of 5% (0.05). These values are translated to the mean $\mu_0$ and standard deviation $\sigma_0$ of the logarithm of the mean using the formulas in the previous section. The initial margin mean value of 1.25 and relative standard deviation of 0.05 are used because they seem to be representative of some MOVs.

Figures 5.11–5.14 illustrate how unavailability is very sensitive to the length of test interval, the RMC, and the renewal option. For the example shown, the contribution to unavailability by the testing downtime becomes negligible for testing intervals over 10 years. The benefits of testing with renewal are evident—similar unavailabilities are obtained for an RMC of 2.5% with renewal as for an RMC of 1% without renewal.

#### 5.3.4.3.1 Unavailability When Margin Tests Are Followed by Renewal

Figures 5.11 and 5.12 show the component unavailability vs margin test interval when each test is followed by renewal. Both figures are for a margin mean of 1.25 and a relative standard deviation of 5% (0.05). Figure 5.11 is for a downtime of 8 hours

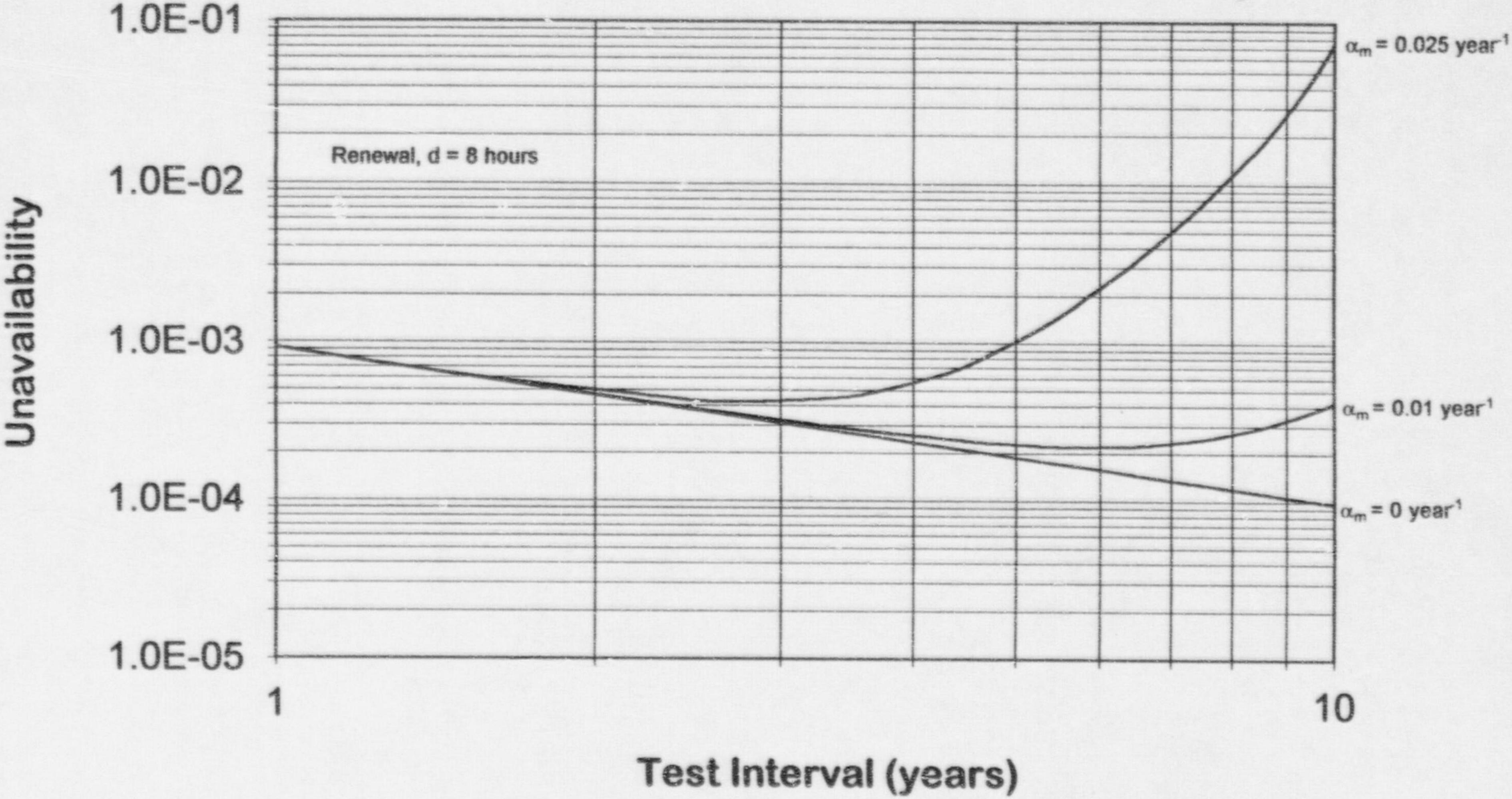


**Figure 5.11** Unavailability vs test interval: follow-up renewal, downtime d = 8 hours, margin mean = 1.25, relative standard deviation = 0.05, rate of margin change ($\alpha_m$) year$^{-1}$ = various values

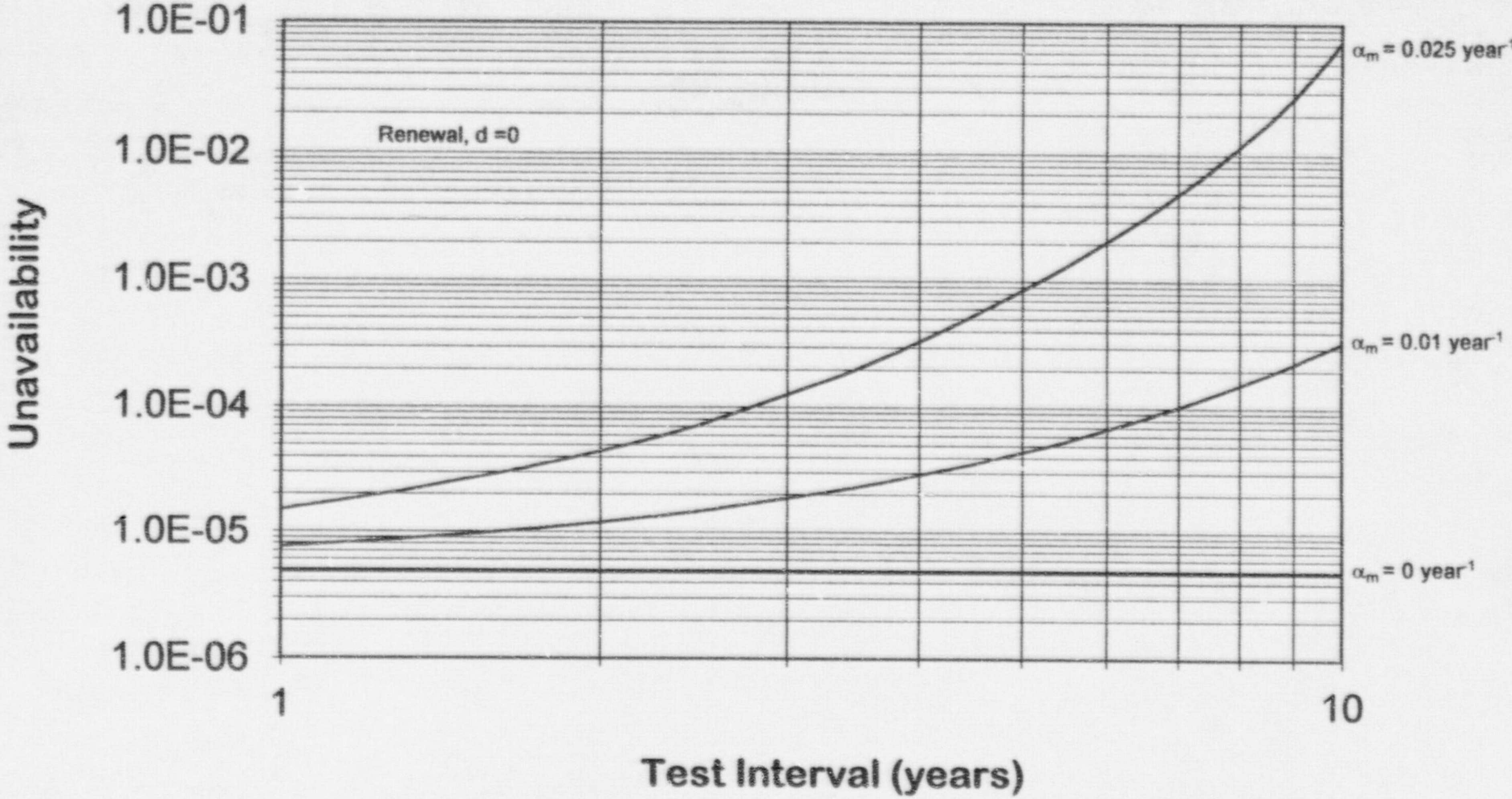


**Figure 5.12** Unavailability vs test interval: follow-up renewal, negligible downtime (d = 0), margin mean = 1.25, relative standard deviation = 0.05, rate of margin change ($\alpha_m$) year$^{-1}$ = various values

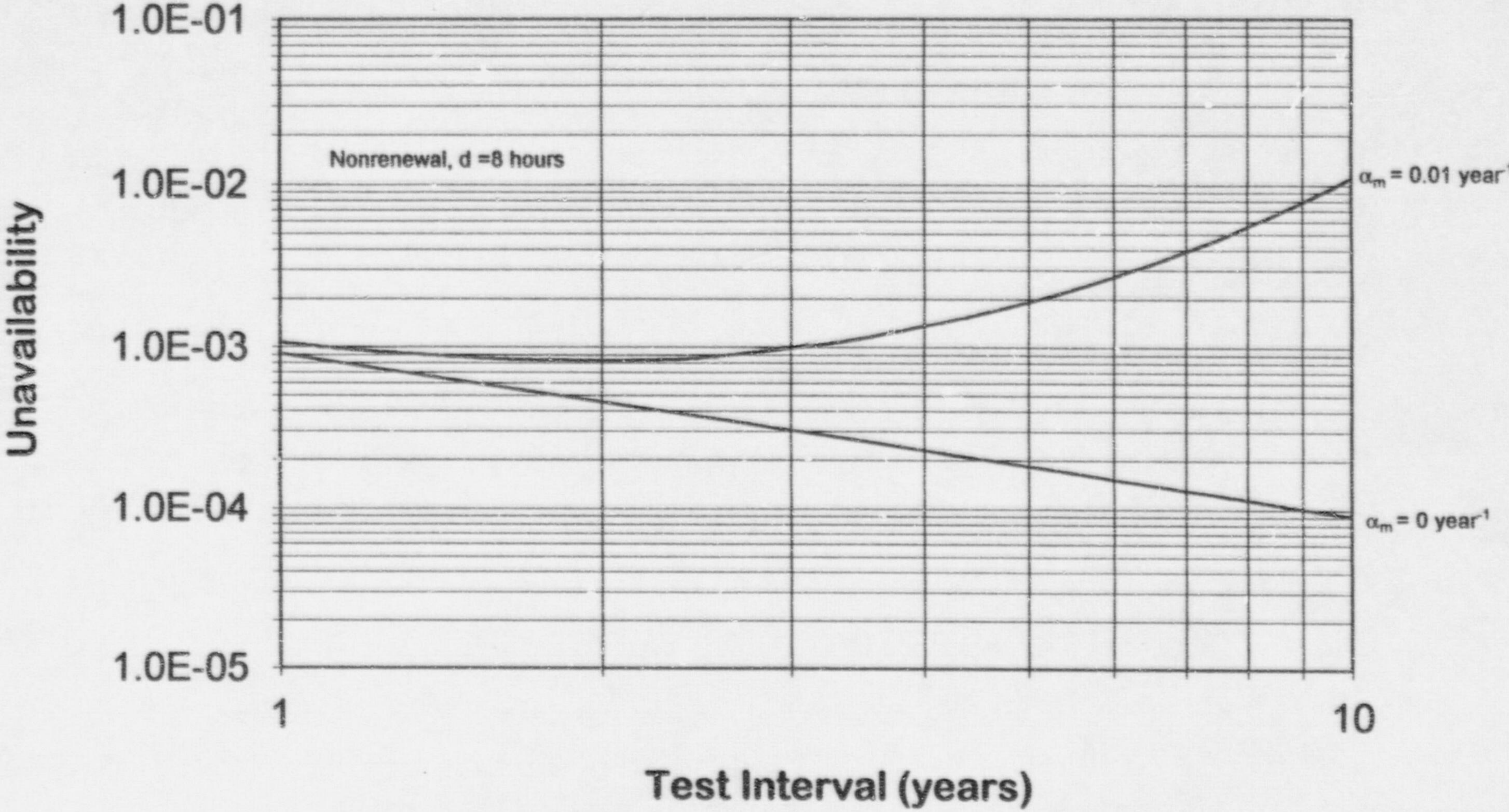


**Figure 5.13** Unavailability vs test interval: nonrenewal, downtime contribution d = 8 hours, margin mean = 1.25, relative standard deviation = 0.05, rate of margin change ($\alpha_m$) year$^{-1}$ = various values, component lifetime s = 10 years

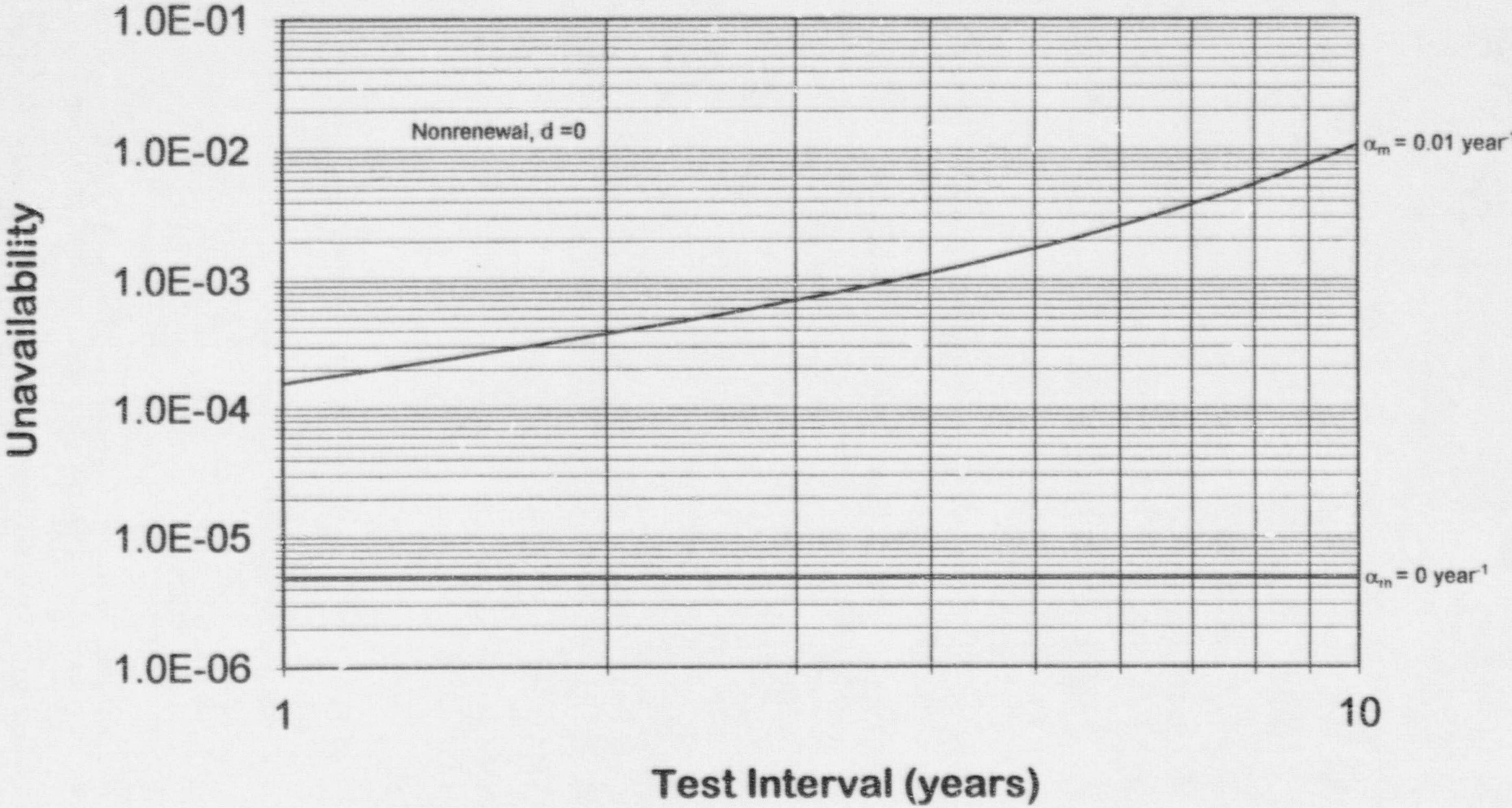


**Figure 5.14** Unavailability vs test interval: nonrenewal, negligible downtime (d = 0), margin mean = 1.25, relative standard deviation = 0.05, rate of margin change ($\alpha_m$) year$^{-1}$ = various values, component lifetime s = 10 years

per test (associated with the conduct of the test and with follow-up renewal activities). Figure 5.12 is for a zero downtime associated with the test conduct and renewal activity. In each figure, curves are shown for no deterioration ($\alpha_m = 0$), for a 1% RMC per year ($\alpha_m = 0.01$ year$^{-1}$), and for a 2.5% per year RMC ($\alpha_m = 0.025$ year$^{-1}$).

In Figure 5.11, for a downtime of 8 hours, the $\alpha_m = 0$ curve is a decreasing line due to diminishing relative contribution of the downtime as the test interval increases. As observed in both figures, the unavailability due to inadequate margin is more sensitive to the testing interval when the RMC is 2.5% per year ($\alpha_m = 0.025$ year$^{-1}$). Greater RMCs will show even greater sensitivities and have higher unavailabilities. For an RMC of $\alpha_m = 0.025$ year$^{-1}$, test intervals > 5 years result in unavailabilities, with renewal, surpassing $10^{-3}$.

#### 5.3.4.3.2 Unavailability When Margin Tests Are for Assurance Only

Figures 5.13 and 5.14 show the component unavailability vs margin test interval when the test has no follow-up renewal; the test is for assurance only. The initial margin mean is again 1.25, and the relative standard deviation is 0.05. A component life of 10 years is assumed, which is also equivalent to assuming that the margin is preventively maintained every 10 years. Only the case of an RMC of 1% per year ($\alpha_m = 0.01$ year$^{-1}$) is shown because for higher RMCs, the unavailability approaches unity rapidly with time as the testing interval increases. For a negligible downtime, even for an RMC of 0.01 per year, the unavailability surpasses $10^{-3}$ when the test intervals are more than 4 years. For test intervals of 10 years unavailability surpasses $10^{-2}$.

## 5.4 Unavailability vs Test Interval for a Component with Exponentially Time-Dependent Failure Rate

This section presents parametric studies of unavailability vs test interval for a hypothetical component whose overall failure rate exhibits an exponential age dependency. This complements NUREG/CR-6508, "Component Unavailability Vs. Inservice Test (IST) Interval: Evaluations of Component Aging Effects With Applications to Check Valves,"[31] in which linear and Weibull functions were used to model the time dependency of the failure rates.

The formulas and parametric studies discussed in this section are different from those presented in the previous section that focused on the margin statistics and margin time dependence. The failure rate was obtained from the margin statistics (lognormal) and the time dependence of the mean (exponential); consequently, only the inadequate margin failure mode was modeled. Because of the impossibility to extract from existing failure data the failure mode component corresponding to inadequate margin, in this section an overall time-dependent failure rate is assumed a priori. The unavailability formulas and evaluations performed in this section are more extensive than those carried out in the previous section and cover wider ranges of initial parameters and possible aging behaviors.

### 5.4.1 Use of an Exponential Failure Rate to Model Component Aging Behavior

If $\lambda(t)$ is the age-dependent component failure rate at age t, then when an exponential failure rate model is used, $\lambda(t)$ is given by the formula:

$$\lambda(t) = \lambda_0 e^{\alpha t} \quad , \tag{5.34}$$

where $\lambda_0$ = the initial failure rate, and $\alpha$ = the initial rate of change of the failure rate [subsequently referred to as the rate of failure rate change (RFRC)].

The exponential failure rate model, Eq. (5.34), can also be written in the form

$$\lambda(t) = p_0 \alpha e^{\alpha t} \quad , \tag{5.35}$$

where $p_0$ = the initial failure probability per demand at t = 0.

The exponential failure rate model could be interpreted either as an overall operational failure rate or as an inadequate margin failure rate. When interpreted as an overall operational failure rate, then $\lambda_0$, $p_0$, and $\alpha$ apply to operational failures such as those tested for in most present ISTs. When interpreted as an inadequate margin failure rate, then $\lambda_0$, $p_0$, and $\alpha$ apply to the inadequate margin failure mode contribution to the total failure rate. For an inadequate margin failure rate interpretation, $\alpha$

becomes $\alpha_m$, the RMC ($\alpha_m = \alpha_c + \alpha_r$), and $p_0$ becomes the initial probability of having inadequate margin discussed in the previous sections [i.e., $p_0 = P(c_0 < r_0)$].

The exponential failure rate model has useful properties for parametric studies and has been empirically found to fit some component failure data. With regard to fitting failure data, Atwood[32], in an NRC-sponsored study, found that the exponential failure rate model fit the MOV data studied as well as the linear failure rate and Weibull failure rate models. In addition, the exponential failure rate was found to provide more readily determined statistical and reliability characteristics.

For small values of the product of the RFRC and time (e.g., $\alpha t < 0.2$), the exponential failure rate model becomes a linear failure rate model. This can be seen by expanding the exponential to its first-order approximation:

$$\lambda(t) \cong \lambda_0(1+\alpha t) \quad ; \quad \text{for} \quad \alpha t << 1 \ .$$

For larger RFRCs, the exponential failure rate implies that aging is a compounding process; the failure rate accelerates as the component ages. This may be realistic for some components affected by processes such as erosion and corrosion, but may be too conservative for components such as those affected predominantly by wear and age almost linearly.

Similar to the previous model used to characterize the time dependence of the margin, the assumption for the exponential failure rate model is that the failure rate changes in a constant relative fashion with age. This can be seen by differentiating Eq. (5.34), which gives

$$\frac{1}{\lambda(t)}\frac{d\lambda(t)}{dt} = \alpha \ . \tag{5.36}$$

The exponential failure rate model for component failure rate aging thus parallels the model used for the aging of the average margin.

### 5.4.2 Application to IST

Present ISTs generally only test for the operational status of the component, that is, the "go" vs "no-go" status. Thus, for the following formulas and parametric studies to be applicable to ISTs, the test interval should be interpreted as the IST interval, and the failure rate should be interpreted as the failure rate for failures affecting the operational status, that is, the go/no-go status.

Presently, margin tests are not generally conducted on components to check the magnitude of the margin. The following formulas and parametric studies can be applicable to proposed margin tests by interpreting the test interval as the margin test interval and the failure rate as the failure rate for inadequate margin.

The following formulas and parametric studies consider two cases: one in which the test is followed by renewal of the component and the other in which the test is only an assurance test, that is, not followed by any renewal. Again, "renewal" means a condition check of the component in which significant deteriorations and aging effects are removed even though failure has not yet occurred. Testing followed by renewal represents the best performance testing can achieve. Testing only for assurance does not correct any degradation before failure occurs. When failure occurs, it is assumed that the failures are corrected and the causes of failure are removed.

For operational testing, renewal is interpreted as removing degradations affecting operational failures. For margin testing, renewal is interpreted as removing degradations affecting margin.

Finally, in the following formulas and parametric studies, a downtime contribution is associated with the test. For operational testing, the downtime contribution is that associated with the operational test. For margin testing, the downtime contribution is that associated with the margin test. If there is no relevant downtime contribution, then this term is set to zero.

### 5.4.3 Unavailability Formula When Tests Are Followed by Component Renewal

When the test is followed by maintenance resulting in renewal of the component, then significant aging and deterioration effects are removed before they cause failure. The component after the test is basically as good as new, and the failure rate $\lambda(t)$ starts again at $t = 0$ because it is left as good as new. For a test with follow-up renewal,

Q = the component unavailability including any associated test downtime contribution,
$p_0$ = the initial component failure probability per demand,
$\alpha$ = the initial rate of change of the failure rate (referred to as RFRC),
L = the interval at which tests are conducted,
d = the average test and maintenance downtime per test.

As shown in Appendix C, the unavailability Q is then given by the formula

$$Q = p_0 + 1 - \exp\left[-p_0\left(e^{\frac{\alpha L}{2}} - 1\right)\right] + \frac{d}{d+L} , \tag{5.37}$$

which is the sum of the different contributors.

Figures 5.15 and 5.16 illustrate the behavior of the unavailability Q for the case of an initial failure per demand probability $p_0 = 10^{-4}$, and a RFRC of $\alpha = 0.10$ year$^{-1}$, for downtimes d = 24 hours and d = 0, respectively. As observed in Fig. 5.15, the diminishing contribution of the downtime as the test interval L increases produces a minimum in the unavailability curve.

### 5.4.4 Unavailability Formula When Tests Are Not Followed by Renewal

When each test is for assurance only, there is no follow-up maintenance to correct aging effects before they cause failure. After testing the component is left in the same condition as before; its failure rate $\lambda(t)$ is unaffected by the conduct of the test.

Again,

$Q_{nr}$ = the component unavailability with no renewal including any associated test downtime contribution,
$p_0$ = the initial component failure probability with no aging,
$\alpha$ = the initial RFRC,
L = the interval at which tests are conducted,
d = the average test downtime per test associated with the test including the downtime associated with maintenance.*

Also, now S is the time interval between preventive maintenances or lifetime of the component. When preventive maintenance is performed on the component, then it is assumed that degradations are removed and the component is restored to as good as new condition. If no preventive maintenance is performed, then the lifetime of the component is used for the value of S.

As Appendix D shows, the unavailability Q is given by

$$Q_{nr} = p_0 + 1 - \exp\left[-p_0 e^{\frac{\alpha S}{2}}\left(e^{\frac{\alpha L}{2}} - 1\right)\right] + \frac{d}{d+L} , \tag{5.38}$$

which is the average nonrenewal unavailability in the time interval represented by S.

Figure 5.17 illustrates the behavior of $Q_{nr}$ for $p_0 = 10^{-4}$, $\alpha = 0.10$ per year, d = 24 hours, and a component lifetime S = 40 years. Figure 5.18 illustrates the behavior of $Q_{nr}$ when there is no test downtime, that is, d = 0. Again, Fig. 5.17 shows a test interval for which the unavailability is minimum. The test interval that produces the minimum unavailability depends on the magnitudes of the downtime and the RFRC. The unavailability for no-downtime increases monotonically with the length of the testing interval. Figures 5.19 and 5.20 compare the renewal curves in the previous section with the nonrenewal curves given here. As observed, the difference in unavailabilities between the nonrenewal and renewal cases increases with the length of testing interval.

*Note that if maintenance is done on average after n tests, then $d = d_m/n$, where $d_m$ is the actual maintenance downtime.

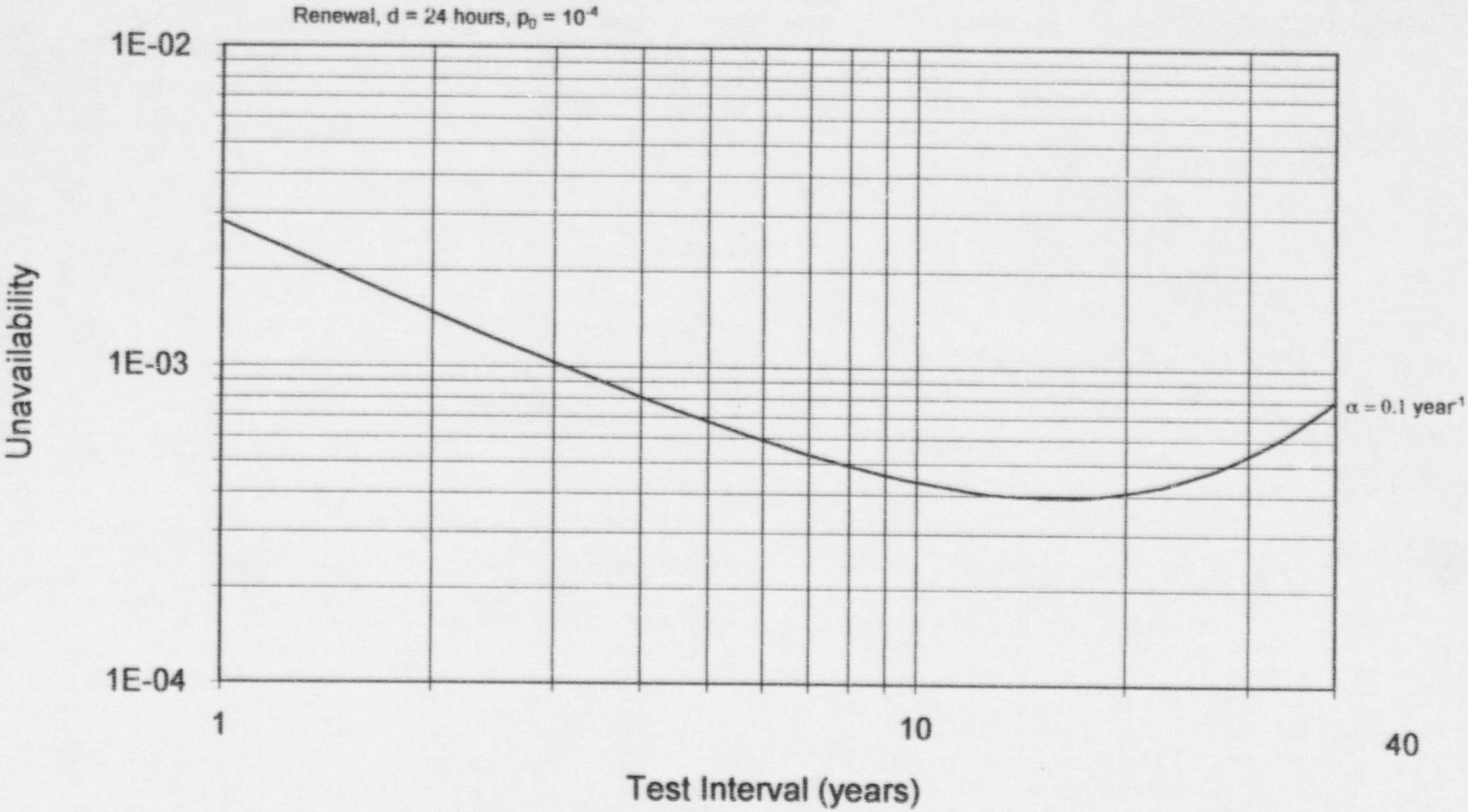


**Figure 5.15** Unavailability vs test interval: follow-up renewal, downtime contribution d = 24 hours, exponential models, initial failure probability $p_0 = 10^{-4}$, rate of failure rate change $\alpha = 0.10\ year^{-1}$

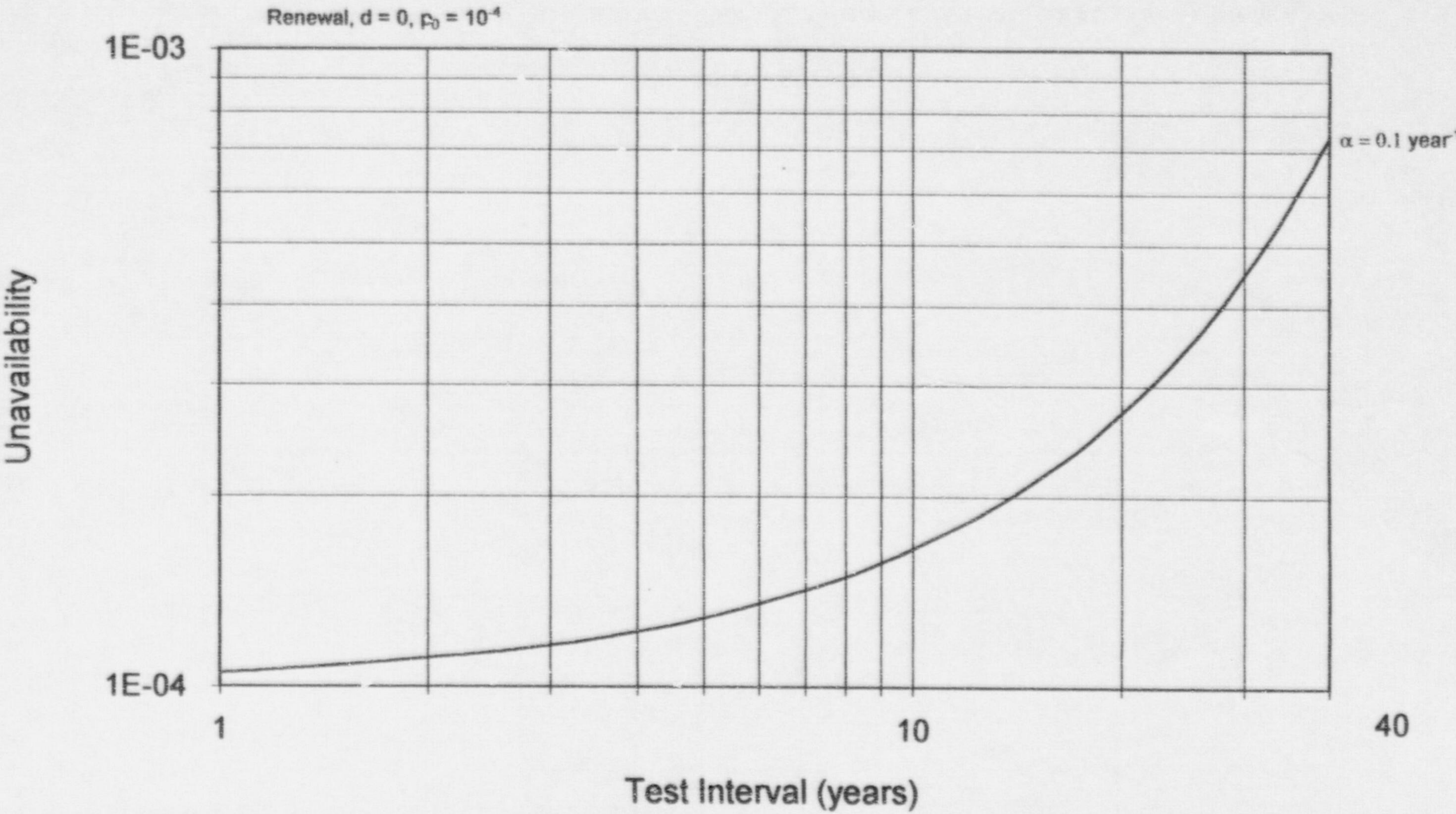


**Figure 5.16** Unavailability vs test interval: follow-up renewal, negligible downtime (d =0), exponential models, initial failure probability $p_0 = 10^{-4}$, rate of failure rate change $\alpha = 0.10$ year$^{-1}$

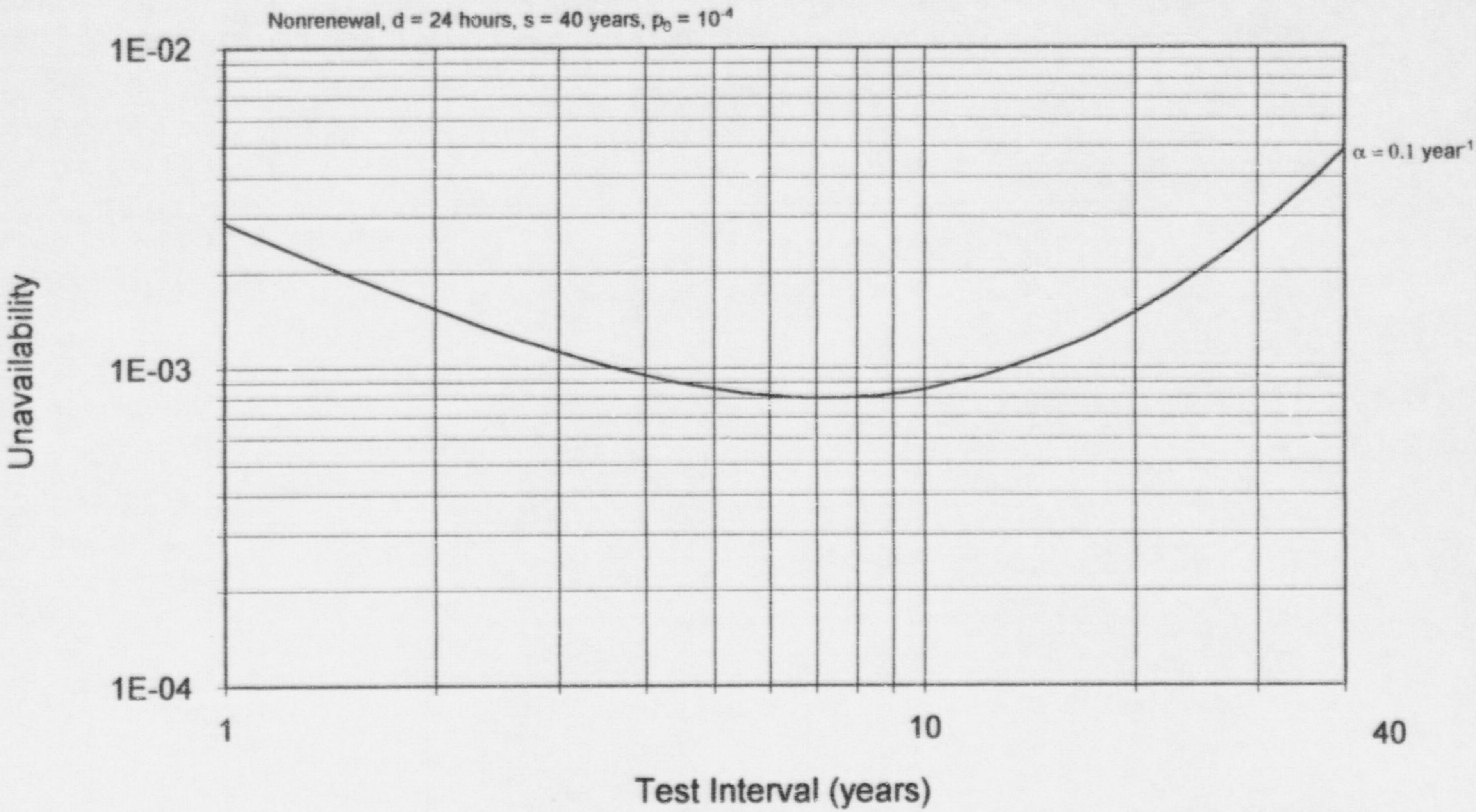


Figure 5.17 Unavailability vs test interval: nonrenewal, downtime contribution d = 24 hours, exponential models, initial failure probability $p_0 = 10^{-4}$, rate of failure rate change $\alpha = 0.10$ year$^{-1}$, component lifetime s = 40 years

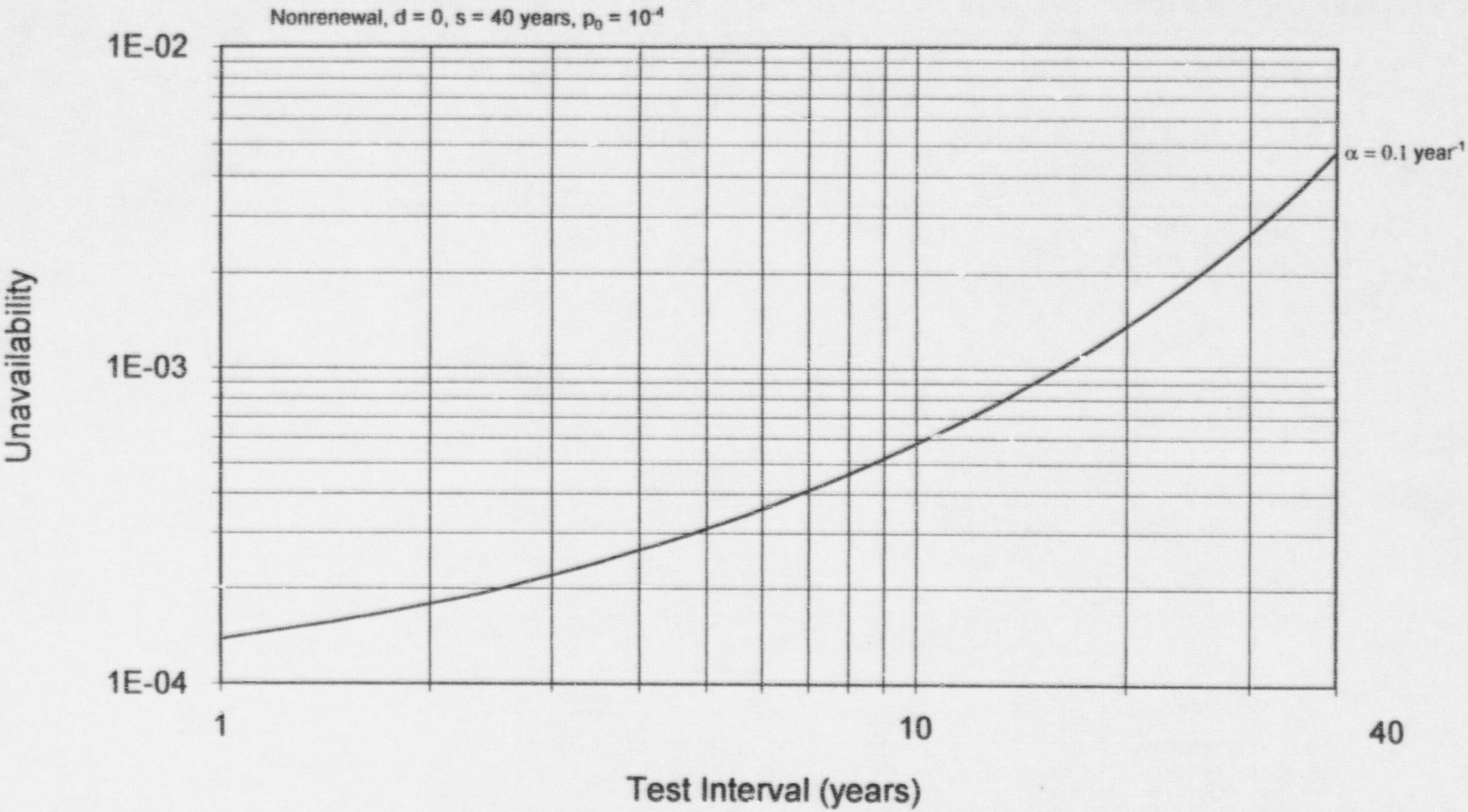


**Figure 5.18** **Unavailability vs test interval: nonrenewal, negligible downtime (d = 0), exponential models, initial failure probability $p_0 = 10^{-4}$, rate of failure rate change $\alpha = 0.10$ year$^{-1}$, component lifetime s = 40 years**

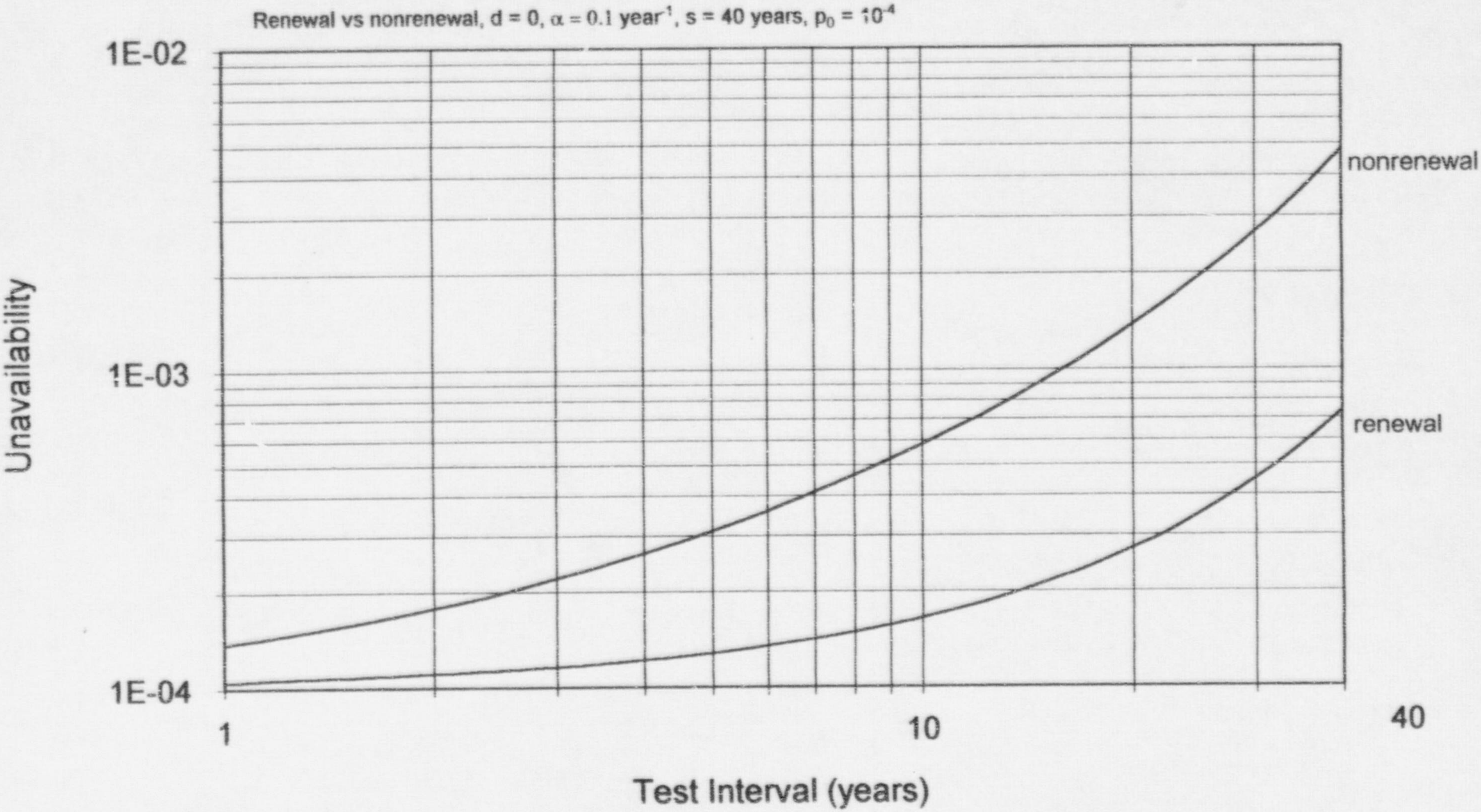


**Figure 5.19** **Unavailability vs test interval - renewal vs nonrenewal: negligible downtime ($d = 0$), exponential models, initial failure probability $p_0 = 1 \times 10^{-4}$, rate of failure rate change $\alpha = 0.10$ year$^{-1}$, component lifetime $s = 40$ years**

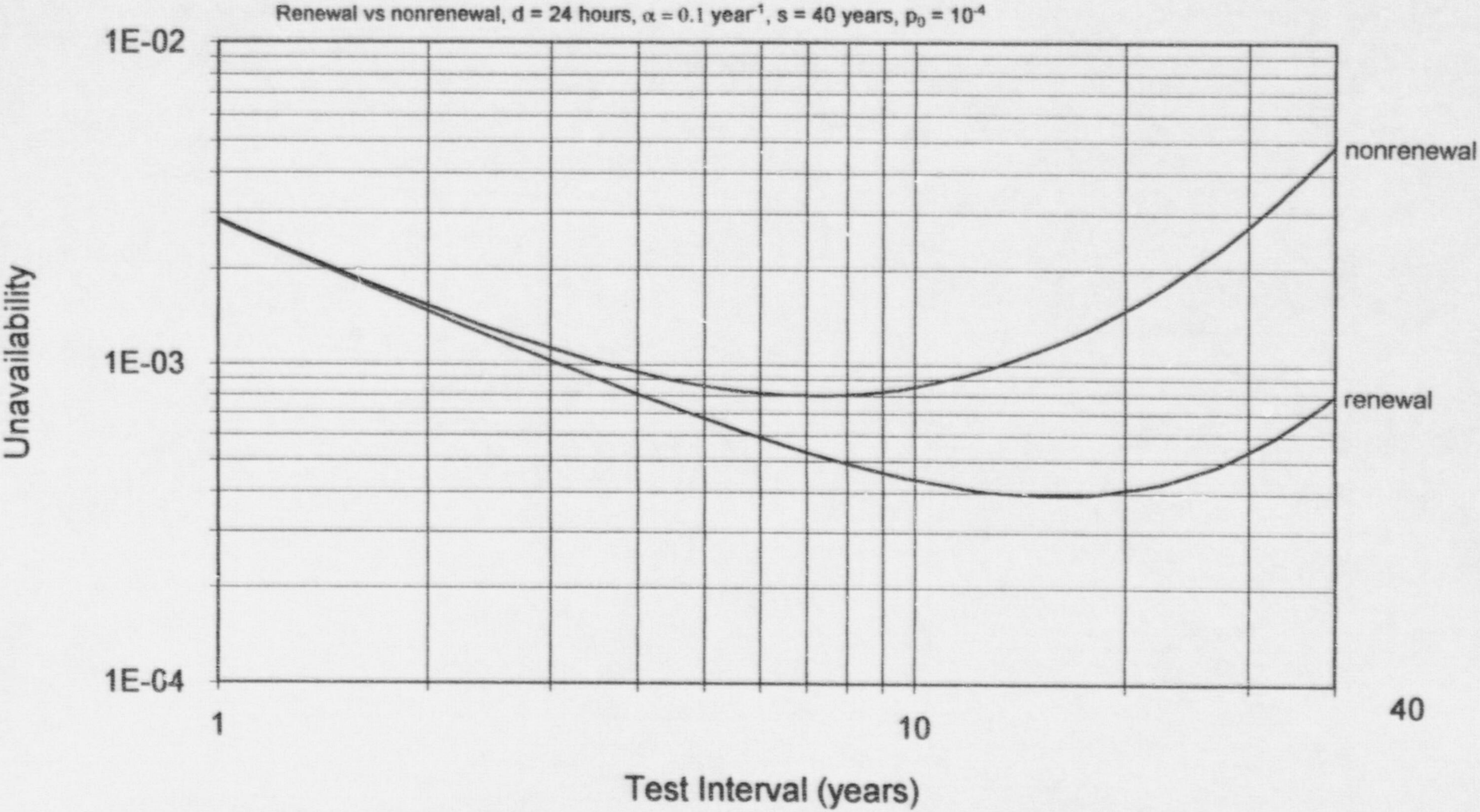


**Figure 5.20** Unavailability vs test interval - renewal vs nonrenewal: downtime contribution d = 24 hours, exponential models, initial failure probability $p_0 = 10^{-4}$, rate of failure rate change $\alpha$ = 0.10 year$^{-1}$, component lifetime s = 40 years

### 5.4.5 Simplified Approximations for Unavailability With and Without Renewal

Useful, simple expressions for the unavailability can be obtained by expanding the first exponential terms in the formulas by their linear approximations. As Appendix E shows, for a test with follow-up renewal, the simplified unavailability formula is given by

$$Q \cong p_0 + p_0\left(e^{\frac{\alpha L}{2}} - 1\right) + \frac{d}{d+L} : \text{renewal} \quad . \tag{5.39}$$

For no renewal, the simplified formula becomes

$$Q_{nr} \cong p_0\left[1 + e^{\frac{\alpha S}{2}}\left(e^{\frac{\alpha L}{2}} - 1\right)\right] + \frac{d}{d+L} : \text{no renewal} \quad . \tag{5.40}$$

The formulae in Eqs. (5.39) and (5.40) are accurate for unavailabilities below 10% (i.e., $Q < 0.1$ and $Q_{nr} < 0.1$) and are conservative for larger values.

These simplified formulae allow easier evaluations and implementations. Direct bounding results can also be obtained for the test interval L that achieves a specified unavailability Q when the test has no downtime. Solving Eqs. (5.39) and (5.40) for L as a function of Q and $Q_{nr}$ when the downtime is negligible (i.e., $d = 0$) gives

$$L = \frac{2}{\alpha}\ln\frac{Q}{p_0} : \text{renewal, } d = 0 \quad , \tag{5.41}$$

and

$$L = \frac{2}{\alpha}\ln\left[e^{\frac{-\alpha S}{2}}\left(\frac{Q_{nr}}{p_0} - 1\right) + 1\right] : \text{no renewal, } d = 0 \quad . \tag{5.42}$$

These simplified formulas also allow useful expressions to be obtained for the relative unavailability. Note that Eqs. (5.41) and (5.42), show that the value of L depends on the ratio of $Q/p_0$, that is, the relative unavailability. Therefore, if f(L) is defined as

$$f(L) = \frac{Q - p_0}{p_0} \quad , \tag{5.43}$$

then f(L) = the increase in unavailability relative to the initial unavailability $p_0$.

As a result, if unavailability is not affected significantly by changes in the length of the test interval L, then f(L) will remain constant. If there is no aging, then f(L) will be zero. From Eqs. (5.41) and (5.42):

$$f(L) = e^{\frac{\alpha L}{2}} - 1 : \text{renewal, } d = 0 \quad , \tag{5.44}$$

and

$$f(L) = e^{\frac{\alpha S}{2}}\left(e^{\frac{\alpha L}{2}} - 1\right) : \text{no renewal, } d = 0 \quad . \tag{5.45}$$

These equations for the relative increase in unavailability f(L) are useful because they only involve the RFRC ($\alpha$), the test interval L, and for no follow-up renewal the preventive maintenance interval or component lifetime S. The initial unavailability (failure per demand probability) $p_0$ does not appear in this formula.

The formulae for the relative failure probability change f(L) can also be inverted to solve for the test interval L, which yields a given value f:

$$L = \frac{2}{\alpha}\ln(f+1)\text{: renewal, } d = 0 \ , \qquad (5.46)$$

$$L = \frac{2}{\alpha}\ln\left(e^{\frac{-\alpha S}{2}} f + 1\right)\text{: no renewal, } d = 0 \qquad (5.47)$$

Figures 5.21 and 5.22 illustrate test intervals that achieve specified absolute unavailabilities using Eqs. (5.41) and (5.42) and the same parameters as in previous examples. Parametric evaluations for the relative unavailability based on Eqs. (5.44) and (5.45) are presented in the next section.

## 5.4.6 Effect of Aging on Unavailability: Parametric Evaluations

Component unavailability formulas incorporating the effects of test intervals and component aging were given in the previous section. These formulas are evaluated in this section using RFRCs to investigate the effects of different rates of component aging. As in the previous section, the evaluations are grouped according to whether the test is followed by component renewal. The curves presented in Figs. 5.23–5.26 are based on the assumption of an initial unavailability (failure probability per demand) of $p_0 = 10^{-4}$; however, the primary focus of this section is the relative change in unavailability for different values of the test intervals and RFRCs.

### 5.4.6.1 Tests Followed by Component Renewal

Figure 5.23, based on Eq. (5.37), shows the unavailability Q vs test interval L for RFRC ($\alpha$) values ranging from 0 to 100% per year for the case in which testing is followed by renewal. A 24-hour downtime d is associated with the tests. The effects of different downtimes are studied in a subsequent section. Figure 5.24 shows similar component unavailability curves for the case in which there is no downtime associated with the test. The $\alpha = 0$ curves in all figures represent the behavior for no component aging. In Fig. 5.24, the $\alpha = 0$ line is the horizontal line of unavailability of $10^{-4}$.

The curves in Figs. 5.23 and 5.24 show how unavailability increases with RFRC as a function of length of the test interval. The increases in unavailability become more pronounced as RFRCs and test intervals increase. For test intervals longer than 5 years, RFRC values of 30 to 50% per year ($\alpha = 0.3$ year$^{-1}$ to $\alpha = 0.5$ year$^{-1}$) result in significant unavailability increases.

Figure 5.23 shows that a definite minimum unavailability corresponds to an optimal test interval when the test has an associated downtime. The optimal test interval decreases as the RFRC increases. Figure 5.24 shows that unavailability increases monotonically with the length of the test interval when testing has no downtime.

### 5.4.6.2 Tests Not Followed by Component Renewal

Figures 5.25 and 5.26 show the component unavailability vs test interval for RFRCs from 0 to 0.5 year$^{-1}$ for the case in which the tests are not followed by component renewal. Figure 5.25 shows the results when the test has an associated downtime of 24 hours, and Fig. 5.26 shows the results when the test has a negligible associated downtime.

Figures 5.25 and 5.26 again show that the specified test interval becomes more significant as the RFRC increases. Aging effects are even more pronounced for tests that have no follow-up renewal, which is obvious because the aging effects accumulate and the tests do not affect the component. Figure 5.25 shows that for 24-hour downtimes and $10^{-4}$ initial failure probability, the optimal test interval goes from 7 years to 7 months when the RFRC changes from 10% to 30% per year ($\alpha = 0.1$ to 0.3 year$^{-1}$).

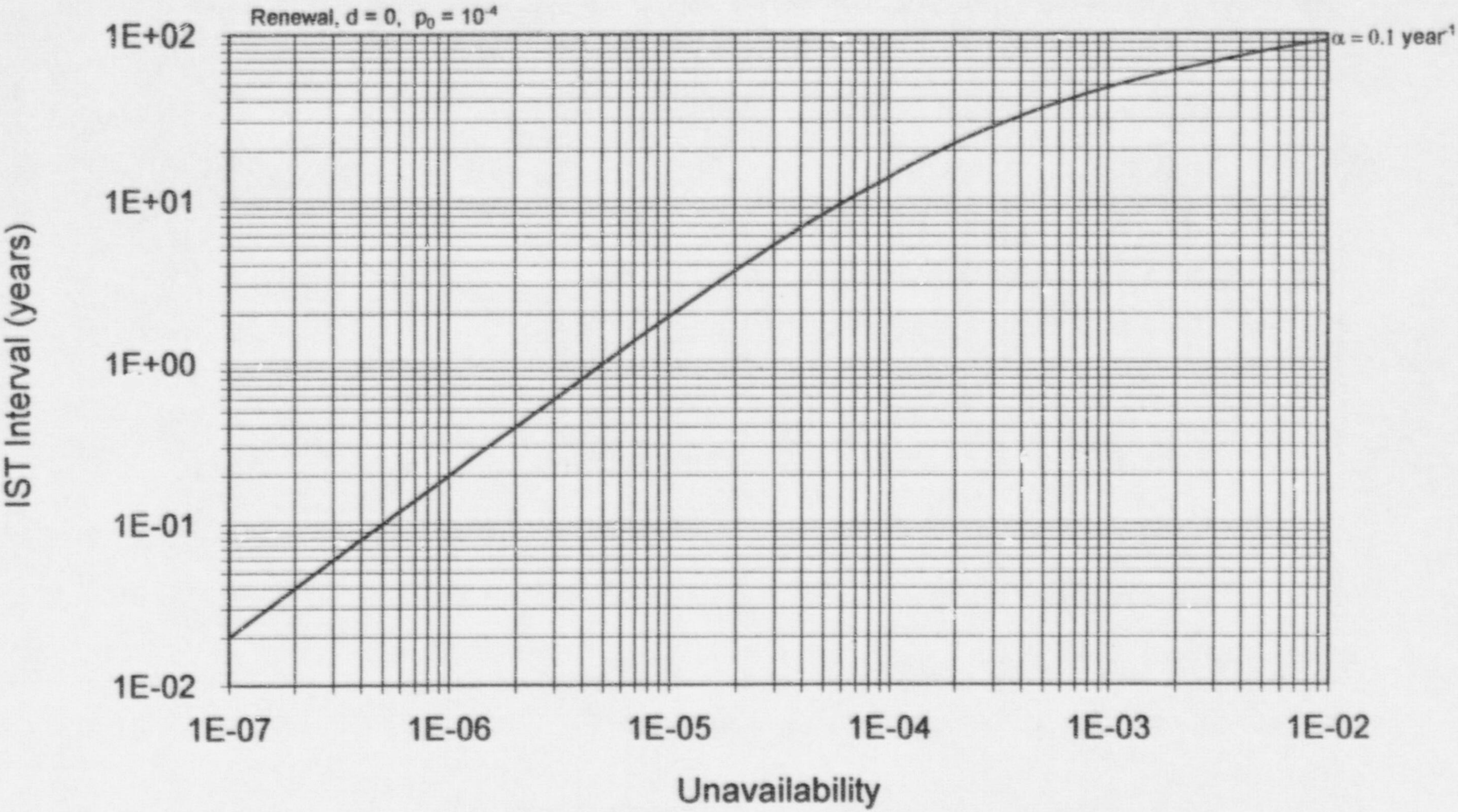


**Figure 5.21** IST interval vs failure probability: follow-up renewal, negligible downtime, exponential models, initial failure probability $p_0 = 10^{-4}$, rate of failure rate change $\alpha = 0.10$ year$^{-1}$

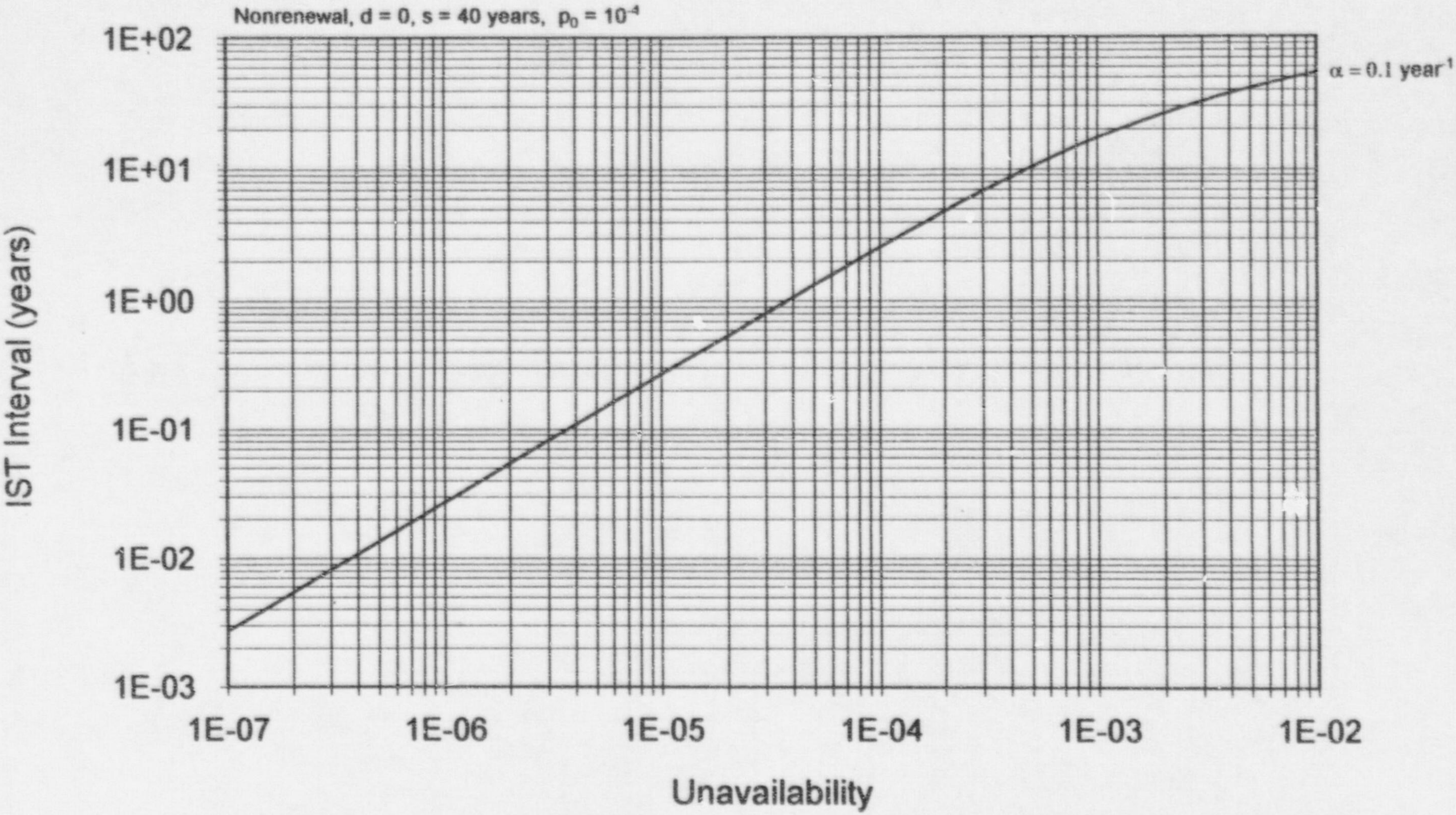


**Figure 5.22** **IST interval vs failure probability: nonrenewal, negligible downtime (d = 0), exponential models, initial failure probability $p_0 = 10^{-4}$, rate of failure rate change $\alpha = 0.10$ year$^{-1}$, component lifetime s = 40 years**

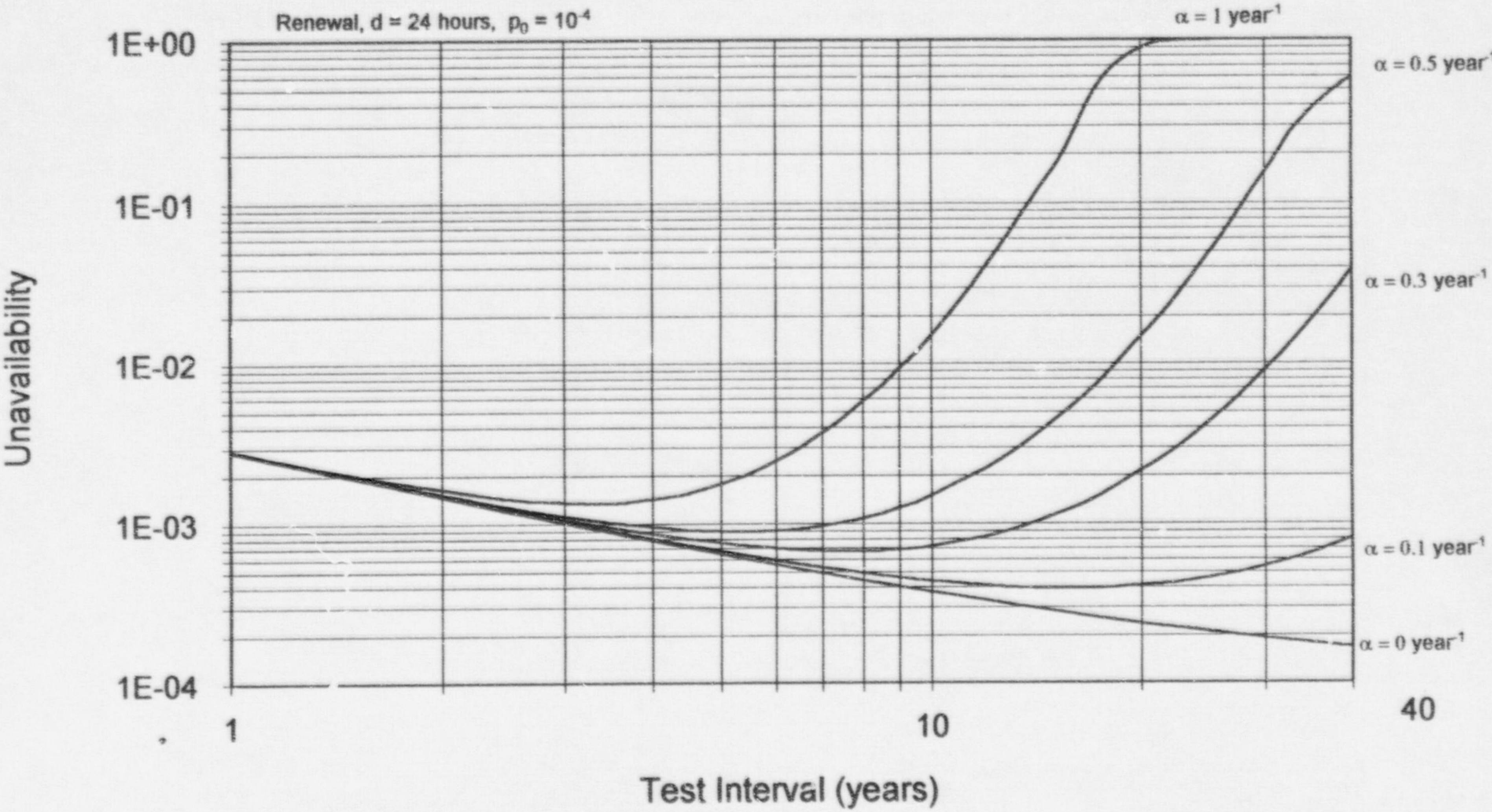


**Figure 5.23 Unavailability vs test interval: follow-up renewal, downtime contribution d = 24 hours, exponential models, various rates of failure rate change, initial failure probability $p_0 = 10^{-4}$**

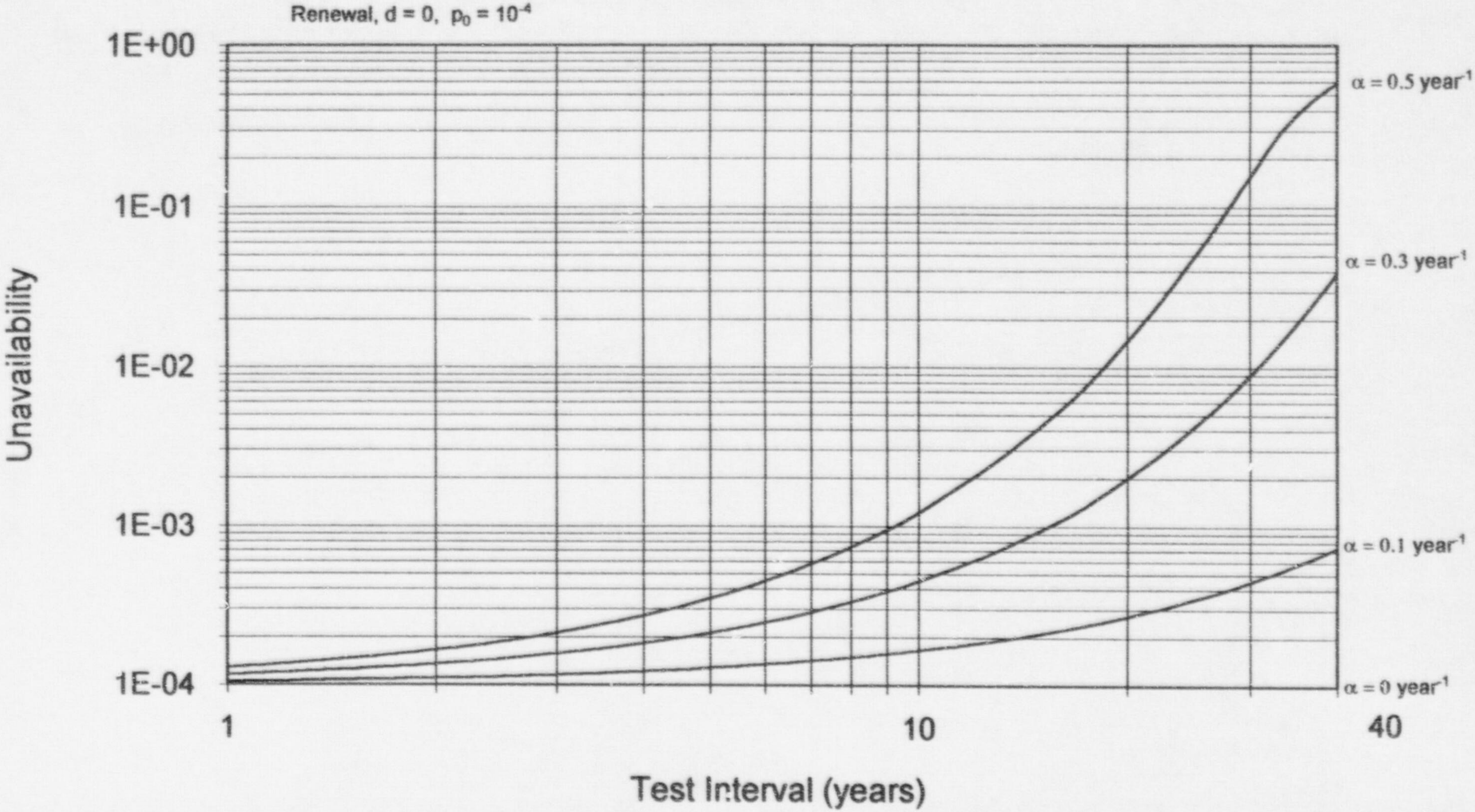


**Figure 5.24** **Unavailability vs test interval: follow-up renewal, negligible downtime (d = 0), exponential models, different rates of failure rate change ($\alpha$), initial failure probability $p_0 = 10^{-4}$**

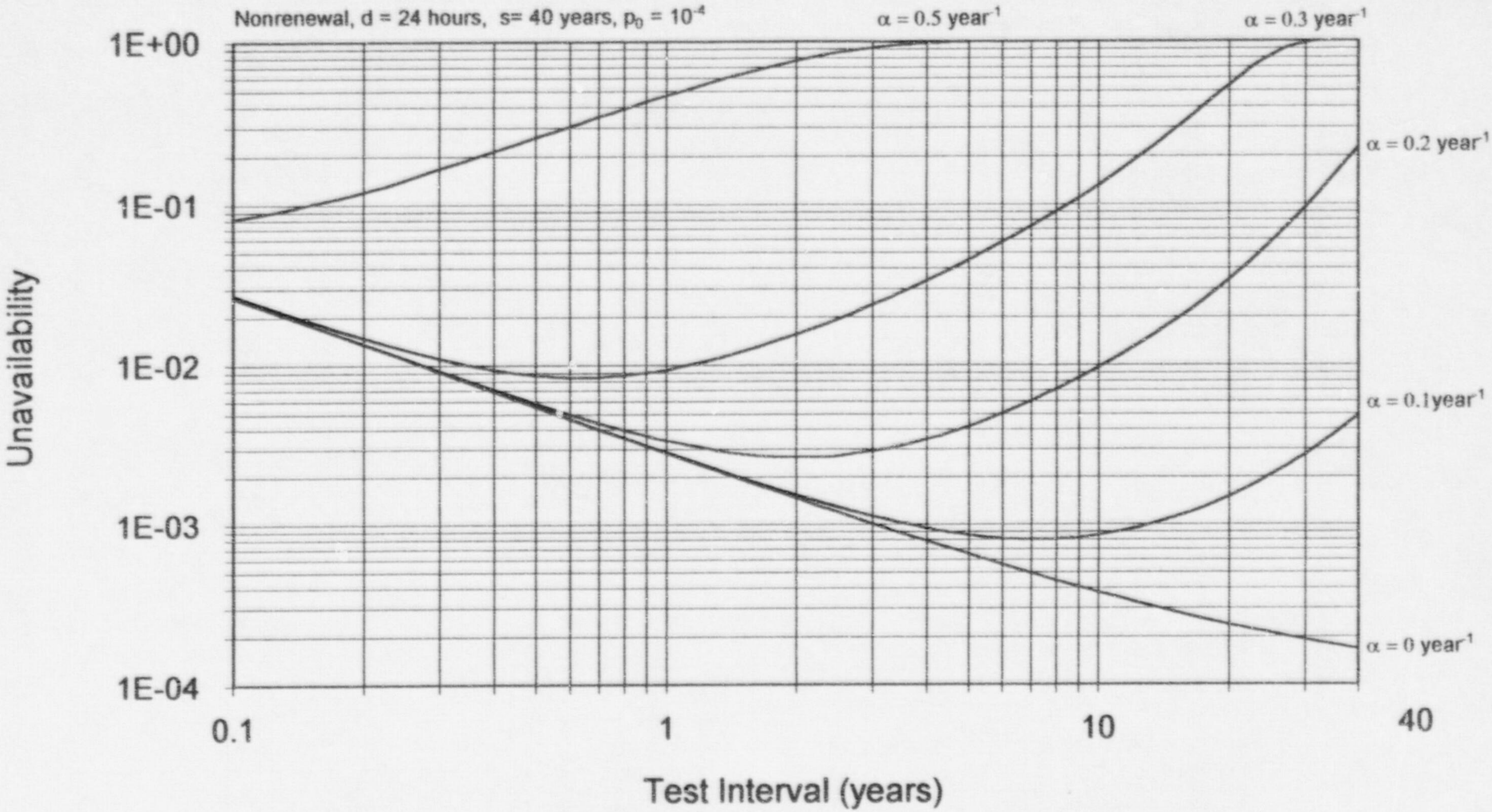


**Figure 5.25** **Unavailability vs test interval: nonrenewal, downtime contribution d = 24 hours, exponential models, different rates of failure rate change ($\alpha$), initial failure probability $p_0 = 10^{-4}$, component lifetime s= 40 years**

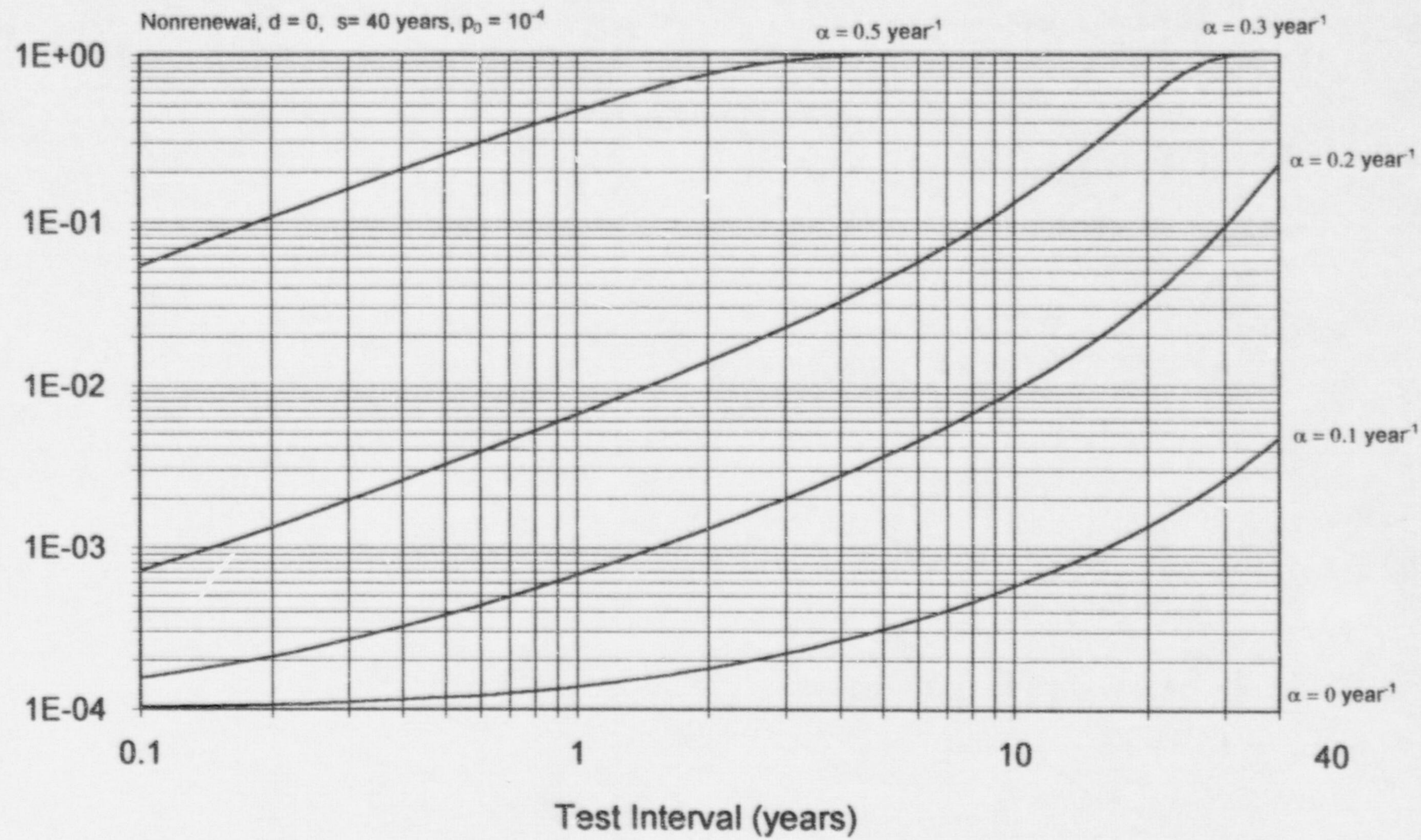


**Figure 5.26** **Unavailability vs test interval: nonrenewal, negligible downtime ($d = 0$), exponential models, different rates of failure rate change ($\alpha$), component lifetime $s = 40$ years, initial failure probability $p_0 = 10^{-4}$**

### 5.4.7 Effect of Test Downtime on Unavailability: Parametric Evaluation

The parametric studies discussed in this section (Figs. 5.27 and 5.28) evaluate the effect on unavailability of test-associated downtime durations ranging from 0 to 144 hours. The other parameters have the same reference values used in the previous examples; all cases use an RFRC of 10% per year ($\alpha = 0.10$ year$^{-1}$) and an initial unavailability of $p_0 = 10^{-4}$. The evaluations are grouped as to whether the tests are followed by component renewal.

#### 5.4.7.1 Tests Followed by Component Renewal

Figure 5.27 shows the case of testing followed by renewal. For test intervals below 10 years, the unavailability is approximately proportional to the downtime length (e.g., the unavailability for a downtime of 8 hours is approximately one-third of the unavailability for a downtime of 24 hours). The difference between the curves decreases continuously as the test interval increases. For an IST interval of 1 year the unavailability for a negligible (zero) downtime is approximately a factor of 10 lower than it is for a downtime of 8 hours. For a 10-year interval, the difference between the zero and 8-hour downtime cases is only a factor of 2.

#### 5.4.7.2 Tests Not Followed by Component Renewal

Figure 5.28 shows the case of testing not followed by renewal. The unavailability curves show similar behaviors as the previous renewal curves. For any nonzero downtime and for a test interval <10 years, the unavailability changes in proportion to the downtime length. For intervals above 40 years, the curves converge and indicate that contribution of the exponentially increasing failure rate, governed by the 0.1 year$^{-1}$ value of the RFRC, has become dominant.

### 5.4.8 Effect of the Initial Unavailability on Unavailability: Parametric Evaluation

The parametric evaluations discussed in this section (Figs. 5.29–5.32) investigate the effects of $p_0$ (the initial unavailability or failure probability per demand) on the curves of unavailability vs test interval. Initial failure probabilities varying from $10^{-6}$ to $10^{-2}$ are used, while the reference RFRC of $\alpha = 0.10$ year$^{-1}$ is held constant. The focus is on the relative change in unavailability.

#### 5.4.8.1 Tests Followed by Component Renewal

Figures 5.29 and 5.30 show the case of follow-up component renewal. Figure 5.29 is for tests with an associated downtime of 24 hours, and Fig. 5.30 is for tests with a negligible associated downtime. Figure 5.29 shows how, for small values of the initial failure probability ($p_0 \leq 10^{-6}$), a 24-hour downtime dominates the unavailability for test intervals up to 40 years. Figure 5.30 shows that all curves have similar shapes for no downtime; that is, they are scaled by the value of $p_0$.

#### 5.4.8.2 Tests Not Followed by Component Renewal

Figures 5.31 and 5.32 show the case of no follow-up renewal. Figure 5.31 is for tests with an associated downtime of 24 hours, and Fig. 5.32 is for tests with a negligible associated downtime. Figure 5.31 shows that, as the test interval decreases, downtime becomes more significant. All curves converge to value of the downtime contribution, $d/(d + L)$. Figure 5.32 also shows that all curves have similar shapes for no downtime; the unavailability is proportional to the value of $p_0$.

### 5.4.9 Effect of Aging on the Relative Increase in Unavailability: Parametric Evaluation

The relative increase in unavailability $f(L)$ was defined in Eqs. (5.44) and (5.45) as the difference between the unavailability Q and the initial unavailability $p_0$ divided by $p_0$. The parametric studies in this section (Figs. 5.33 and 5.34) evaluate the relative increase in unavailability vs the length of test intervals for RFRC values of 10 to 50% per year.

#### 5.4.9.1 Tests Followed by Component Renewal

Figure 5.33, based on Eq. (5.44), shows the case of renewal with negligible associated downtime. It can be used to identify test intervals that give small increases of relative unavailability in the range of RFRC values assessed to be plausible for the component. For example, Fig. 5.33 shows that for test intervals of 5 years or less, the relative increase in unavailability is less than 100% ($f < 1.0$) for RFRCs up to 30% per year. This means that with test intervals of less than 5 years, the unavailability will be kept within a factor of 2 of the initial value, as obtained from Eq. (5.43). Figure 5.33 can also be used for renewal tests that have associated downtimes, if the test interval is not so small, or the downtime so large, as to let the test downtime contribution become dominant.

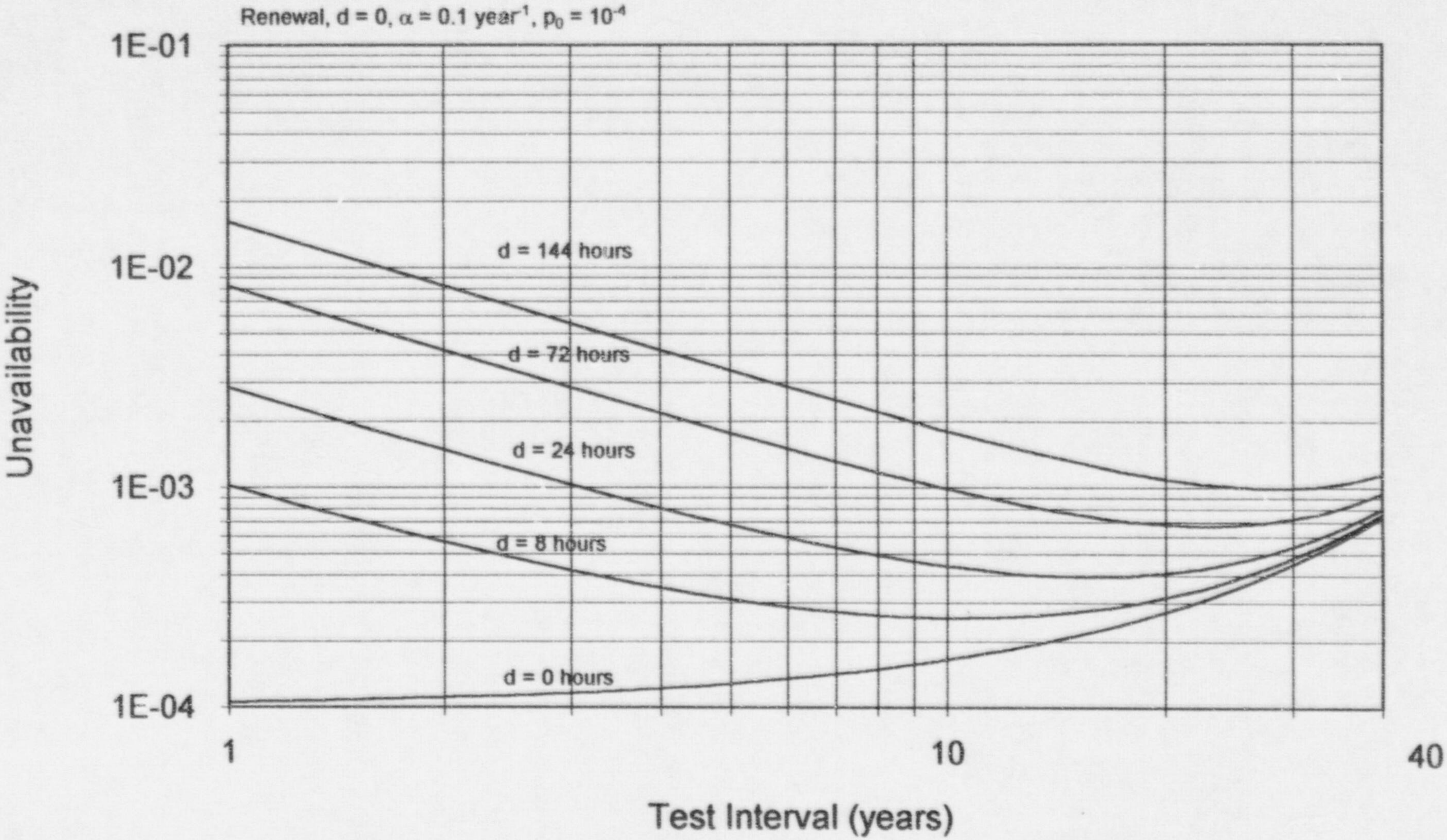


**Figure 5.27** **Unavailability vs test interval: follow-up renewal, downtime contribution, exponential models, different downtimes, initial failure probability $p_0 = 10^{-4}$, total rate of failure rate change $\alpha = 0.10$ year$^{-1}$**

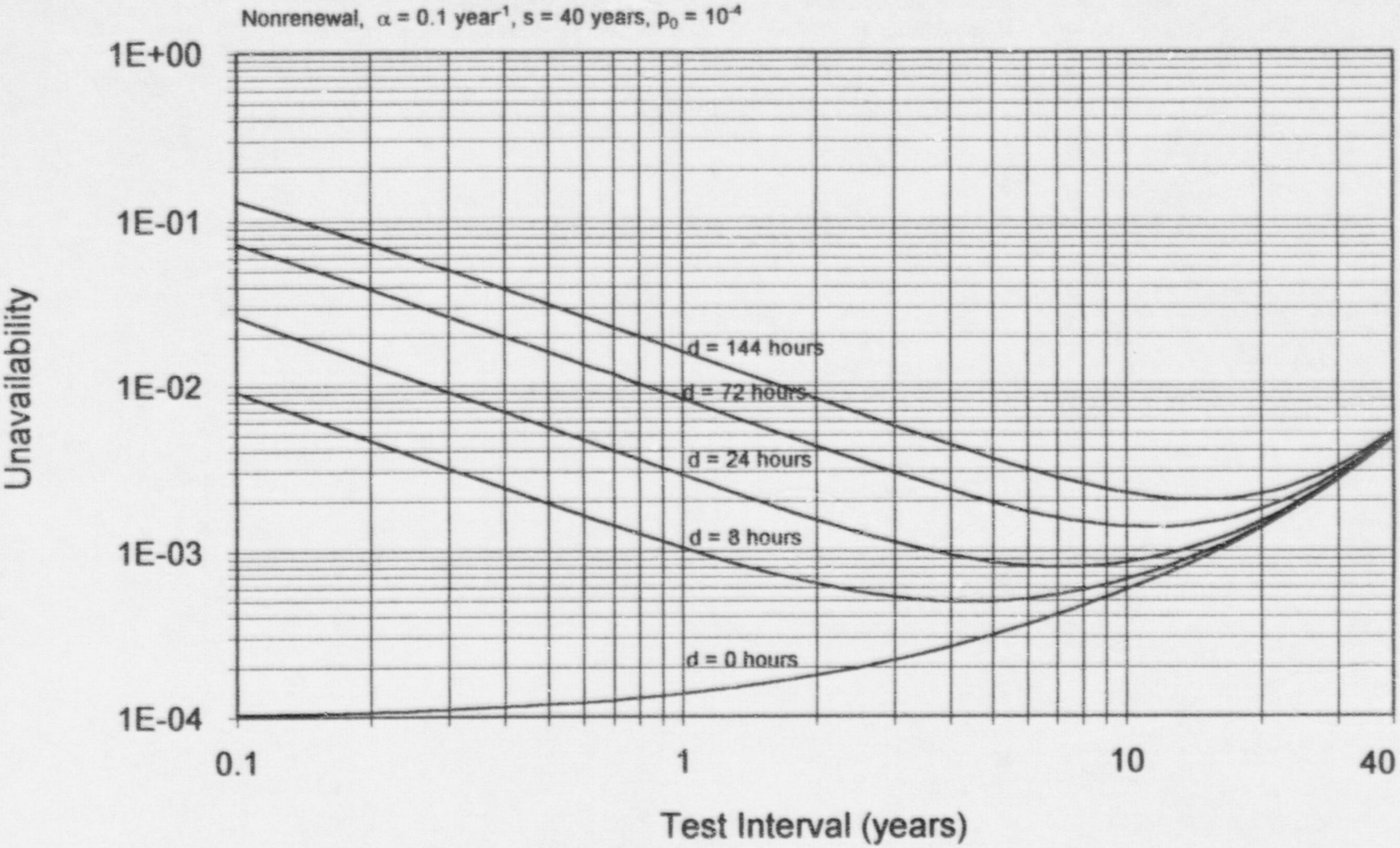


**Figure 5.28** **Unavailability vs test interval: nonrenewal, downtime contribution, exponential models, different downtimes, initial failure probability $p_0 = 10^{-4}$, component lifetime s = 40 years, total rate of failure rate change $\alpha$ = 0.10 year$^{-1}$**

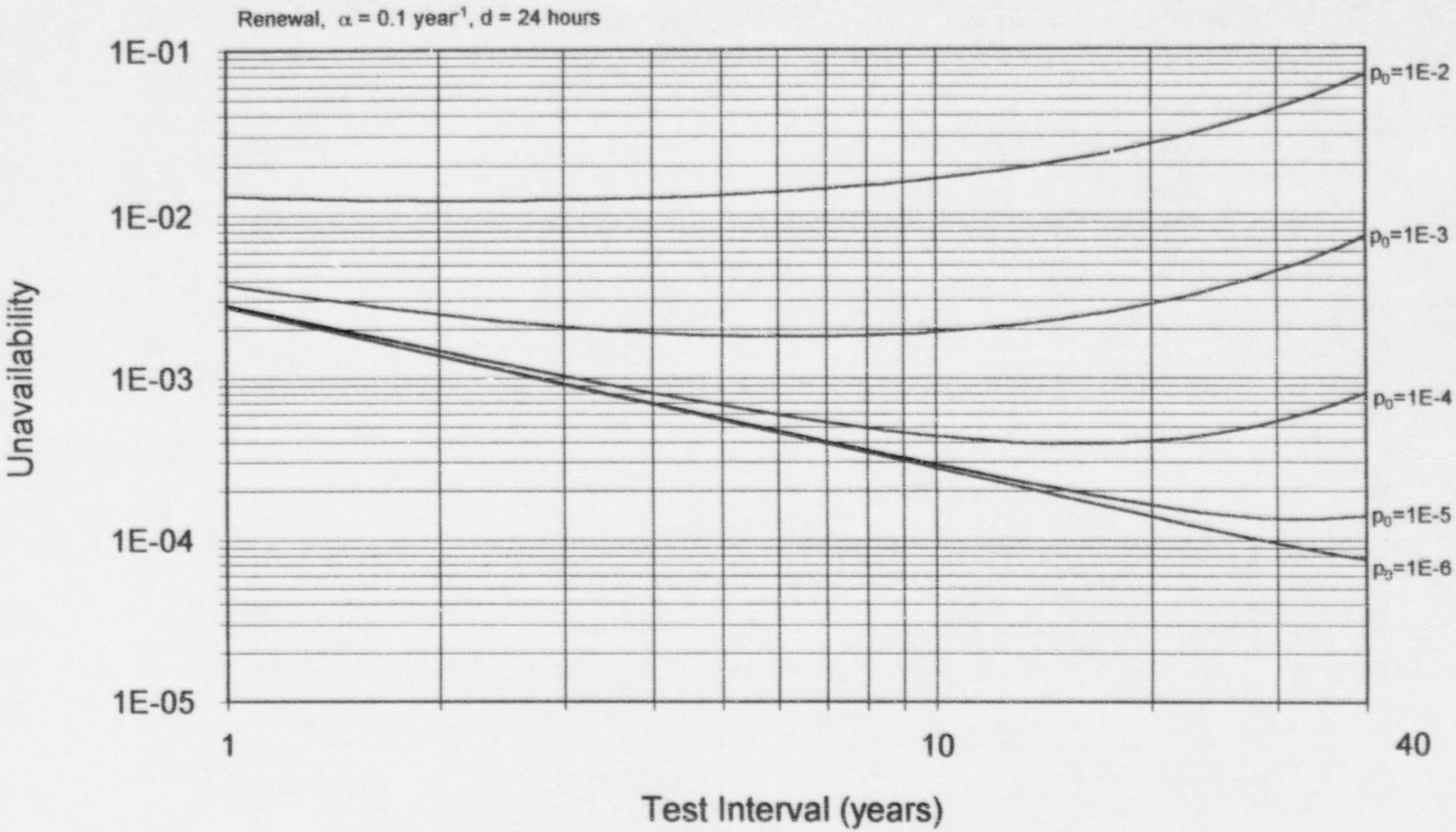


**Figure 5.29** **Unavailability vs test interval: follow-up renewal, downtime contribution d = 24 hours, exponential models, different initial failure probabilities, total rate of failure rate change $\alpha$ = 0.10 year$^{-1}$**

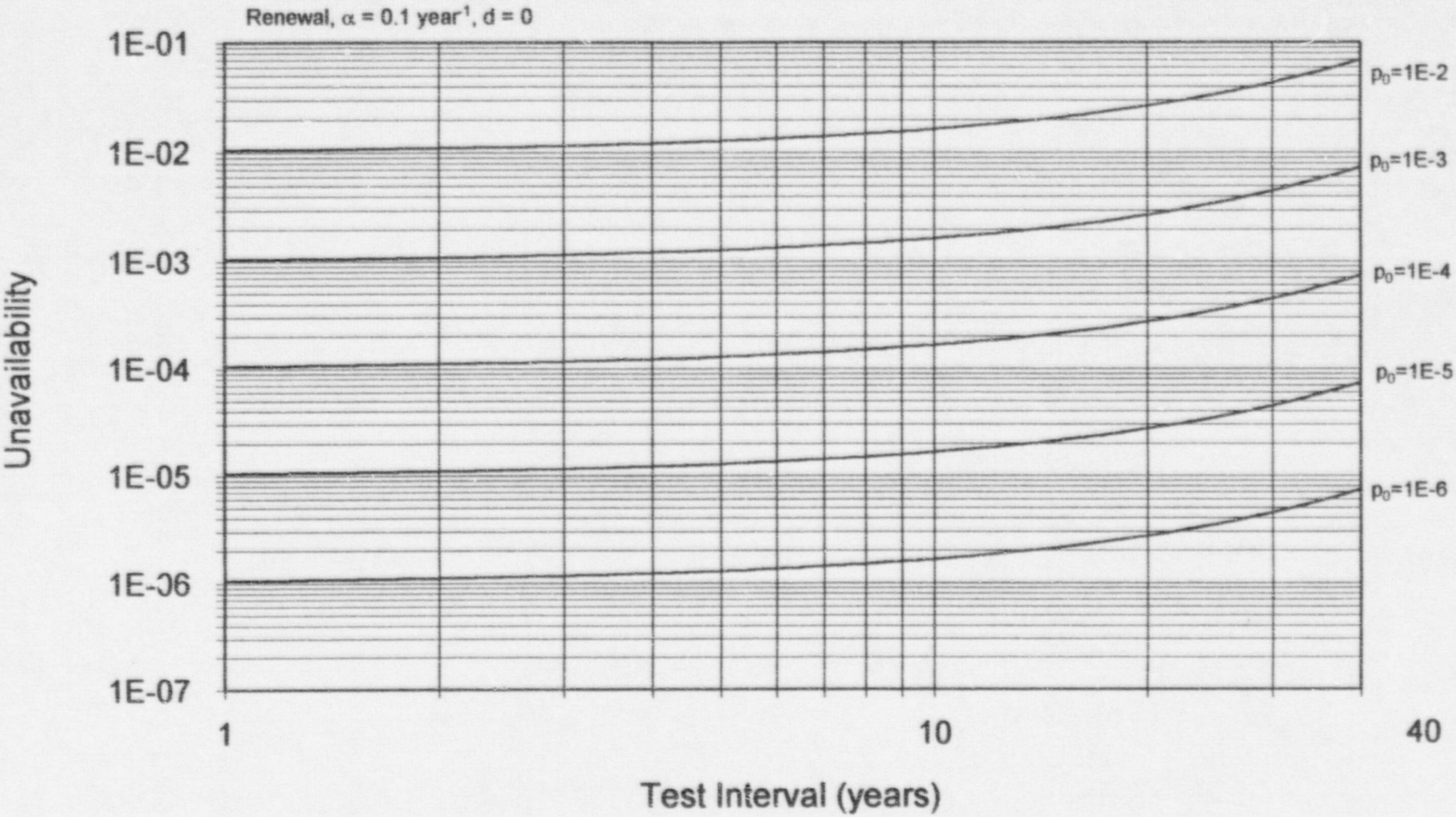


**Figure 5.30** **Unavailability vs test interval: follow-up renewal, negligible downtime (d = 0), exponential models, different initial failure probabilities, total rate of failure rate change $\alpha$ = 0.10 year$^{-1}$**

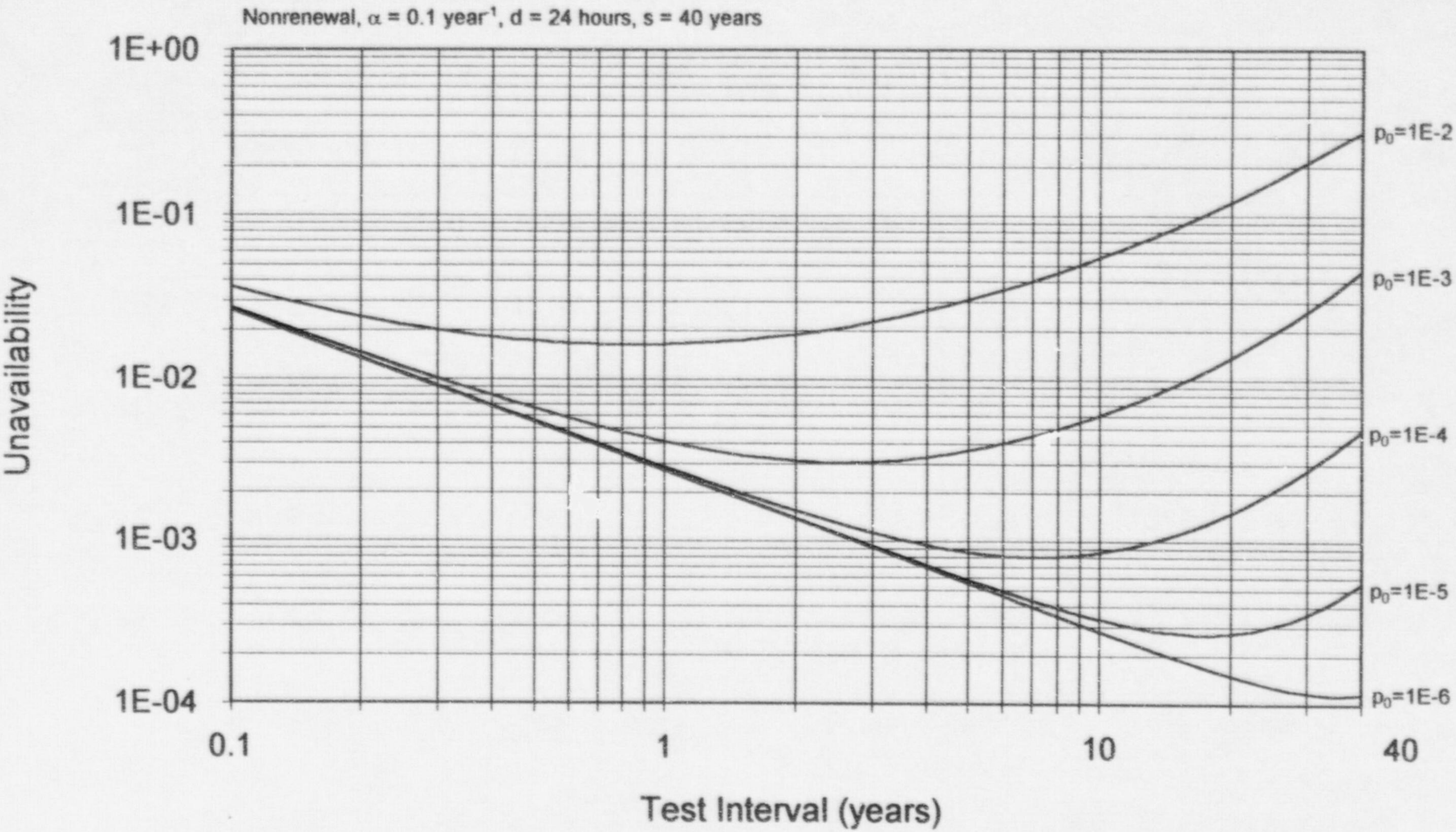


**Figure 5.31** **Unavailability vs test interval: nonrenewal, downtime contribution d = 24 hours, exponential models, different initial failure probabilities, component lifetime s = 40 years, total rate of failure rate change $\alpha$ = 0.10 year$^{-1}$**

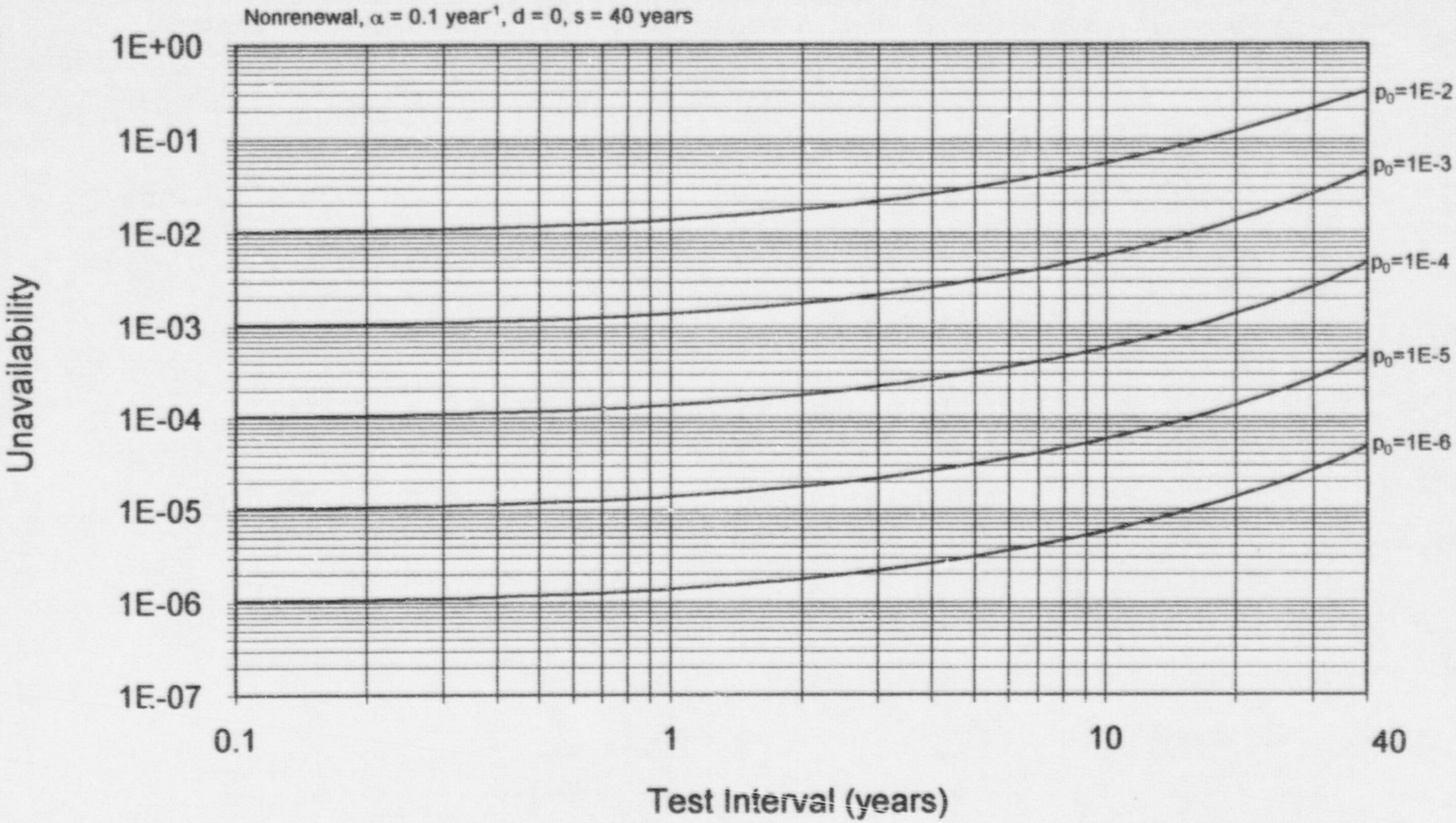


**Figure 5.32** **Unavailability vs test interval: nonrenewal, negligible downtime (d = 0), exponential models, different initial failure probabilities, component lifetime s = 40 years, total rate of failure rate change $\alpha$ = 0.10 year$^{-1}$**

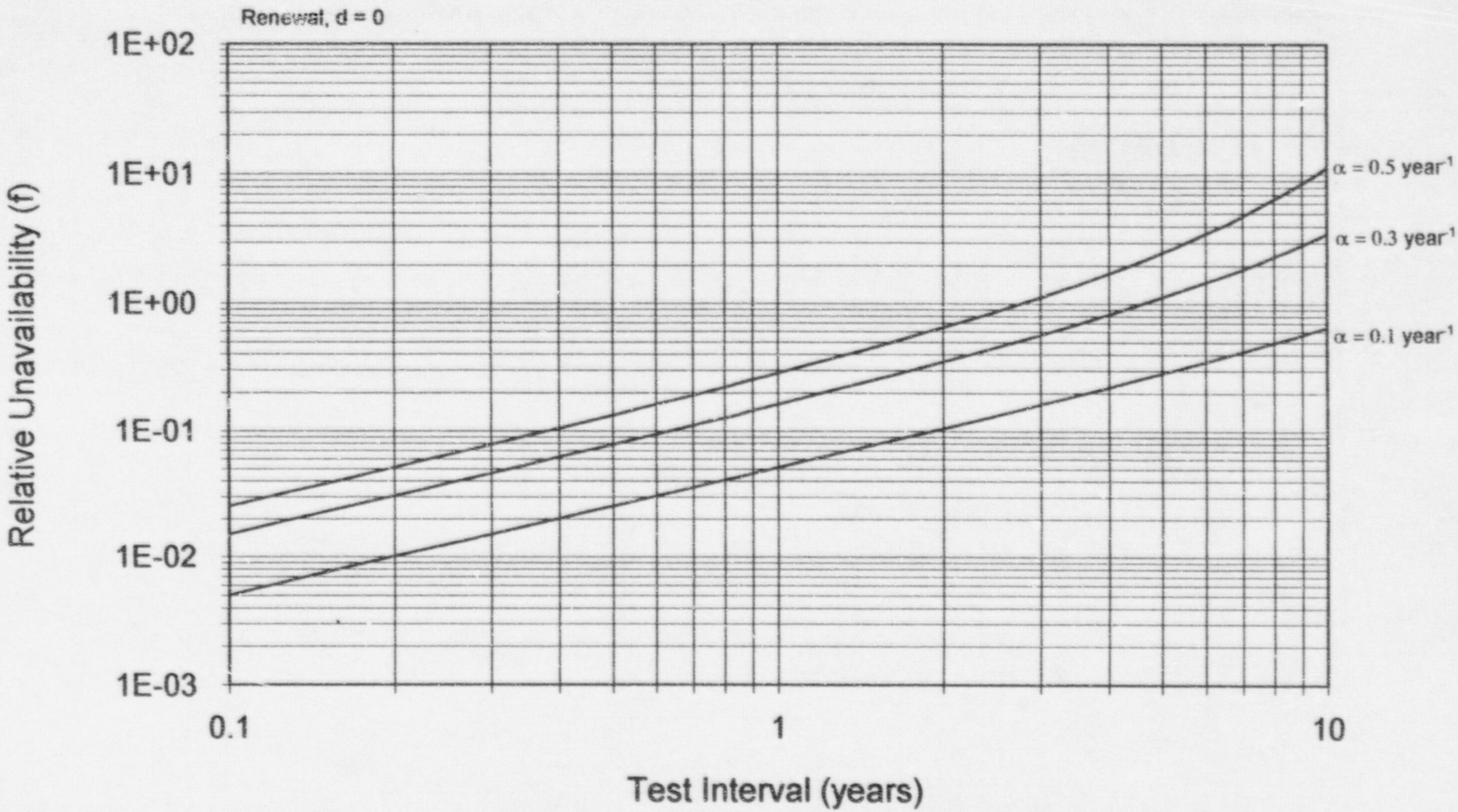


**Figure 5.33 Unavailability increase vs test interval: follow-up renewal, negligible downtime (d = 0), exponential models, first-order relationship, different rates of failure rate change (α)**

#### 5.4.9.2 Tests Not Followed by Component Renewal

Figure 5.34, based on Eq. (5.45), shows the case of no renewal with negligible associated downtime. For example, for a non-renewal test, the RFRC should be close to 10% and the test interval below 3 years to limit the relative unavailability increase to be less than 100%. This goal is unachievable with a 30% RFRC when there is no renewal.

### 5.4.10 Effect of Test Interval on Unavailability: Parametric Evaluations

The effect of the length of the test interval on unavailability is studied by means of Eqs. (5.46) and (5.47) and their graphical representations in Figs. 5.35 and 5.36. With them, the test interval that results in a particular unavailability increase is determined explicitly. RFRCs in the range of 10% to 100% per year are used to explore sensitivities. The results in this section are similar to those given in the previous section but are in a different, easier to analyze, form. The impact of renewal is made dramatically evident by comparison of these two figures.

#### 5.4.10.1 Tests Followed by Component Renewal

Figure 5.35, based on Eq. (5.46), shows the test interval L that produces a given unavailability increase for the case of follow-up renewal with negligible associated downtime. The highest plausible RFRC curve can be selected to explicitly give the test interval, providing a desired maximum relative increase. Equation (5.46) can be used to obtain the test interval for any RFRC and target relative increase in unavailability value f. For instance, to keep f in the 0.1 range, test intervals should be 0.4, 0.65, or 2 years for RFRCs of 50, 30, and 10%, respectively. Equation (5.46) can also be used to obtain guidelines for test intervals with associated downtimes as long as the downtime is not a significant contribution to the total unavailability.

#### 5.4.10.2 Tests Not Followed by Component Renewal

Figure 5.36, based on Eq. (5.47), shows the test interval L that produces a given unavailability increase for the case of no renewal with negligible associated downtime. For instance, to keep f in the 0.1 range, test intervals should be 0.00002, 0.0015, or 0.25 years for RFRCs of 50, 30, and 10%, respectively. Again, Eq. (5.47) can be used to obtain the test interval for any RFRC and target relative increase in unavailability value f when the test has no follow-up renewal.

## 5.5 Conclusions

This chapter discussed relationships between the margin of a component and the failure probability associated with inadequate margin, as well as the unavailability of component with an overall failure rate that changes exponentially with time.

To quantify aging effects for the inadequate margin failure mode and because existing databases do not have information related to how the margin of components, such as valves and pumps, behaves with time, a hypothetical component was modeled with a margin that deteriorates exponentially with time—with a constant relative rate of change—and that exhibits lognormal statistics. The model chosen for the overall component unavailability presumes a failure rate that changes exponentially with time—with a constant relative rate of change.

For the inadequate margin failure mode, when the margin is near 1, then the failure probability due to inadequate margin has high values when the standard deviation is not low, that is, the margin is not accurately known. For instance, for a mean margin of 1.25, the failure probability due to inadequate margin increased from $10^{-4}$ to $10^{-1}$ as the relative standard deviation of the margin increased from 6% to 12%. Margin reduction due to aging further increases the sensitivity to the accuracy of the margin. These situations, which result in high failure probabilities due to inadequate margin, are consistent with earlier findings.[33,34] High failure probabilities can be expected when the margin is low and/or not accurately known, when the test intervals are too large, and when margin degradation is not controlled by renewal or by other means.

Parametric studies were used to show the variation in overall component unavailability vs test interval for tests with and without follow-up renewal. Tests with and without downtime associated with the conduct of the test were also evaluated. Different relative deterioration rates were used, ranging from no aging to significant aging. Test downtime durations ranged from zero to 144 hours. Initial failure probabilities per demand ranging from $10^{-4}$ to $10^{-6}$ were used. The test intervals ranged from 0.1 year to 40 years

Parametric studies of relative changes in unavailability show clearly the positive effect of renewal after testing. With a test interval of 5 years and RFRC of 10%, the unavailability is approximately a factor of 6 lower when renewal is performed. The effect of testing downtime increased the unavailability in proportion to the downtime duration for all test intervals where the

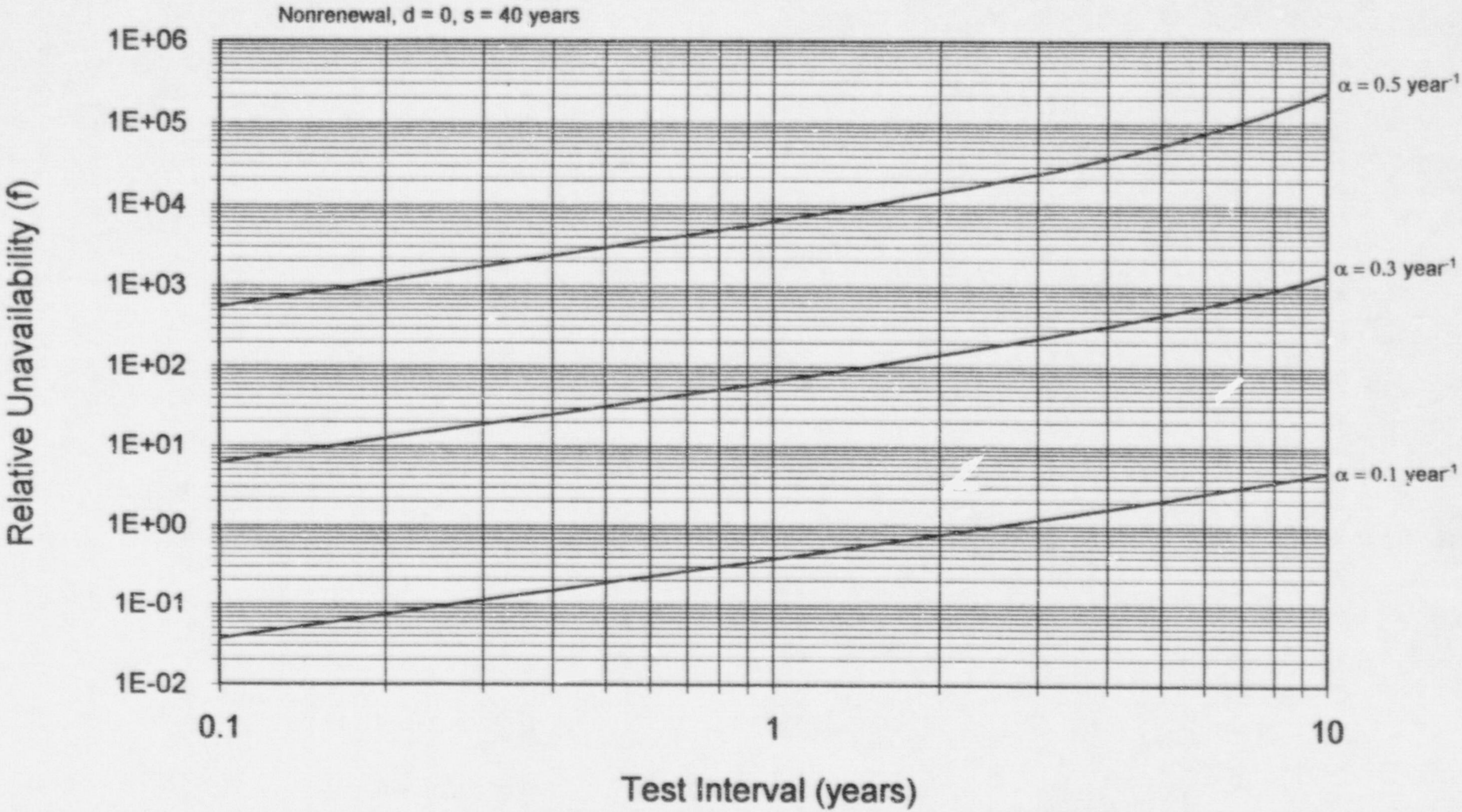


**Figure 5.34** **Unavailability increase vs test interval: nonrenewal, negligible downtime (d = 0), exponential models, first-order relationship, different rates of failure rate change (α), component lifetime s = 40 years**

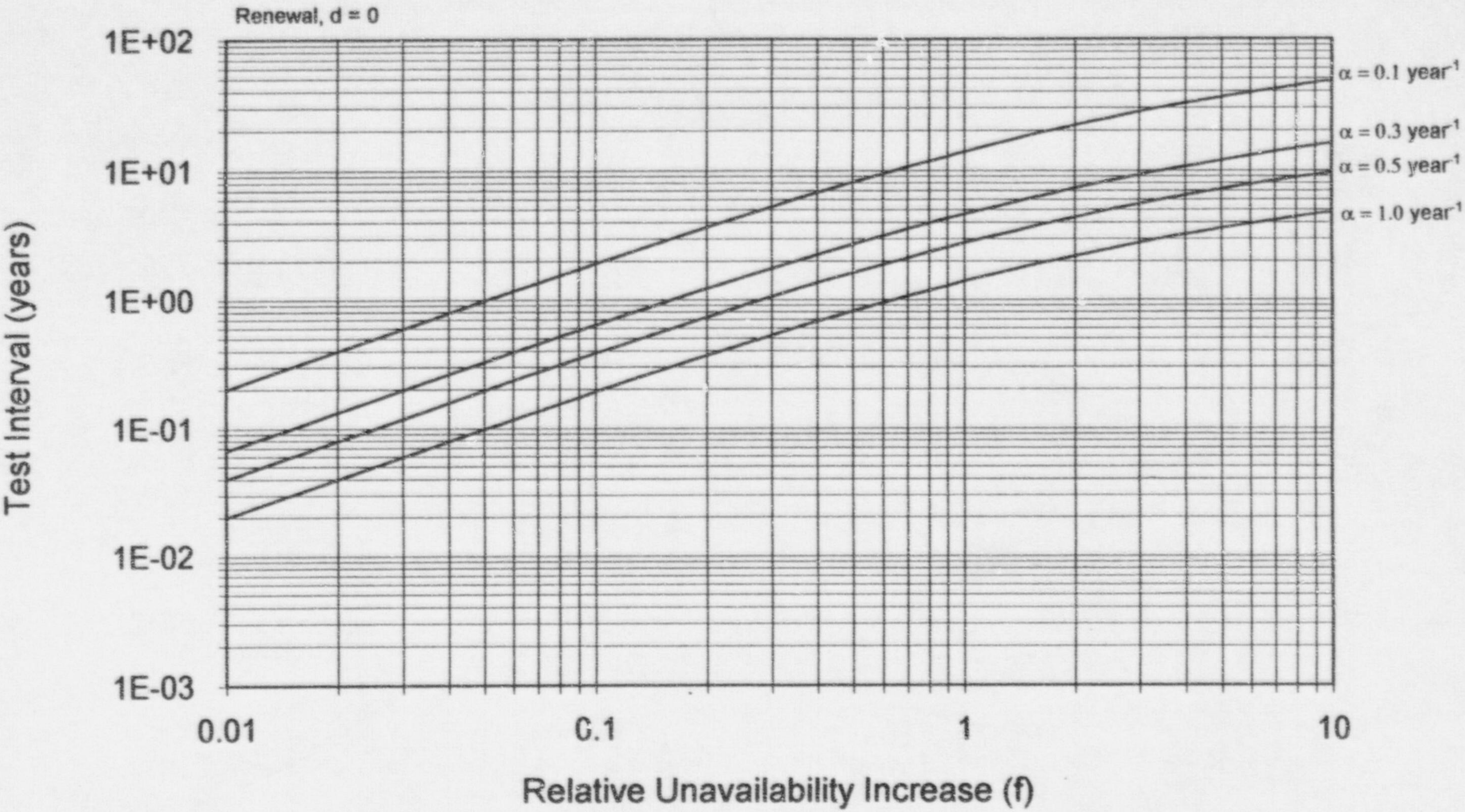


**Figure 5.35** **Test interval vs unavailability increase: follow-up renewal, negligible downtime (d = 0), exponential models, first-order relationship, different rates of failure rate change (α)**

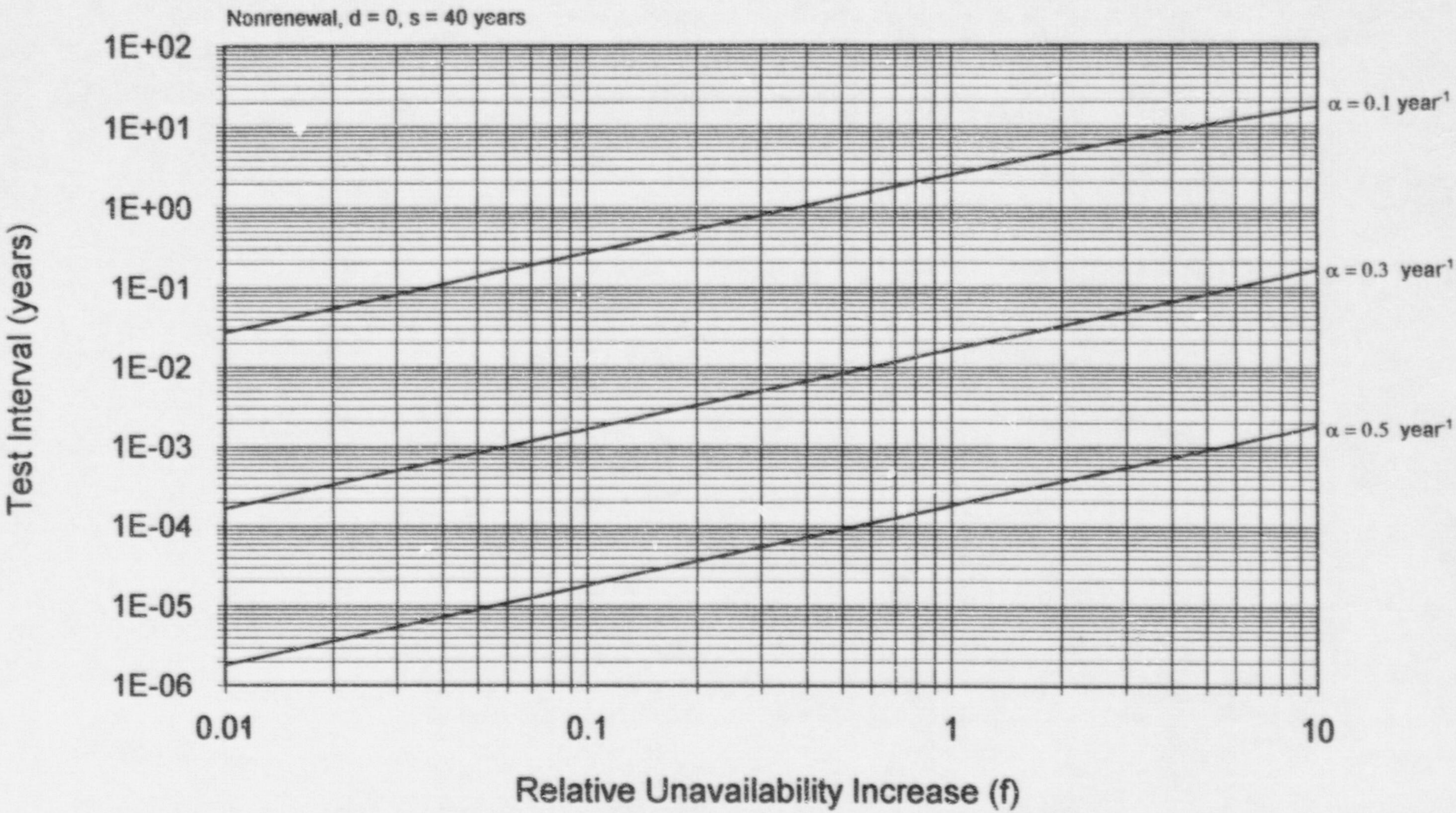


**Figure 5.36** Test interval vs unavailability increase: no renewal, negligible downtime (d = 0), exponential models, first-order relationship, different rates of failure rate change ($\alpha$), component lifetime s = 40 years

downtime contribution was significant. For the same RFRC of 10% and test interval of 5 years, the unavailability is approximately a factor of 2 lower for zero than for 8-hour downtimes.

## 5.6 Summary

Key points and results from Chap. 5 are provided in Table 5.1.

**Table 5.1 Summary of key points and results**

| Section | Key points and results |
|---|---|
| 5.2 General methodology for development of capability and requirement models | ❑ The failure probability due to inadequate margin<br>▪ is the probability that the capability is less than the requirement<br>▪ has the same mathematical bases as standard stress-vs-strength methodologies<br>▪ is determined by the degree of overlap between the statistical distributions of capability and requirement at the time under consideration.<br><br>❑ Because of the statistical nature of the population of components, when the average margin is larger than 1, the probability of inadequate margin is not zero. Similarly, the probability of adequate margin is not necessarily zero when the average margin is less than 1.<br><br>❑ Age-dependent relationships for the statistical descriptors (mean, shape, and standard deviation) of the capability and requirement should take into consideration external factors affecting performance, such as voltage, load, and humidity. |
| 5.3 Probability of inadequate margin: selection of margin time dependence and statistics | ❑ When probability distributions for capability and requirement are not available from measurement data and standard distribution forms are assumed,<br>▪ the assumptions behind the chosen statistical distributions should always be checked for reasonability, and alternate distributions should be considered if needed.<br><br>❑ Component margin is numerically defined as the ratio of the capability to the requirement:<br>▪ Capability is assumed to decrease with component age at a constant relative rate $\alpha_c$<br>▪ Requirement is assumed to increase with component age at a constant relative rate $\alpha_r$<br>▪ Margin is therefore assumed to decrease with age at a rate $\alpha_m$ (sum of the rates of capability and requirement)<br>▪ The time dependence of margin in relative terms to the initial value depends solely on the RMC ($\alpha_m$). |

| | |
|---|---|
| | ❑ When the capability and requirement are lognormal distributions with independent means and standard deviations, then the following results.<br>▪ The margin also has a lognormal distribution. The equations to obtain its mean and standard deviation from the values describing the capability and requirement are included.<br>▪ When the margin is near 1, then the failure probability due to inadequate margin is very sensitive to the standard deviation. For a mean margin of 1.25, the failure probability due to inadequate margin increased from $10^{-4}$ to $10^{-1}$ as the relative standard deviation of the margin increased from 6% to 12% in the illustration provided.<br><br>❑ The age-dependent failure probability due to inadequate margin is derived for the case of exponential time-dependence of the margin.<br><br>❑ Margin reduction due to aging further increases the sensitivity to the accuracy of the margin. High failure probabilities can be expected when the margin is low and/or not accurately known, when the test intervals are too large, and when margin degradation is not controlled by renewal when testing or by other means. |
| 5.4 Component unavailability vs test interval for a component with exponentially time-dependent failure rate | ❑ Formulae are derived for overall component unavailability vs test interval using an age-dependent exponential component failure rate (instead of the margin-based failure rate used earlier.) Simpler approximations are also derived.<br><br>❑ The exponential failure rate model<br>▪ represents operational failures such as those tested for in most present ISTs when interpreted as an operational failure rate<br>▪ corresponds to failure to have adequate margin when interpreted as a margin failure rate.<br><br>❑ Parametric studies of the equations for the bounding cases of full renewal and no renewal are shown graphically for combinations of initial failure rate probabilities, RFRCs, testing interval, test and maintenance downtime, and interval between preventive maintenance operations. |
| Conclusions | *Within the assumptions of the parametric analyses presented here, the following conclusions may be made (these conclusions should not be used in a generic sense without validation of the models and input parameters):*<br><br>❑ High failure probabilities for the inadequate margin failure mode can be expected when the margin is low and/or not accurately known, when the test intervals are too large, and when margin degradation is not controlled by renewal or by other means.<br><br>❑ Renewal after a test reduces the unavailability for all test intervals and for all RFRCs. The amount of reduction increases with the test interval. With a test interval of 5 years and RFRC of 10%, the unavailability is approximately |

| | |
|---|---|
| | a factor of 6 lower when renewal is performed (may vary depending on chosen models).<br><br>❑ Testing downtime increases the unavailability in proportion to the downtime duration for all test intervals where the downtime contribution is dominant. For a RFRC of 10% and test interval of 5 years, the unavailability is approximately a factor of 2 lower for zero than for 8-hour downtimes (may vary depending on chosen models).<br><br>❑ Aging can have a significant impact on unavailability. The effect is more significant when the tests have no follow-up renewal.<br><br>❑ It is recommended that appropriate actions be taken to ensure that the necessary data is available in the near future for a rational application of margin-based techniques to nuclear plant components.<br><br>❑ Renewal to less-than-full initial condition and with higher probability of failure caused by faulty renewal should be added to the models. |

# 6 Summary and Conclusions

The objective of this study was to provide guidelines to support the evaluation of IST intervals for pumps and MOVs. These guidelines should support the assessment of (1) proposed changes to IST programs based on risk-informed methodologies, (2) relief requests to extend IST intervals, and (3) issues related to margin availability. Specific engineering information pertinent to the performance and monitoring/testing of pumps and MOVs was presented, and a methodology for assessing the bounding effects of component aging on margin behavior and unavailability was discussed. The basic elements of an overall program to help ensure component operability were also outlined, because the primary objective of the study was to support the evaluation of the programmatic aspects of licensee initiatives for IST changes as well as the specific test intervals. Guidance for assessing probabilistic methods and the risk importance and safety consequences of the performance of pumps and MOVs has not been specifically included within the scope of this report, but these elements may be included in licensee change requests. Conclusions and observations from the study follow.

## 6.1 Component Performance

Discussions of MOV and/or pump performance should not focus only on the primary components themselves but also on the subcomponents and auxiliary and control equipment that comprise the complete MOV or pump *assembly*. The effectiveness of testing and maintenance programs should therefore be evaluated based on their ability to maintain, monitor, and detect failures in the entire pump or valve assembly because the degradation or failure of any subcomponent or auxiliary equipment could potentially lead to functional failure of the valve or pump. The broadening of scope to include the entire component assembly will inherently result in an increase in the base of failure modes and mechanisms, which will make it necessary to broaden the parameters (and thus available technologies) used to diagnose component assembly problems.

The characteristics of component failure behavior need to be understood because of their resulting effects on maintenance and monitoring requirements. Age dependent degradation is not necessarily the dominant factor influencing failure probability for pumps or MOVs. In fact, the traditional view of failure behavior (that most components operate reliably for some period and then wear out) does not apply to most complex components and systems in nuclear power plants. Most failures involve a combination of factors. However, although many failures may occur at any time during the operating life of a component, this does not imply that they are either unpredictable or have no time dependence. Early warning indications of degradation or impending failure are available for many failure modes, if properly monitored. Depending on the sensitivity of the monitoring system, these early warning indications usually provide enough lead time so that actions can be taken to prevent failure.

Because of unavoidable differences in maintenance practices, human interactions, system transients, and general operating modes and environments, individual components will exhibit individual performance characteristics. ORNL studies have shown that variation exists in the relative performance measurement of components with various parameters and cross-correlations. Two significant factors influencing component performance have been shown to be design and service conditions (application).

Critical potential failure modes should be identified, and the condition of key components that could degrade over time should be monitored to provide assurance of the operational readiness of a component.

To obtain valid measures of component performance, logical groupings should be established based on the *parameters with which their performance is most likely to correlate*. In this way, a more homogeneous population may be established and used to determine probabilities of failure, maintenance programs, and test plans.

Generic failure rate values for components are inappropriate because component performance (and therefore failure probability) may vary considerably from one component to another, depending on a number of factors. Realistic estimates of failure rates should be obtained for individual components or groupings to establish effective IST and maintenance programs. Both plant-specific and industry data should be considered for the estimation of failure rates.

## 6.2 Testing and Maintenance

There are important differences between diagnostic testing (e.g., condition monitoring) and performance testing (e.g., margin testing). A performance test usually verifies that equipment operations are "within specification" and/or within acceptable limits (i.e., verifies that a functional failure has not occurred). A diagnostic test gathers information that, if correctly interpreted, can help to assess the general condition of the monitored equipment. A successful performance test cannot by itself guarantee that significant equipment degradation is not present (i.e., the presence of "margin" does not necessarily ensure availability). If the location of the degradation is such that it does not impact the performance parameter being measured, the degradation may go undetected by the performance test and may subsequently lead to an unexpected failure.

Two of the basic elements of any program to address component operability issues are testing and maintenance. Testing activities may include failure prediction (such as diagnostic testing and condition monitoring) and performance testing (such as ISTs and margin tests). Maintenance practices, including preventive, predictive, and corrective activities, play an important role in assuring the continued safe and reliable operation of components such as pumps and valves. Without proper maintenance, components would undoubtedly exhibit higher failure rates. Without testing, many failures would remain hidden until the component had to operate in a demand situation. Measures such as failure prevention, failure prediction, and failure identification should be *complementary* to each other (i.e., each plays a part in an integrated component operability assurance program).

When there is little or no relationship between failure probability and age (and the failures can therefore occur at any time during the component operating life), fixed interval (age-dependent) intrusive maintenance, inspection, and/or test activities can actually *increase* the probability of failure by upsetting an otherwise stable system. Maintenance and test/inspection activities should be properly planned to provide the most benefit while inflicting the least interruption to the component assembly. The assumption that maintenance activities *always* reduce the likelihood of component failure is false; in many cases they may actually *increase* it. Likewise, testing components to verify their conformance with some performance criterion or condition can also affect component condition.

Analysis has shown that in 92 of 246 (37%) significant pump failures, the affected part was a pump bearing; in 36 of 78 (46%) significant pump motor failures, a motor bearing was the affected part—yet the current regulatory/Code required monitoring finds very few bearing problems. Even more significantly, there is no required monitoring for pump circuit breaker condition, and evidence is clear that circuit breaker failures are primary contributors to pump unavailability. These results reinforce the difference in intent or purpose of Code tests vs predictive tests—Code tests are not meant to predict future problems or assess component condition.

An effective program to assure component operability should be *integrated in nature* (i.e., it must consider maintenance, operation, failure prediction, and failure detection). In general, proactive measures that seek to prevent failures should take precedence over those that can only detect or correct them.

For many failure modes, it is possible to find suitable condition monitoring (diagnostic testing) to detect potential failures so that action may be taken to prevent functional failure. To be effective in assuring the operational readiness of a component (i.e., to ensure detection *before* failure), condition monitoring should be done at intervals less than the lead-time-to-failure interval. This interval may be measured in time or cycles and is dependent on the failure mode that it is intended to detect. These measures are predictive (i.e., proactive) in nature and are designed to ensure that a component *does not fail*, as opposed to activities intended to find out if the component *has already failed*. Condition monitoring may be applied both to age-related and nonage-related failure modes because usually in both cases, functional failures are preceded by some kind of warning. The warning period may vary depending on the failure mode and operating conditions. Only one failure mode at a time should be considered when defining appropriate condition monitoring intervals because (1) not all technologies can detect all failure modes and (2) different failure modes exhibit different characteristics and occur on different time frames.

Performance tests *should be able to determine whether any part of a component assembly* (the pump or valve and all its associated subcomponents and supporting components) *has failed*. Of equal importance is that the process of checking for functional failure or performance acceptance *not induce failure or degradation*. The possibility that the component might be left in the failed state *because of the test* should also be considered.

## 6.3 Component Margins

Pump hydraulic performance has potential for margin trending because it can gradually deteriorate as a result of wear-related causes such as impeller wear or diffuser/volute wear. Bearing life analysis and degradation in the pump motor, turbine drive, or circuit breaker, however, cannot be adequately assessed by margin trending unless detailed analysis using modern diagnostic techniques is applied. Similarly for MOVs, comparing developed and required torque may provide some indication of overall performance; however, margin testing alone (such as that described in ASME Code Case OMN-1) cannot likely detect all significant degradation that may be present in either the valve or the actuator. If it is desired for a component to have a high level of availability, performance tests such as margin tests should be supplemental to, not replacements for, the other proactive measures.

By relying on torque measurements (converted to thrust via the design-basis stem factor) rather than thrust measurements directly, functional margin as defined in ASME Code Case OMN-1 is always verified under the assumption that the actual stem factor never exceeds the design-basis stem factor. If torque and thrust are not simultaneously measured, the actual stem factor cannot be determined to prove that it is not greater than the design-basis stem factor. The possibility exists that if the actual stem factor were greater than the design-basis stem factor, insufficient thrust would be delivered to the valve under design-basis conditions, although the torque-based functional margin was acceptable. The approach allowed by OMN-1 does not take into account a sudden loss of margin and MOV functionality as a result of degradations that do not directly impact the OMN-1 margin measurement. If the list of MOV concerns as defined in GL 89-10 were considered, degradation in many of the identified MOV areas could go undetected if only the available stem torque was measured. The measurement of margin as defined in OMN-1 is focused on the torque switch trip setting.

## 6.4 Test Intervals

The required frequency of failure detection tasks should depend on two parameters—the desired availability of the component and its reliability. *Appropriateness of test intervals is determined by the importance of the component and its likelihood of failure*. Calculation of appropriate test intervals is therefore only valid for individual components (or groups of similar components with the same requirements for availability and estimated failure rates) rather than for whole groups of unrelated components.

Failure and diagnostic data trending and feedback mechanisms are necessary to validate and, where required, to modify test intervals. Any proposed extensions of test intervals should also take into account the factors in Table 4.3 for condition monitoring programs and should be validated by review of both plant and industry experience with the component(s) under consideration for extension.

## 6.5 Analytical Methods

Within the assumptions and limitations of the mathematical models and parametric analyses discussed in Chap. 5, the following observations were made for the virtual component modeled:

For an inadequate margin failure mode, it was shown that when the margin is near 1, the failure probability due to inadequate margin has high values when the standard deviation is not low (the margin is not accurately known). For instance, for a mean margin of 1.25, the failure probability due to inadequate margin increased from $10^{-4}$ to $10^{-1}$ as the relative standard deviation of the margin increased from 6% to 12%. Margin reduction due to aging further increases the sensitivity to the accuracy of the margin. High failure probabilities can be expected when the margin is low and/or not accurately known, when the test intervals are too large, and when margin degradation is not controlled by renewal or by other means.

Parametric studies of relative changes in unavailability show clearly the positive effect of renewal after testing. With a test interval of 5 years and RFRC of 10%, the unavailability is approximately a factor of 6 lower when renewal is performed. The effect of testing downtime increased the unavailability in proportion to the downtime duration for all test intervals where the downtime contribution was significant. For the same RFRC of 10% and test interval of 5 years, the unavailability is approximately a factor of 2 lower for no downtime than for 8 hour downtimes.

Since actual data on component margin behavior is presently unavailable, the information presented in Chap. 5 is only intended to illustrate a potential methodology. The results and conclusions derived from these parametric studies are therefore not necessarily applicable to any particular component.

## 6.6 Evaluation of Licensee Change Requests

Evaluation of licensee change requests for IST interval extension for pumps and MOVs should follow the technical review process described in Sects. 4.1–4.3. The evaluation process should contain three basic elements:

1. evaluation of the licensee's engineering analysis used to determine IST interval allowances,
2. evaluation of the licensee's overall program to assure component operability, and
3. evaluation of the licensee's trending and feedback mechanisms that ensure that test intervals are reevaluated and updated as necessary.

## 6.7 Recommendations

It is recommended that appropriate actions be taken to ensure that the necessary data is available in the near future for a rational application of margin-based techniques to nuclear plant components. Valve and pump manufacturers as well as vendors presently performing margin determination tests should be encouraged to incorporate their data into public databases. Margin tests, including future revisions to ASME Code Case OMN-1, could be improved by specifying actual measurements of true engineering margin rather than limiting the test to "go/ no-go" assessment above threshold values.

Studies considering the realistic possibility that renewal operations may not be perfect should be performed. Terms dealing with renewal to less-than-full initial condition (a fraction of "as good as new") and the increased probability of failure right after maintenance or renewal (e.g., due to human error) should be added to the models.

Studies should be performed to provide upper-tier guidance on classifying pumps and MOVs based on their risk and safety significance (using results of plant-specific PRAs as inputs) and component condition assessment criteria to establish IST intervals and test methods. Further, using this report as a basis, studies should be performed to explicitly incorporate risk and safety consequences of these components in *systems*, and document their historical performance.

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39. Electric Power Research Institute, "Common Aging Terminology," EPRI BR-101747, February 1993.

* Available in NRC PDR for inspection and copying for a fee.
† Available in public technical libraries.
‡ Copies are available from U.S. Government Printing Office, Washington D.C. 20402. ATTN: Regulatory Guide Account
** Available for purchase from National Technical Information Service, Springfield, Virginia 22161.

# Glossary

*Age related.* A change in characteristics, condition, or performance as a function of time or use.

*Aging.* The process in which characteristics, condition, or performance gradually change with time or use.

*Aging rate.* Rate of change of some characteristic, condition, or performance.

*Alternate or default activity.* An activity, such as corrective maintenance, which deals with a component that has already failed.

*Available stem torque.* The operator output torque measured at torque switch trip. (*Source*: ASME Code Case OMN-1.)

*Capability.* The actual level of performance that a component is able to achieve without being limited by switches, governors, or other control devices.

*Component assembly (component system).* The component [(e.g., motor-operated valve (MOV) or pump)], its subcomponents, and its auxiliary equipment.

*Condition indicator parameter.* A parameter or characteristic that can be observed, measured, and usually trended to infer, predict, or estimate the present and future ability of a component to perform its design functions.

*Condition monitoring.* An activity or set of activities (observation, measurement, and/or test that usually involves trending applicable condition indicator parameters with time or use) intended to gather information about the state or physical condition of a component to infer, predict, or estimate its current and future ability to function within acceptance criteria.

*Design-basis conditions.* Specified service conditions used to establish the specifications (requirements) for component function.

*Design-basis stem factor.* The greatest value for the stem factor expected during design-basis operation of an MOV. (*Source*: ASME Code Case OMN-1.)

*Deterioration rate.* Rate of degradation of some characteristic, condition, or performance. Also see *aging rate.*

*Diagnostic test.* A test designed to gather information that, if correctly interpreted, can help to assess the general condition of the monitored equipment. Spectral vibration analysis is an example of a diagnostic test.

*Electrical signature analysis (ESA).* A diagnostic technique whereby electrical signals (e.g., current, voltage, power, and/or power factor) are used to gather information related to the condition and performance of electrical and electromechanical components and systems. Also see *Motor current signature analysis.*

*Emission spectroscopy.* An analytical technique to identify metal elements in solution by measuring characteristic radiation as the thermally excited elements release energy.

*Failure.* Inability or interruption of ability to perform a design function within acceptance criteria.

*Failure detection activity.* An activity designed to check whether a component has failed.

*Failure mode.* The manner or state in which a component fails. For example, potential failure modes would include failure to stroke (MOVs) and failure to start (pumps).

*Failure/degradation mechanism.* A physical process that leads to component failure/degradation, such as corrosion (age related) and water hammer (nonage-related).

*Fourier transform infrared spectroscopy*. A sensor technology based on the Michelson interferometer that produces a spectrum for the target radiation for identification of constituent materials.

*Functional failure*. The inability of a component to fulfill a function within a specified acceptance criteria.

*Functional margin*. The increment by which an MOV's available capability exceeds the capability required to operate the MOV under design-basis conditions. (*Source*: ASME Code Case OMN-1.) *Note that "capability" as used in this definition means capability at a given torque switch value. This differs from the definition of capability used to calculate true engineering margin.* Also see *Capability* and *True engineering margin*.

*Generic failure rate data*. Component data generally taken from a broad spectrum of components whose service parameters (e.g., application, service condition, duty cycle) are diverse.

*Grouping*. The process of equipment classification by key parameters with which component performance is likely to correlate. Also, the subsets of components resulting from this process. For example, pumps of the same model, size, manufacturer, and system might be considered an appropriate grouping for the purpose of a particular type of inservice test (IST).

*High potential test*. A motor stator pass/fail test involving the application of high voltage to the motor windings for (typically) 1 minute. The test voltage is determined by the rated voltage of the motor and whether the motor is new or reconditioned. This test is designed to detect the presence of insulation degradation/imperfections. (*Source*: IEEE Std. 432-1992.)

*Inductive imbalance test*. A motor stator diagnostic test designed to detect inductive imbalance in the windings The inductance between each of the three phases of the motor winding is measured and compared. Excessive imbalance between the measurements, or a growing trend in imbalance, can indicate a problem in the stator.

*Infant failure*. A failure occurring in a new component or just after refurbishment, overhaul, or maintenance.

*Inservice test*. A test to determine the operational readiness of a component system. (*Source*: ASME OM Code-1997.)

*Insignificant (moderate) failure*. A less serious failure than a significant failure; these failures usually involve discernable levels of component degradation without effect on operability and where near-term operation is not expected to be in jeopardy. Moderate internal valve leakage is an example of this type of failure.

*Lead time to failure period*. The period of time between the point when there is an identifiable condition that indicates a functional failure is either about to occur or is in the process of occurring and the functional failure occurrence. (*Source*: Moubray.)

*Mean time between failure (MTBF)*. Arithmetic average of operating times between failures of an item. (*Source*: IEEE Std. 100-1996.)

*Megger test*. A motor stator diagnostic test designed to assess the condition of the insulation by measuring the megohm resistance between the windings and ground. This test is valuable for detecting moisture intrusion or contamination in winding insulation. (*Source*: IEEE Std. 43-1974.)

*Motor current signature analysis (MCSA)*. A diagnostic technique whereby electrical signals are used to gather information related to the condition and performance of the motor and driven equipment (e.g., motor operator and valve). Also see *electrical signature analysis*.

*Normalizing*. A process of accounting for population effects in the calculation of relative failure rates.

*Nuclear Plant Reliability Data System (NPRDS) component age*. (NPRDS calculated value.) Either the current age in hours, months, or years a component has been in service at a specific location in the plant or the age of a component that has been taken out of service at a specific location in the plant from the time it was placed in service. The component age is the time between the component's in-service date and either the calculation date or the component's out-of-service date, whichever is earlier. This value may not portray the actual age of the component. Prior to March 1994, assignment of an out-of-service date was optional for component replacements having the same manufacturer and model number. An out-of-service date is not required for major repair or refurbishment of a component if identical parts are used as replacements (no design change). (*Source*: INPO-89-001, Rev. 5.) See *Operating age*.

*NPRDS component engineering record*. Physical data about a component, including, but not limited to, size, manufacturer, material, pressure rating, system in which it is installed, and in-service date.

*NPRDS failure record*. Information on individual component failures, including, but not limited to, failure narratives, failure discovery date, failure cause code, and failure mode code.

*NPRDS in-service date*. The actual date the component started operational service. (*Source*: INPO-89-001, Rev. 5.)

*NPRDS out-of-service date*. The date when the component was removed from service at a particular position in the unit or when a significant design change was made to the component. (*Source*: INPO-89-001, Rev. 5.)

*NPRDS time-in-service at failure discovery*. (NPRDS calculated value.) The number of hours, months, or years a component has been in service at a specific location in the plant when it is discovered unable to perform its intended function. This value may not accurately indicate time-related degradation of a component due to replacement of piece parts that did not warrant placing the component out-of-service and submitting a new component engineering record. (*Source*: INPO-89-001, Rev. 5.)

*OMN-1 margin*. The comparison of torque switch trip measurement with other predetermined constants as outlined in ASME Code Case OMN-1.

*Operating age*. Usually the time between initial component installation and some specified point in time. Actual operating age is difficult to determine and may be affected by maintenance activities, partial refurbishment, subcomponent replacement, and other factors.

*Operator torque at design-basis motor torque*. The estimated torque that is available from the motor operator based on the motor and gear train capabilities at the design-basis torque. OMN-1 specifies that this calculation consider several factors, including rated motor start torque, minimum voltage conditions, elevated ambient temperature conditions, operator efficiency, and other appropriate factors. (*Source*: ASME Code Case OMN-1.)

*Performance test*. A test designed to verify that equipment operations are "within specification" and/or within acceptable limits; i.e., to verify that a functional failure has not occurred. ISTs and margin tests are examples of performance tests.

*Polarization index*. A motor stator test to assess potential insulation flaws that uses a high voltage dc source to determine leakage current between windings. The measured insulation resistance of a winding will normally increase as the test voltage is applied. The measurement taken at 10 minutes should typically be at least twice the measurement taken at 1 minute. (*Source*: IEEE Std. 43-1974.)

*Predictive activity*. An activity designed to assess whether – and possibly when – a component is likely to fail, based on factors such as current condition, a comparison of test results, trending analysis, etc.

*Preventive activity*. An activity designed to preclude an event or failure from occurring. Examples include scheduled, periodic maintenance and scheduled component replacement.

*Proactive activity*. An activity, such as preventive maintenance, undertaken to prevent or anticipate failure.

*Probability density function*. A function of a continuous random variable, the integral of which, over a given interval, gives the probability that the value of the variable will fall within the interval.

*Probability distribution function*. A function of a discrete random variable yielding the probability that the variable will have a given value.

*Pump-years*. The number of pumps in service (population) multiplied by the cumulative number of service years.

*Random failure.* Any failure whose cause or mechanism, or both, makes its time of occurrence unpredictable. (*Source*: IEEE Std. 100-1996.)

*Random variable.* A variable that takes on numerical values in accordance with some probability distribution. Random variables may be either continuous (taking on real numbers) or discrete (usually taking on nonnegative integer values).

*Raw data.* Data taken directly from databases such as NPRDS and Equipment Performance & Information Exchange (EPIX) that has not been reviewed, filtered, characterized, and/or coded by an independent analyst.

*Relative failure rate.* Indicates how the failure rate of components in a subgroup compares with the failure rate of other subgroups. A relative failure rate of 1 indicates that the particular subgroup's failure rate is equal to the failure rate of the population as a whole.

*Relative margin.* The ratio of the margin at a given age to the initial margin.

*Reliability.* The ability of an item to perform a required function under prescribed conditions. Reliability can be expressed in terms of average time or average number of operational cycles between failures. Also see *Mean time between failures (MTBF)*.

*Required torque.* Motor operator output torque (stem nut torque or "stem torque") needed to operate an MOV under design-basis conditions. (*Source:* ASME Code Case OMN-1.)

*Requirement.* The minimum acceptable level of performance for a component.

*Risk.* A measure of the potential adverse consequence of a failure that considers both reliability and the potential result of a failure (e.g., in monetary terms). It may be quantitatively expressed as the product of failure rate and the potential cost of the consequence.

*Risk-informed.* Insight derived from probabilistic risk assessment combined with traditional engineering analysis to focus attention or resources on issues commensurate with their importance to safety.

*Selective waveform inspection method (SWIM).* A diagnostic technique that utilizes selective filtering of demodulated motor current signals to obtain a unique time waveform that reflects the amplitude modulations of a specific periodic load component such as a worm gear tooth meshing frequency.

*Signature analysis.* Diagnostic analysis of a time waveform, a frequency spectrum, or other meaningful data display containing much more information about the condition of a device than does a single measured variable.

*Significant failure.* A serious failure generally involving a complete loss of a component function, severe degradation of a component function, or a situation where near-term operation is jeopardized. A stuck closed valve is an example of this type of failure.

*Stem factor.* The conversion factor between stem torque and stem thrust. Stem torque = (stem thrust) x (stem factor). (*Source*: ASME Code Case OMN-1.)

*Thermography.* A graphical display or image whose color intensity is proportional to temperature.

*Time in service.* The time interval from initial operation to some specified point in time. (*Source*: EPRI BR-101747.)

*Timed response analysis.* A diagnostic technique that determines the time interval for certain mechanical operations to take place in equipment and trends the data as a means to detect degraded mechanisms/components.

*Time dependence.* See *Age related.*

*True component margin (true engineering margin).* The difference between the capability (the level of performance that a component is able to achieve) and the requirement (the minimum acceptable level of performance) without being limited by switches, governors, or other control devices.

*Unavailability.* An expression of that portion of time when a component is incapable of fulfilling a stated function to a specified level, usually expressed as a percentage.

*Wear-out failure.* Failure produced by a specific process that gradually changes characteristics, condition, or performance of a component with time or use.

# Appendix A
# SIGNATURE ANALYSIS

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# SIGNATURE ANALYSIS

The purpose of this appendix is to describe the benefits of analyzing component diagnostic signals via "signature analysis." In this context, a signature is a time waveform, a frequency spectrum, or another meaningful data display that contains much more than a single measurable value. Signature analysis techniques are applicable to a wide variety of signals from many sources. In this appendix, several motor-operated valve (MOV) signatures are provided as examples. The same signature analysis techniques can be applied to pump diagnostics as well as to other components.

## A.1 Background

As discussed within the body of this report, the measurement of MOV actuator torque or valve stem thrust at the torque switch trip point can be used as a measure of MOV performance. While this single measurement can indicate whether the MOV is capable of meeting functional requirements, a torque or thrust "signature" acquired over the entire valve stroke can be instrumental in identifying degraded MOV performance *at any point* during its operation. This can be particularly important if the degradation might prevent the MOV from completing its stroke and thus failing to perform its function.

MOV signature analysis techniques were investigated by Oak Ridge National Laboratory (ORNL) during 1985–1989 as part of a comprehensive assessment of MOV monitoring methods, performed in support of the Nuclear Regulatory Commission's (NRC's) Nuclear Plant Aging Research (NPAR) Program.[1] The NPAR Program was established by the Office of Nuclear Regulatory Research in 1985 primarily as a means to resolve technical safety issues related to the aging of electrical and mechanical components, systems, and structures in commercial nuclear power plants. A primary objective of the NPAR program was to identify and recommend methods of inspection, surveillance, and monitoring that would provide timely detection of service wear (aging) affecting important components and systems so that maintenance could be performed prior to loss of safety function(s).

## A.2 MOV Fundamentals

Because the MOV signatures require a basic understanding of how a motor operator actuates a valve, the following tutorial is provided. Figure A.1 provides a cutaway view of a typical motor-operated gate valve for reference purposes. During motor operation, an electric motor with a helical pinion mounted on its shaft drives the worm shaft clutch gear, which turns freely on the worm shaft. The worm shaft clutch gear in turn drives the worm shaft clutch via lug-to-lug contact. The worm shaft clutch is splined to the worm shaft; thus, as the worm shaft clutch rotates, so does the worm shaft.

A worm, also splined to the worm shaft, rotates with the worm shaft and in turn rotates the worm gear. The worm gear is equipped with two lugs that can contact two similar lugs present on the drive sleeve. The lugs are spaced so that when the rotation of the motor is reversed, there is free rotational motion of the worm gear before the lugs reengage and initiate drive sleeve rotation in the opposite direction. This reengagement results in a "hammerblow" effect within the operator. The primary purpose of the hammerblow is to allow the motor time to acquire full speed before being significantly loaded.

The stem nut is splined to fit inside and rotate with the drive sleeve. The stem nut is threaded internally to fit the thread of a rising valve stem (e.g., gate and globe valves) or is simply bored and keyed to fit a nonrising valve stem (e.g., butterfly valve). It is held in place within the drive sleeve with a locking ring to permit only rotational movement.

The torque transferred by the worm to the worm gear results in a net reaction force that pushes the worm axially along the worm shaft splines and compresses the spring pack, which is composed of a series of Belleville washers. The distance the worm moves axially is proportional to the worm gear forces encountered and the spring constant of the spring pack. The Belleville washers contained in the spring pack are initially compressed (preloaded) by the stop nut on the end of the spring pack assembly. Axial motion of the worm can only occur when axial worm loads exceed the spring pack preload. The axial movement of the worm is transferred to rotation of the torque switch by means of a rack-and-pinion or a cam-follower arrangement. When a preset angular position of the torque switch is reached, the mechanical motion opens electrical contacts, normally removing electric power from the motor.

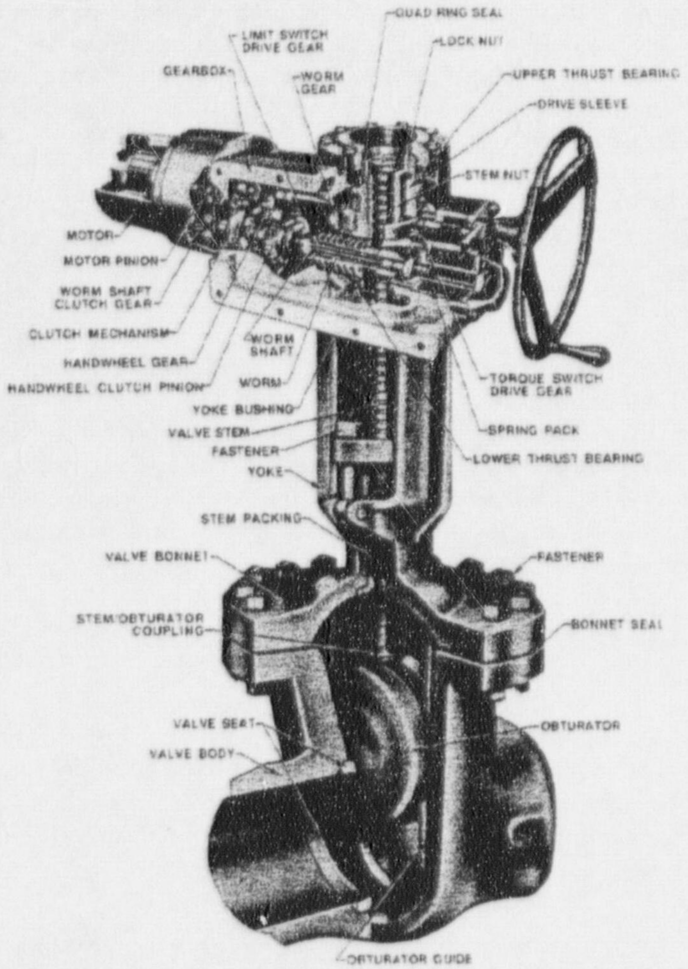


**Figure A.1 Cutaway view of a typical MOV**

The limit switch is geared directly to the worm shaft. It is designed to "count" rotations of the worm shaft and actuate up to four rotors during a valve stroke, with each rotor containing four pairs of electrical contacts. Depending on the wiring configuration determined by the user, the action of limit switch contact openings or closings can turn on or off control room position indicator lamps, provide a torque switch bypass function in the opening stroke, or stop motor operation or other functions. Generally, the torque switch is wired to stop the motor in the closed valve position, and the limit switch is wired to stop the motor in the open valve position. The closed torque switch is generally bypassed during the beginning of the opening valve stroke to prevent an interruption of motor power if there is enough torque switch rotation during operator hammerblow and/or valve unseating to open the torque switch contacts.

During a valve stroke, the motor operator can encounter a variety of forces that oppose valve stem movement. These forces can include stem packing friction, valve seating and unseating, obturator (e.g., gate) differential pressure loading, and unexpected obstructions, which result in variations in motor operator output torque requirements during a valve stroke. These forces and the resulting reactions within the actuator affect the running load "signatures" in a way that can often be easily interpreted.

## A.3 MOV Signature Examples

ORNL evaluations of MOV monitoring methods in support of the NPAR program led to the conclusion that the single most informative MOV measurable parameter was also the one that was most easily acquired, namely, the motor current. Motor current signature analysis (MCSA) was found to provide detailed information related to the condition of the motor, motor operator, and valve across a wide range of levels. MCSA is based on the recognition that the current supplied to a conventional electric motor (ac or dc) driving a mechanical load will change in magnitude as the motor responds to variations in the mechanical loads it drives. The motor thus acts as an efficient and permanently available transducer, detecting both large and small time-dependent motor load variations generated anywhere within the mechanical load and converting them into electric-current noise signals that flow along the power cable.

As illustrated in Fig. A.2, MOV motor current signals can be obtained remotely (e.g., at a motor control center that may be several hundred feet from the equipment to be monitored). By using a clamp-on current probe to acquire raw motor current signals, no electrical connections need to be made or broken; thus, equipment operation is not interrupted, and shock hazard is minimal.

As part of the evaluation of motor current monitoring techniques, signal conditioning electronics were used to transform the raw current signal provided by the clamp-on current probe into two diagnostic signals: one optimized for time-domain analysis and the other optimized for frequency-domain analysis. The basic objective of signal conditioning is to maximize the useful dynamic range in the subsequent data analysis process. This is accomplished in part by demodulation of the raw current signal followed by selective filtration and amplification. The processed signals are then displayed in a variety of formats to reveal MOV condition indicators (within both time and frequency domains) that can be trended over time.

### A.3.1 Time Waveform Analysis

Figure A.3 presents a motor current time waveform acquired during an opening stroke of an 18-in. motor-operated gate valve. This signature includes features that reflect normal gate valve operations such as the relatively large motor inrush current generated during motor starting and the motor current peak associated with valve unseating. This signature is particularly useful in determining the valve stroke time and the average running current.

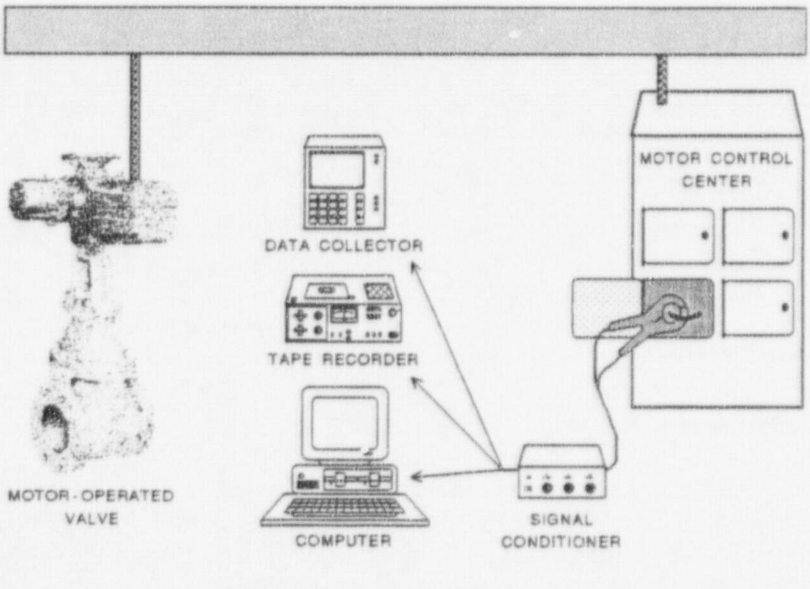


**Figure A.2 MOV motor current monitoring at a remote location**

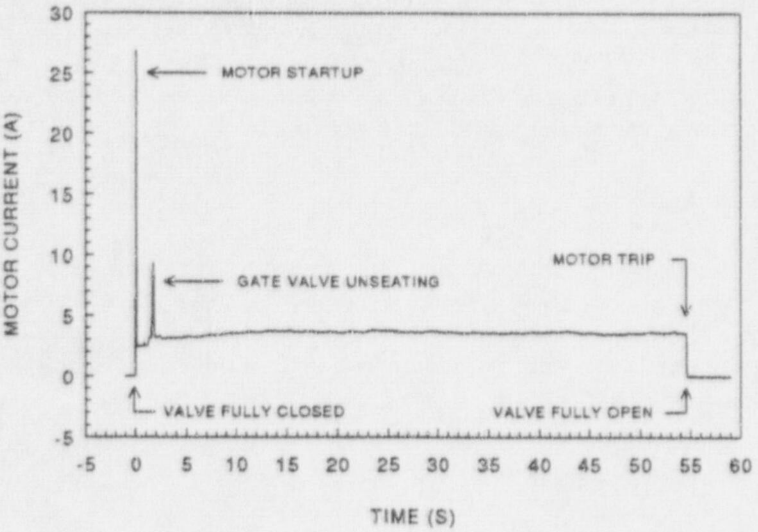


**Figure A.3 Motor current time waveform from the opening stroke of an 18-in. motor-operated gate valve**

Figure A.4 shows the initial 3.5 s of the motor current time waveform shown in Fig. A.3, but it is plotted with an expanded amplitude scale to better illustrate the signature details that are generally seen during the beginning of an opening stroke. In addition to the large valve unseating peak, several other events are observed before unseating, including the motor operator hammerblow and the indication of initial valve stem movement. The increase in motor running current observed when the valve stem begins to move reflects the increase in motor running torque required to overcome the friction between the valve stem and the stem packing.

Any observed changes in magnitude of any of these motor current signature characteristics would indicate that running loads had changed in a manner that might be indicative of a problem worth further investigation. The specific MOV problem area (e.g., actuator drive sleeve, valve stem packing, valve gate/seat interface) would be clearly identified from the location in the signature where the change takes place.

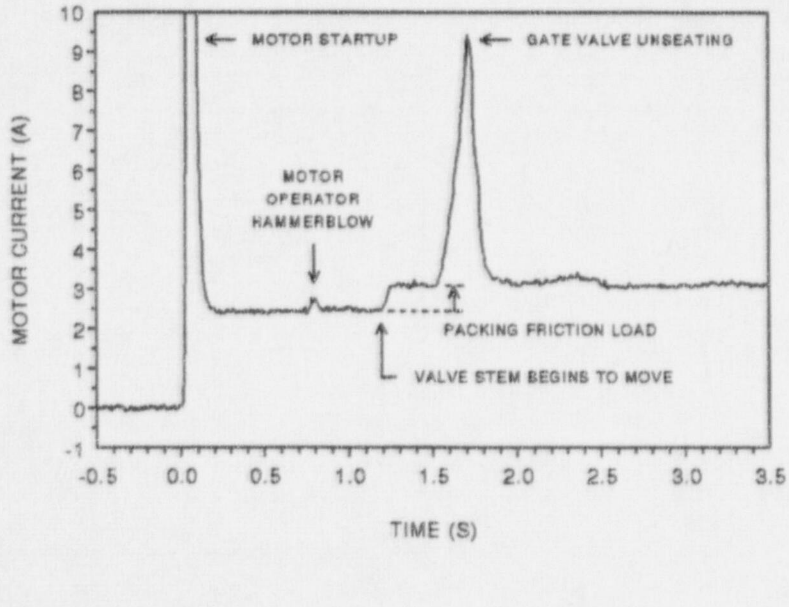


**Figure A.4 Initial 3.5 s of an MOV motor current time waveform showing the detection of several transient loads in the motor operator and valve**

In addition to magnitude changes, the times of occurrences of these features provide useful condition indicators that can be trended over time. For example, the time differential between the hammerblow and initial stem movement generally reflects the clearance between the stem nut and stem thread surfaces. Likewise, the time between initial stem movement and gate unseating reflects the clearance between the gate and stem coupling surfaces. Thus, an increase in either (or both) of these time measurements can provide an early indication of wear in these regions.

### A.3.2 Frequency Spectrum Analysis

If properly preconditioned (e.g., demodulated, filtered, and amplified), motor current signals can be effectively examined for frequency content using standard spectrum analysis equipment. Figure A.5 illustrates a motor current frequency spectrum for the same 18-in. MOV described in the previous examples. Included in the frequency spectrum are two peaks that provide direct motor speed indication: a frequency component at the true motor shaft speed and a peak referred to as the "slip-poles" frequency (SPF). The relationship between the SPF and the motor speed is

$$SPF = NP\,(SS - MS)\ , \tag{A.1}$$

where SS is the synchronous speed for the motor, and MS is the actual motor speed, all in Hertz, and NP is the number of motor poles. Recognizing that the motor's synchronous speed is equal to twice the power line frequency divided by the number of motor poles, Eq. (A.1) may be rewritten as follows:

$$SPF = 2(LF) - NP(MS)\ , \tag{A.2}$$

where LF is power line frequency (e.g., 60 Hz or 50 Hz). Because the number of motor poles is typically two to six, the SPF is a sensitive means of detecting otherwise subtle changes in motor speed that may provide indications of running load changes within the valve or operator.

A more detailed characterization of running loads is accomplished by an examination of the remaining spectral peaks. A major frequency component in this and other MOV motor current spectra is the worm gear tooth meshing (WGTM) frequency. The existence of this peak indicates that a significant motor load component is associated with the meshing of the worm and worm gear. In addition to the fundamental WGTM frequency, its second harmonic was also observed along with worm gear rotational sidebands, which indicate further MOV condition related to the worm gear drive.

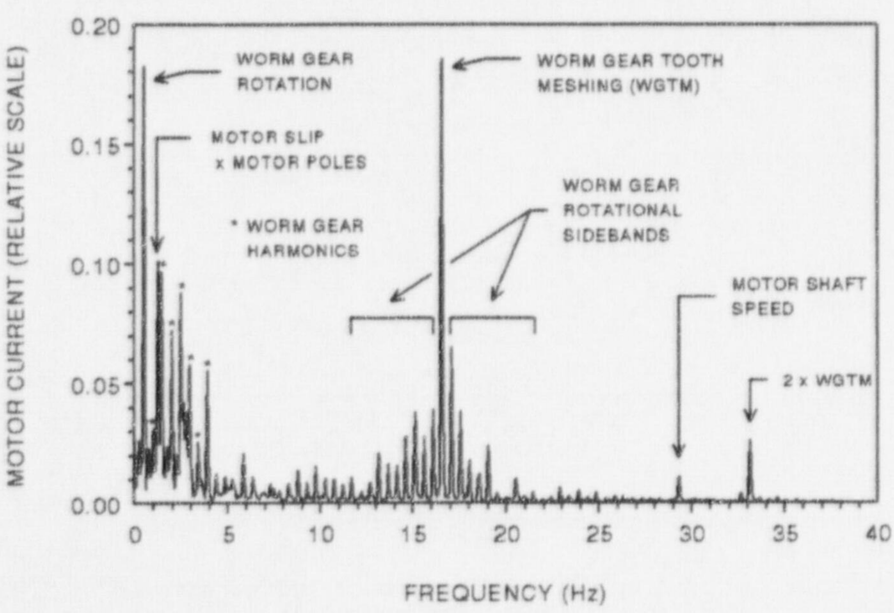


**Figure A.5 Demodulated motor current spectrum from an 18-in. MOV**

### A.3.3 SWIM Analysis and Other Techniques

As previously discussed, the MCSA method offers high sensitivity and selectivity for monitoring MOV operational characteristics. These benefits are further exemplified through the use of the selective waveform inspection method (SWIM). By selectively filtering the demodulated motor current signal, a unique time waveform is obtained that reflects the amplitude modulations of a specific periodic load component. Thus, if the WGTM frequency component is "singled out" using this technique, a tooth-by-tooth gear meshing profile can be produced, as shown by Fig. A.6. As shown in this figure, the signature exhibits a basic repetitive pattern consisting of a fixed number of peaks equal to the number of teeth on the worm gear (34 for the tested MOV). Reproducibility of this pattern throughout a valve stroke is generally observed. Some slight modifications may be seen during a valve stroke as a result of the worm sliding axially along the worm shaft in response to changing running loads, which results in slight variations in the worm and worm gear meshing surfaces.

Other MCSA techniques have been identified for MOVs such as estimating motor voltage (at the MOV) from motor current amplitude and frequency information acquired at the motor control center, determining motor operator gear ratios from motor current spectra, and estimating valve stem travel from motor current time and frequency signatures. Further information on these and other techniques may be found in ref. 1.

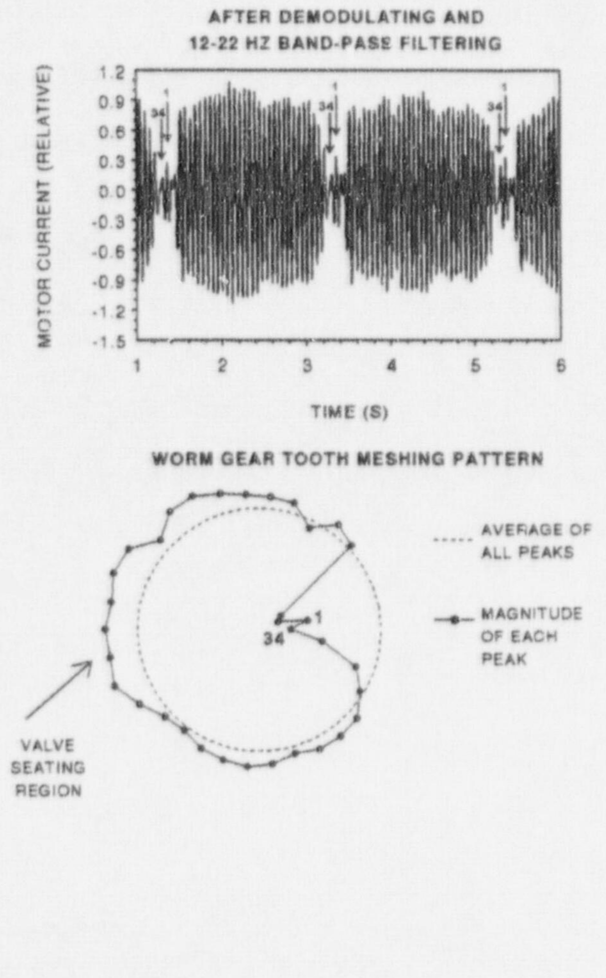


**Figure A.6 Application of SWIM to the demodulated motor current signal from an MOV with 34-tooth worm gear**

### A.3.4 Summary of MCSA Capabilities

MCSA has a number of inherent strengths. The most notable being that it

- provides nonintrusive monitoring capability at a location remote from the equipment;
- provides diagnostic information comparable to conventional instrumentation but without the attendant disadvantages of added sensors and signal cables;
- offers high sensitivity to a variety of mechanical disorders;
- offers means for separating one form of disorder from another (via signature analysis techniques);
- can be performed rapidly and as frequently as desired using portable, inexpensive equipment; and
- is applicable to high-powered and low-powered machines, driven by either ac or dc motors.

While motor current analysis cannot presently provide a direct measurement of MOV stem thrust, numerous performance indicators are extractable from MOV motor current time- and frequency-domain signatures that may be quantified, documented, and trended over time. These include

- mechanical and frictional loads such as gear train friction, packing friction, and gate/guide friction;
- initiation time, duration, and magnitude of transients including motor starting and stopping, hammerblow, valve seating, unseating, backseating, and any unusual transient events;
- WGTM waveforms on a tooth-by-tooth basis using the selective waveform inspection method; and
- periodic load variations within the MOV drivetrain such as WGTM, stem nut and worm gear rotation, motor shaft speed, and motor slip.

## A.4 Signatures from MOVs with Degradations and Implanted Defects

ORNL carried out several tests to investigate the capabilities of monitoring methods (especially MCSA) for detecting, differentiating, and tracking the progress of the following MOV abnormalities:

- degraded valve stem lubrication
- obstructions in valve seat area
- disengagement of motor pinion gear
- stem packing degradation or tightness changes
- incorrect torque and limit switch settings
- abnormal line voltage
- worm gear tooth wear
- stem nut thread wear
- valve stem taper
- degraded gearcase lubrication

Two of these, degraded stem lubrication and degraded gearcase lubrication, are described briefly below. Reference 1 discusses all abnormalities listed above and describes their effects on MOV performance and on a variety of diagnostic measurements.

## A.4.1 Degraded Valve Stem Lubrication

As discussed in the body of this report, an MOV torque switch inherently responds more directly to changes in operator output torque than to changes in stem thrust. The relationship between stem nut torque and valve stem thrust can be strongly influenced by frictional losses, which depend largely on the state of lubrication between the stem nut and stem and on the smoothness of the mating surfaces.

Figure A.7 presents the results of an experiment performed on an MOV in 1985. After initially greasing the valve stem, a baseline relationship was established between torque switch angular position (obtained with an angular displacement transducer mounted on the torque switch shaft) and stem thrust (obtained with a stem-mounted strain gage). Subsequently, 165 cycles were carried out without maintaining proper stem lubrication. After the 165 cycles, the delivered stem thrust was observed to have been reduced by 17% (6900 lb) at a torque switch setting of 1.5 as a result of stem lubrication (degradation). Regreasing the valve stem returned the stem thrust levels to about those attained during the baseline tests.

Figure A.7 also shows that during the initial 50 valve cycles, the stem thrust delivered per unit of torque switch rotation decreased at a rate of about 0.3% per cycle. This was followed by a leveling off in the thrust/torque relationship during the remaining 115 cycles.

## A.4.2 Degraded Gearcase Condition

The gearcase of an MOV is normally packed with grease to provide sufficient lubrication to reduce friction and wear of drivetrain elements, including the worm and worm gear. One test, carried out by ORNL at a utility training facility, demonstrated the adverse effect of insufficient gearcase lubrication on MOV operations. This MOV was normally used by the utility for training purposes only and was frequently assembled and disassembled; thus, only a light coating of lubricant was used on the internal drivetrain components rather than packing the entire gearcase with grease.

Motor current signatures were obtained during valve actuations with insufficient lubrication under two conditions of load: the as-found condition when the valve packing was loose and after the packing was tightened. The results (Fig. A.8) yielded a normal signature for the loose packing but a high motor load condition when the packing was tightened moderately. Because the high loads occurred in the drivetrain at a location between the motor and the torque switch, the normal torque switch cutout of the motor did not occur and the motor stalled. When the worm and worm gear were subsequently lubricated, actuations with both loose and tight packing, also shown in Fig. A.8, yielded normal motor current signatures.

While this extreme lubrication deficiency would be unexpected in an MOV installed in a nuclear power plant system, it should be pointed out that other gearcase degradations (e.g., gear mesh binding, shaft bearing problems, etc.) would likely impact MOV operation in a similar manner.

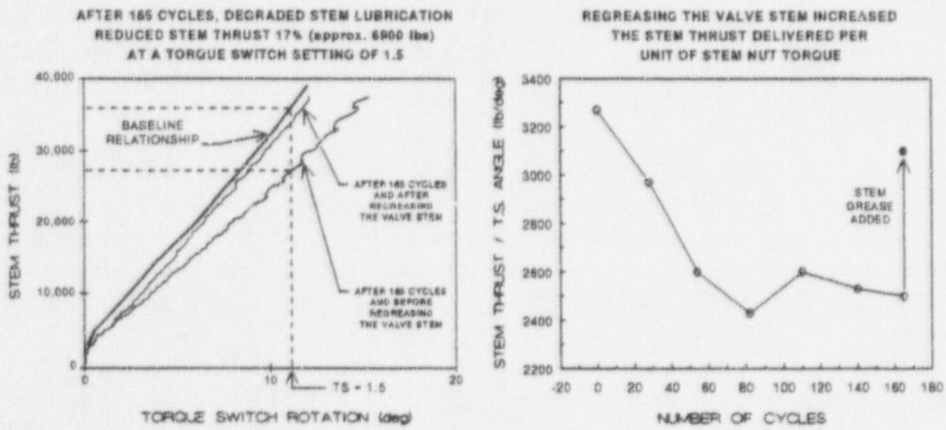


**Figure A.7 Impact of valve stem lubrication on stem thrust**

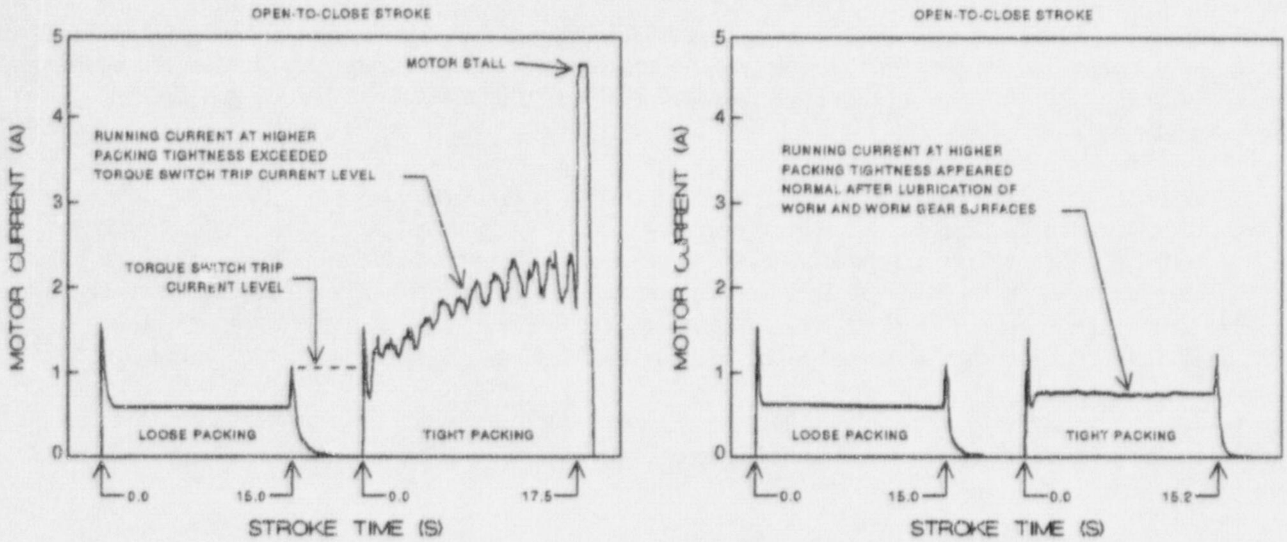


**Figure A.8 Motor current time waveforms for an MOV with insufficient gearcase lubrication (left) and after relubrication (right).** The effect of the degraded gearcase condition is evident under high running loads, created by the tight packing.

## A.4.3 Impact of Inactivity

In support of the NPAR program, signature analysis tests were performed by ORNL on a total of 20 MOVs at a nuclear power plant. In all tests, MOV motor current signals were acquired at the motor control center with a clamp-on current transformer, demodulated and further processed by battery-powered signal conditioning electronics, and recorded on a portable tape recorder for off-site analyses. Selected results from those tests are described in Ref. 1 and illustrate differences in motor current signatures from similar MOVs that reflect switch setting variations and differences in component wear. In addition, several nuclear plant MOVs exhibited notable motor-running current level changes between their first and second actuations following a period of inactivity. These changes were clearly seen by comparing time waveforms from the first two strokes in the same direction.

Figure A.9 illustrates the first two opening strokes for one of the MOVs tested. An analysis of the first stroke time waveform showed that the no-load current level was 4.72 A and was followed by an initial running current level after unseating of 5.13 A. The no-load current level reflects the motor torque needed to turn the operator's internal gearing and does not include other loads (e.g., those associated with stem travel).

The second opening stroke, when compared with the first, showed about a 5% reduction (4.72 to 4.48 A) in no-load current and about a 10% reduction (5.13 to 4.64 A) in the initial running current level after valve unseating occurred. The reduction in the no-load current level indicated that less motor torque was required to turn the MOV gear train during the second opening stroke, which suggests that the gear train was operating with less internal friction. This likely was a result of improved gear and bearing lubrication within the operator, as would be expected for most lubricated mechanical devices during their initial operation after a period of inactivity.

In addition to the reduction in running current levels between the first and second actuations, comparisons in motor current frequency spectra showed reductions in the WGTM peak amplitude and an increase in motor shaft speed, all of which provide supportive corroborative evidence of a smoother operating gear train after the initial cycle. It is not known how long this MOV or other tested MOVs were inactive before the tests.

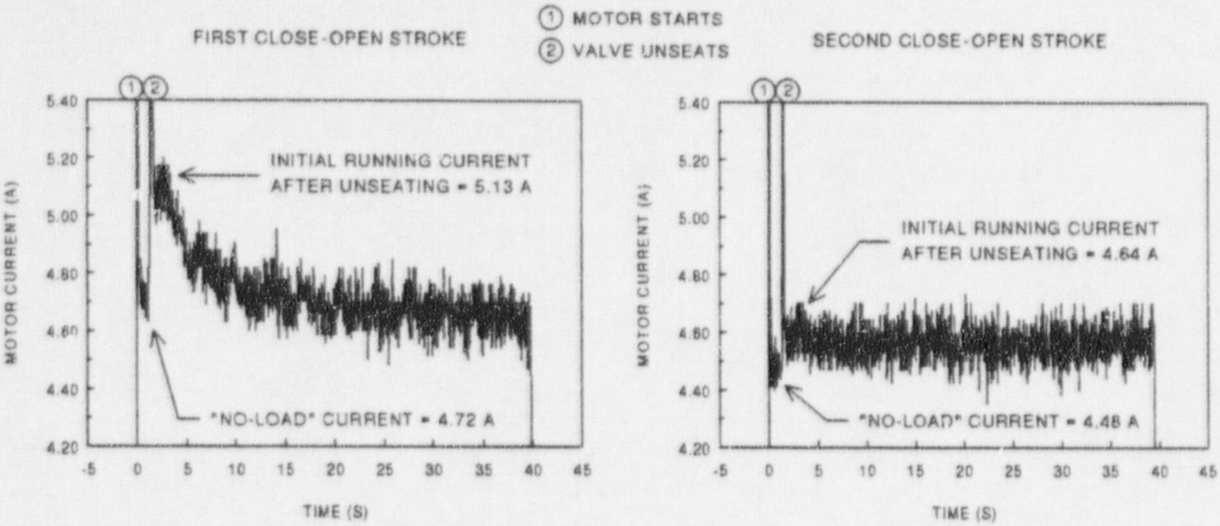


**Figure A.9 Impact of inactivity on MOV motor current signatures.** Increased motor- running current levels during the first stroke indicate increased internal friction within the operator.

## A.4.4 High-Flow (Blowdown) Conditions

ORNL participated in the NRC-sponsored Gate Valve Flow Interruption Blowdown tests carried out in Huntsville, Alabama, during April–June 1988. These tests were intended primarily to determine the behavior of motor-operated gate valves under the temperature, pressure, and flow conditions expected to be experienced by isolation valves in boiling-water reactors (BWRs) during a high-energy line break (blowdown) outside of containment. In addition, the tests provided an excellent opportunity to evaluate signature analysis methods for MOVs under these conditions. Detailed results from those tests are described in Ref. 1.

Motor current and torque switch angular position signatures were acquired on the two MOVs at various times throughout the test program. Signals acquired from the valve-mounted sensors were transmitted along a 250-ft cable to a remote site where they were conditioned and recorded.

Figure A.10 illustrates the effect of a system blowdown on the closure of one of the MOVs as seen via motor current and torque switch position signatures. For comparison, signatures are also shown which were obtained during an closing stroke carried out before the blowdown at similar valve internal fluid pressure conditions but with no flow. Examination of these signatures indicated that the flow-induced valve running loads were so significant that they nearly tripped the MOV torque switch before to valve seating.

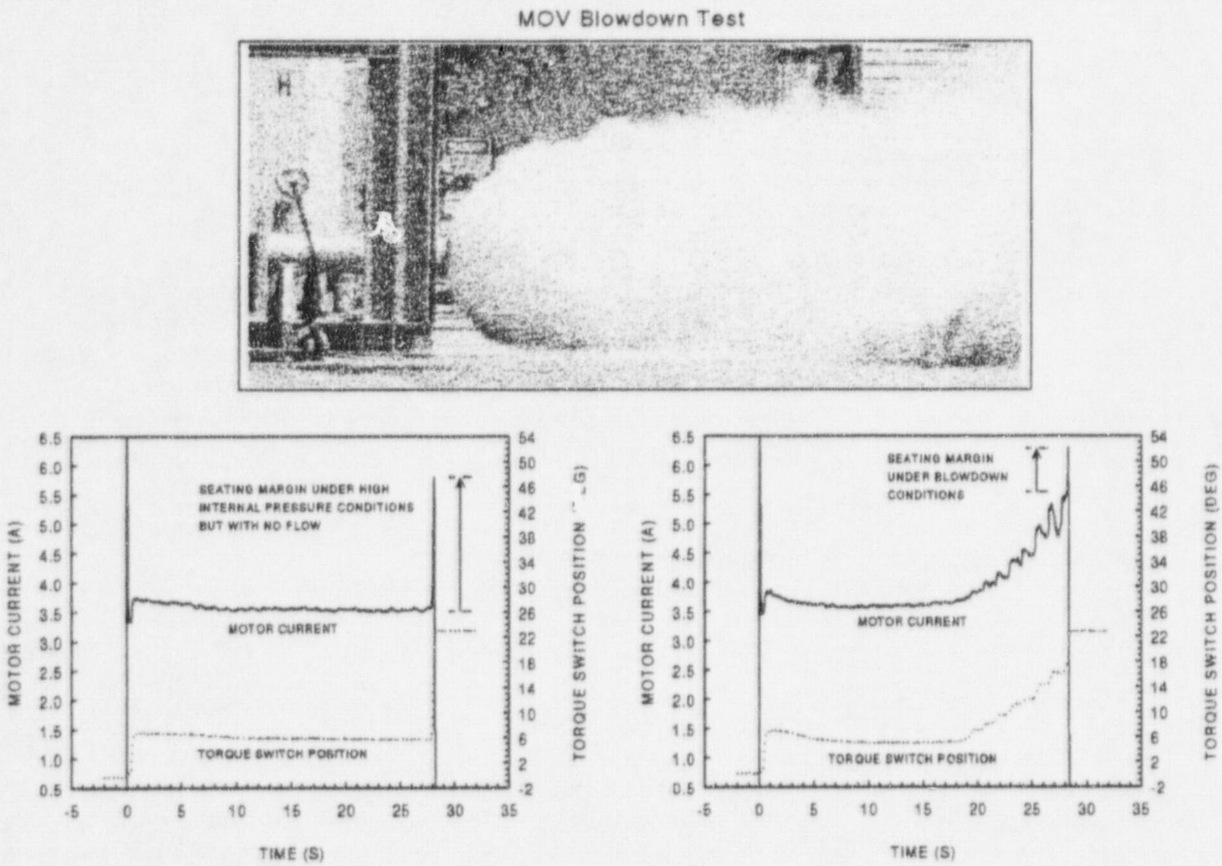


**Figure A.10 Impact of high flow-induced loads on MOV motor current and torque switch angular position signatures**

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1. H. D. Haynes, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, "Aging and Service Wear of Electric Motor-Operated Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants - Vol. II, Aging Assessments and Monitoring Method Evaluations," USNRC Report NUREG/CR-4234, (ORNL-6170), August 1989.[*]


[*]Available for purchase from National Technical Information Service, Springfield, Virginia 22161.

# Appendix B
# DERIVATION OF THE UNAVAILABILITY FORMULAS INCORPORATING AGING AND MARGIN TEST INTERVALS

# Appendix B
# DERIVATION OF THE UNAVAILABILITY FORMULAS INCORPORATING AGING AND MARGIN TEST INTERVALS

We first derive the equation for follow-up renewal after the test and then for no follow-up renewal after the test (i.e., for the margin test as an assurance check only). For renewal after the test, the average failure probability F(L/2) at the midpoint of the test interval is

$$F(L/2) = 1 - \Phi\left(\frac{\mu_0 - \alpha_m L/2}{\sigma_0}\right). \tag{B.1}$$

For the margin test as only an assurance test, the probability $F_\ell(t)$ of margin failure in time interval $\ell$ from the last test, given the age of the component t, is given by

$$F_\ell(t) = 1 - \frac{\overline{F}(\ell + t)}{\overline{F}(\ell)} 2\,, \tag{B.2}$$

where $\overline{F}(\ell + t)$ and $\overline{F}(\ell)$ are the complementary cumulative distribution functions evaluated at $\ell + t$ and $\ell$, respectively. The above relation is a standard reliability definition of $F_\ell(t)$. Evaluating $F_\ell(t)$ at the midpoints of the intervals ($\ell = L/2$, and $t = S/2$) to give the unavailability Q and using the lognormal distribution gives

$$Q = 1 - \frac{\overline{\Phi}\left(\dfrac{\alpha_m(S/2 + L/2) - \mu_0}{\sigma_0}\right)}{\overline{\Phi}\left(\dfrac{\alpha_m S/2 - \mu_0}{\sigma_0}\right)}\,, \tag{B.3}$$

$$= 1 - \frac{\Phi\left(\dfrac{\mu_0 - \alpha_m(S/2 + L/2)}{\sigma_0}\right)}{\Phi\left(\dfrac{\mu_0 - \alpha_m S/2}{\sigma_0}\right)}\,, \tag{B.4}$$

$$= \frac{\Phi\left(\dfrac{(\mu_0 - \alpha_m S/2)}{\sigma_0}\right) - \Phi\left(\dfrac{\mu_0 - \alpha_m(S/2 + L/2)}{\sigma_0}\right)}{\Phi\left(\dfrac{\mu_0 - \alpha_m S/2}{\sigma_0}\right)}. \tag{B.5}$$

Now Eq. (B.5) does not include the initial probability of margin failure at age t = 0 because the equation is conditioned on the failure being greater than $\ell$, which is evaluated at $\ell = S/2$. The initial probability of failure $p_0$ is

$$p_0 = P(C_0 < R_0) \tag{B.6}$$

$$= 1 - \Phi\left(\frac{\mu_0}{\sigma_0}\right). \tag{B.7}$$

Incorporating the initial probability of failure, the average margin unavailability Q (without the downtime contribution) finally becomes

$$Q = p_0 + (1 - p_0)\left[\frac{\Phi\left(\frac{\mu_0 - \alpha_m S/2}{\sigma_0}\right) - \Phi\left(\frac{\mu_0 - \alpha_m (S/2 + L/2)}{\sigma_0}\right)}{\Phi\left(\frac{\mu_0 - \alpha_m S/2}{\sigma_0}\right)}\right]. \tag{B.8}$$

# Appendix C
# DERIVATION OF THE UNAVAILABILITY WHEN THE TEST IS FOLLOWED BY RENEWAL

## Appendix C
## DERIVATION OF THE UNAVAILABILITY WHEN THE TEST IS FOLLOWED BY RENEWAL

When the test has follow-up renewal, then the unavailability at a given age t from the last test is for any age-dependent failure rate $\lambda(t)$:

$$Q(t) = 1 - \exp\left( - \int_0^t \lambda(t')dt' \right) . \qquad (C.1)$$

Inserting the exponential formula for the failure rate,

$$\lambda(t) = \lambda_0 e^{\alpha t} , \qquad (C.2)$$

Eq. (C.1) becomes

$$Q(t) = 1 - \exp\left( - \int_0^t \lambda_0 e^{\alpha t'} dt' \right) , \qquad (C.3)$$

or

$$Q(t) = 1 - \exp\left( - \frac{\lambda_0}{\alpha} \left( e^{\alpha t} - 1 \right) \right) . \qquad (C.4)$$

Taking the average unavailability Q to be the value of Q(t) at the midpoint L/2 of the test interval gives

$$Q = 1 - \exp\left[ - \frac{\lambda_0}{\alpha} \left( e^{\frac{\alpha L}{2}} - 1 \right) \right] . \qquad (C.5)$$

(C.6)

Adding the initial failure probability per demand term $p_0$ and the downtime contribution, d/(d+L), the total unavailability then becomes

$$Q = p_0 + 1 - \exp\left[ - p_0 \left( e^{\frac{\alpha L}{2}} - 1 \right) \right] + \frac{d}{d + L} ,$$

where (C.7)

$$p_0 = \frac{\lambda_0}{\alpha} .$$

# Appendix D
# DERIVATION OF THE UNAVAILABILITY WHEN THE TEST HAS NO FOLLOW-UP RENEWAL

# Appendix D
# DERIVATION OF THE UNAVAILABILITY WHEN THE TEST HAS NO FOLLOW-UP RENEWAL

The general formula for the unavailability Q(t) at an age t from the last test conducted at age $\ell$ of the component is

$$Q(t) = 1 - \exp\left( - \int_{\ell}^{\ell+t} \lambda(t')dt' \right) . \tag{D.1}$$

The unavailability Q(t) as given by Eq. (D.1) is the contribution associated with the age-dependent failure rate $\lambda(t')$ and does not include the initial failure probability per demand $p_0$ and the downtime contribution, d/(d+L).

Inserting the exponential formula

$$\lambda(t) = \lambda_0 e^{\alpha t} , \tag{D.2}$$

Eq. (D.1) becomes (D.3)

$$Q(t) = 1 - \exp\left( - \int_{\ell}^{\ell+t} \lambda_0 e^{\alpha t'} dt' \right)$$

$$= 1 - \exp\left( - \frac{\lambda_0}{\alpha} \left( e^{\alpha(\ell+t)} - e^{\alpha\ell} \right) \right) . \tag{D.4}$$

For a given $\ell$, taking the average unavailability $Q(\ell)$ to be the value of Q(t) at the midpoint L/2 of the test interval, then $Q(\ell)$ is given by

$$Q(\ell) = 1 - \exp\left[ - \frac{\lambda_0}{\alpha} \left( e^{\alpha\left(\ell + \frac{L}{2}\right)} - e^{\alpha\ell} \right) \right] . \tag{D.5}$$

Finally, taking the average unavailability Q over the lifetime S of the component to be the value of $Q(\ell)$ at the midpoint S/2

$$Q = 1 - \exp\left( - \frac{\lambda_0}{\alpha} \left( e^{\alpha\left(\frac{S}{2} + \frac{L}{2}\right)} - e^{\alpha\frac{S}{2}} \right) \right) \tag{D.6}$$

$$= 1 - \exp\left( - \frac{\lambda_0}{\alpha} e^{\alpha\frac{S}{2}} \left( e^{\alpha\frac{L}{2}} - 1 \right) \right) \tag{D.7}$$

$$= 1 - \exp\left( - p_0 e^{\alpha\frac{S}{2}} \left( e^{\alpha\frac{L}{2}} - 1 \right) \right) , \tag{D.8}$$

where

$$p_0 = \frac{\lambda_0}{\alpha} . \tag{D.9}$$

Adding the initial failure probability per demand contribution $p_0$ and downtime contribution, d/(d+L),

$$Q = p_0 + 1 - \exp\left(-p_0 e^{\alpha\frac{S}{2}}\left(e^{\alpha\frac{L}{2}} - 1\right)\right) + \frac{d}{d+L} \; . \tag{D.10}$$

# Appendix E
# DERIVATION OF APPROXIMATE, FIRST-ORDER EXPRESSIONS FOR THE UNAVAILABILITY

# Appendix E
# DERIVATION OF APPROXIMATE, FIRST-ORDER EXPRESSIONS FOR THE UNAVAILABILITY

The equation for the unavailability Q for a test with follow-up renewal is given by

$$Q = p_0 + 1 - \exp\left(-p_0\left(e^{\alpha\frac{L}{2}} - 1\right)\right) + \frac{d}{d+L} \ . \tag{E.1}$$

Expanding the exponential in a first-order expansion, that is,

$$1 - \exp(-x) \cong x \ , \tag{E.2}$$

Eq. (E.1) becomes

$$Q \cong p_0 + p_0\left(e^{\alpha\frac{L}{2}} - 1\right) + \frac{d}{d+L} \ . \tag{E.3}$$

The unavailability Q for a test with no follow-up renewal is given by

$$Q = p_0 + 1 - \exp\left(-p_0 e^{\alpha\frac{S}{2}}\left(e^{\alpha\frac{L}{2}} - 1\right)\right) + \frac{d}{d+L} \ . \tag{E.4}$$

Expanding the exponential to its first-order approximation

$$Q = p_0 + p_0 e^{\alpha\frac{S}{2}}\left(e^{\alpha\frac{L}{2}} - 1\right) + \frac{d}{d+L} \tag{E.5}$$

$$= p_0\left(1 + e^{\alpha\frac{S}{2}}\left(e^{\alpha\frac{L}{2}} - 1\right)\right) + \frac{d}{d+L} \ . \tag{E.6}$$

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Recent industry reevaluation of component inservice testing (IST) requirements has resulted in requests for IST interval extension and changes to traditional IST programs. To evaluate these requests, long-term component performance and the methods for mitigating degradation need to be understood. Determining the appropriate IST intervals, along with component testing, monitoring, trending, and maintenance effects, has become necessary. This study provides guidelines to support the evaluation of IST intervals for pumps and motor-operated valves (MOVs). It presents specific engineering information pertinent to the performance and monitoring/testing of pumps and MOVs, provides an analytical methodology for assessing the bounding effects of aging on component margin behavior, and identifies basic elements of an overall program to help ensure component operability. guidance for assessing probabilistic methods and the risk importance of safety consequences of the performance of pumps and MOVs has not been specifically included within the scope of this report, but these elements may be included in licensee change requests.

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