NUREG/CR-6002
BNL-NUREG-52332

Risk-Based Maintenance Modeling

Prioritization of Maintenance Importances and Quantification of Maintenance Effectiveness

Manuscript Completed: January 1995
Date Published: September 1995

Prepared by
W. E. Vesely, J. T. Rezos

Science Applications International Corporation
Dublin, OH 43017

Under Contract to:
Brookhaven National Laboratory
Upton, NY 11937

Prepared for
Division of Systems Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001
NRC Job Code A3230

DISCLAIMER

ABSTRACT

This report describes methods for prioritizing the risk importances of maintenances using a Probabilistic Risk Assessment (PRA). Approaches then are described for quantifying their reliability and risk effects. Two different PRA importance measures, minimal cutset importances and risk reduction importances, were used to prioritize maintenances; our findings show that both give similar results if appropriate criteria are used. The justifications for the particular importance measures also are developed.

The methods developed to quantify the reliability and risk effects of maintenance actions are extensions of the usual reliability models now used in PRAs. These extended models consider degraded states of the component, and quantify the benefits of maintenance in correcting degradations and preventing failures. The negative effects of maintenance, including downtimes, also are included. These models are specific types of Markov models. The data for these models can be obtained from plant maintenance logs and from the Nuclear Plant Reliability Data System (NPRDS). To explore the potential usefulness of these models, we analyzed a range of postulated values of input data. These models were used to examine maintenance effects on a component's reliability and performance for various maintenance programs and component data. Maintenance schedules were analyzed to optimize the component's availability. In specific cases, the effects of maintenance were found to be large.

CONTENTS

CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

EXECUTIVE SUMMARY

The NRC published the final version of its Maintenance Rule in the Federal Register on July 10, 1991. The Maintenance Rule describes the need to monitor the effectiveness of maintenance. The supporting information discusses the importance of maintenance in assuring that key structures, systems, and components perform their intended functions. This report describes how a Probabilistic Risk Assessment (PRA) can be used to rank the components according to the importance of their maintenance to control core damage frequency and public risk. This report also describes how the component reliability models used in a PRA can be extended to quantify both the benefits of maintenance and its negative effects. The effectiveness of maintenance thereby can be increased to optimize component availability and plant performance.

The first chapter gives an overview of the report. The approaches to prioritizing maintenance which were developed are summarized, and an example result using a plant specific PRA is presented. The approaches which are developed to extend component reliability models in PRAs to include maintenance are also summarized in the first overview chapter. An example is given of the application of these extended reliability models which illustrates the significant effects that maintenance can have on reliability. The example demonstrates how intervals between maintenances can be chosen to achieve optimal availability.

Chapter 2 fully describes the PRA-based approaches to maintenance prioritization including detailed procedures and applications. Similarly, Chapter 3 presents the details of the extended component reliability models, while Chapter 4 demonstrates applications of these models to optimize maintenance intervals for a variety of cases. The appendices contain supplemental information on the derivations of the results, and show additional plots and tables to demonstrate these applications further. The chapters are sufficiently comprehensive to allow the approaches to be used for specific applications.

The message of the report is that risk-based and reliability-based approaches can provide new information and new perspectives on the effectiveness of maintenance. The demonstrations of maintenance prioritizations show significant differences in the importances of maintenances in assuring the reliability of components, and hence assuring plant risk. Thus, these prioritizations can be useful tools in prioritizing maintenance activities and in developing criteria for monitoring. The evaluations of maintenance effects on component reliability show large effects on performance which, in some cases, is so large that it dominates the risk. Therefore, these evaluations also can be invaluable tools in quantifying the effectiveness of maintenance for establishing superior maintenance programs.

ACKNOWLEDGMENT

Acknowledgment is given to Carl Johnson who was the NRC program monitor for this work and who not only provided competent direction for the project but also provided valuable technical inputs. Good luck in your retirement, Carl. You'll be missed.

We also acknowledge the reviewers of the report: Mahbubul Hassan, James Higgins, and Pranab Samanta of Brookhaven National Laboratory and Frank Coffman, Joel Kramer, and Millard Wohl of NRC. These reviews significantly enhanced the report.

1. OVERVIEW: EVALUATING MAINTENANCE EFFECTS ON RELIABILITY AND RISK

According to the EPRI report on "Nuclear Power Plant Common Aging Terminology"* the term "maintenance" is defined as:

> maintenance: actions that identify and mitigate degradation of a functioning system, structure, or component, or restore the design functions of a failed system, structure or component to an acceptable level.

Maintenance actions can be defined further as either preventative maintenance actions, or corrective maintenance actions. The EPRI report defines these types of maintenance as:

> corrective maintenance: actions that restore, by repair, overhaul, or replacement, the capability of a failed system, structure, or component to perform its defined function within acceptance criteria.
>
> preventative maintenance: periodic, predictive, or planned maintenance performed prior to failure of a system, structure, or component to extend its service life by controlling degradation or failure.

The following chapters in this report describe approaches which can be used to prioritize the risk importances of maintenance actions, and to quantify their reliability and risk effects. Individual types of maintenances, including corrective maintenances and preventative maintenances, can be evaluated with approaches discussed. Maintenance actions can have significant effects on reliability and risk, but it also can involve an expenditure of significant resources. Hence, it is important to prioritize the importances of individual maintenance actions, and to quantify their effects on reliability and risk. By such prioritizing, those maintenances which are most important in controlling risk are identified. By quantifying the reliability and risk effects of different maintenance options and schedules, optimal programs can be developed.

The NRC published the final version of its Maintenance Rule in the Federal Register on July 10, 1991** entitled "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants". The supporting information states that "...effectiveness of maintenance must be assessed on an ongoing basis in a manner which ensures that the desired result, reasonable assurance that key structures, systems, and components (SSCs) are capable of performing their intended function, is consistently achieved". The NRC Maintenance Rule thus identifies the importance of maintenance to safety, and the need to monitor its effectiveness to assure high levels of performance and low levels of risk.

In response to the NRC Maintenance Rule, the Nuclear Management and Resources Council (NUMARC) evaluated various strategies for implementation and issued a report summarizing those deemed most useful. The NUMARC report is entitled "Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants"*** (NUMARC Report 93-01), and the third revision was issued in March 1993. The report presents general guidelines for selecting important SSCs and for establishing risk and performance criteria to assure that they remain able to perform their intended function. General guidelines also are given on the effective applications of various maintenances. As part of the guidelines for selecting SSCs, possible criteria for using PRA importance measures in ranking SSCs are discussed.

---

* "Nuclear Power Plant Common Aging Terminology", EPRI Report TR-100844, Electric Power Research Institute, Palo Alto, CA, November 1992.

** 56 Federal Register 31324.

*** NUMARC Report 93-01, Revision 3, March 1993.

The present report provides detailed approaches for using PRA importance measures to rank SSCs for maintenance applications and describes some applications. Systems then can be ranked, based on the rankings of their components. In principle, these approaches also can be applied to structures, provided that the PRA contains the structures in the accident sequence and system models. This work was done to support development of guidances for implementing the Maintenance Rule. The results are generally consistent with NUMARC 93-01, and provide additional bases and details.

This report also describes specific reliability models which can be used to quantify the effects, both positive and negative, of maintenance actions on component unavailability, system unavailability, and plant risk. Preventative actions, corrective and repair actions, and maintenance schedules can be specifically evaluated for their benefits and drawbacks. The reliability models can be used in PRAs, and provide useful tools for measuring and optimizing maintenance actions and schedules from a reliability and risk perspective. These analyses do not include costs explicitly, although they include variables that affect costs, such as frequency of surveillance, preventative maintenance, and repair. Costs can be included by incorporating explicit cost relations.

Thus, the present report provides tools that can supplement other existing or proposed approaches for evaluating and improving the effectiveness of maintenance. The approaches described here are PRA-based and reliability-based, and because they are quantitative, they can provide important perspectives on maintenance effectiveness. They also can open a new avenue of applications and extensions for PRAs in quantifying maintenance effects on reliability and risk. The next two sections give an overview of the concepts, and results described in the following chapters.

1.1 Using PRA Importance Measures to Prioritize Maintenances

Two basic approaches can be used to prioritize SSCs for maintenance applications using standard PRA importance measures. One approach is to prioritize maintenances according to the risk importance of the SSC. The second approach is to prioritize maintenances according to the risk increase which results if the maintenance is not effective. Chapter 2 describes the procedures for applying either approach and shows that similar prioritizations are obtained if appropriate criteria are used for each approach.

Table 1.1 is an example of the prioritizations that are obtained by ranking the contributors to core damage frequency. The contributors are prioritized by prioritizing the minimal cutset contributions and extracting the maintainable components in the minimal cutsets. The first column gives the event code used in the PRA which describes the component failure. It describes the specific system involved, the specific component, and specific failure mode. The second column of the table gives a general description of the failure. The third column gives the ranking of the minimal cutset containing the component. The fourth column gives the running cumulative minimal cutset contribution to the CDF. The maintainable component failures in the top 90% of the minimal cutsets (or some other suitable percentage) are the dominant failures to CDF. Maintenance actions and monitoring actions then can focus on these top risk important components.

The results in Table 1.1 which are presented in greater detail in Chapter 2 were obtained using a specific PRA. Detailed procedures are set out for calculating the importance, which can be applied with any plant-specific PRA. The prioritizations can be simplified to identify the components most important to risk without regard to their failure mode. The risk-important maintainable components can be grouped by system to identify the risk-important components in a given system. As Chapter 2 shows, many systems contain relatively few such components. The risk-important maintainable components can be grouped further by type of component, such as identifying the specific motor-operated valves which are risk important. These groupings can be useful for maintenance and inspection modules.

Chapter 2 also presents an alternate approach for prioritizing maintenances by prioritizing the risk impact if the maintenance is ineffective, and shows that here, the standard PRA importance measure called the risk reduction worth is the appropriate measure to use. Again, detailed procedures and applications are discussed. The

Table 1.1 Prioritization of the Risk Important Contributors Using the PRA's Minimal Cutsets

Event Index	Event Code*	Event Description	Cutset Rank	Cumulative Cutset Contribution %
1	OEP-DGN-FS	Diesel failure	1	3.5
2	BETA-3DG	Common cause failure (ccf) for 3 diesels	1	3.5
3	RCP-LOCA-750-90M	Reactor pump seal failure	1	3.5
4	K	Failure to scram	2	6.1
5	OEP-DGN-FS-DG01	Diesel failure	3	8.0
6	OEP-DGN-FS-DG02	Diesel failure	3	8.0
7	OEP-DGN-FS-DG03	Diesel failure	4	9.9
8	MSS-SRV-OO-ODSRV	Safety relief valve failure	5	11.7
9	SGTR-SGSRV-ODMD1	Steam generator failure	5	11.7
10	BETA-2DG	ccf of 2 diesels	6	13.5
11	SGTR-SGSRV-ODMD2	Steam generator failure	7	15.0
12	LPR-MOV-FT-1862A	Motor-operated valve failure	8	16.4
13	BETA-2MOV	ccf for 2 motor-operated valves	8	16.4
14	QS-SBO	Station blackout event	9	17.8
15	LPI-MDP-FS	Motor-driven pump failure	10	19.2
16	BETA-LPI	ccf for 2 motor-driven pumps	10	19.2
17	LPI-MOV-PG-1890C	Motor-operated valve failure	11	20.5
18	OEP-DGN-FR-6HDG1	Diesel failure	16	26.2
19	OEP-DGN-FR-6HDG3	Diesel failure	17	27.3
20	OEP-DGN-FR-6HDG2	Diesel failure	18	28.3
21	ACC-MOV-PG-1865C	Motor-operated valve failure	20	30.3
22	ACC-MOV-PG-1865B	Motor-operated valve failure	21	31.3
23	RMT-CCF-FA-MSCAL	Recirculation mode transfer failure	23	33.1
24	HPI-MOV-FT	Motor-operated valve failure	24	33.9
25	LPR-MOV-FT-1860A	Motor-operated valve failure	25	34.7

use of the risk reduction worth is generally simpler because PRA computer codes usually rank all the contributors using the risk reduction worth. The chapter shows that the risk reduction worth, when appropriately normalized, effectively prioritizes the maintenance risk impacts including common-cause effects. Furthermore, these prioritizations are consistent with those obtained using the minimal cutset approach if appropriate criteria are used.

1.2 Quantifying Maintenance Effects on Unavailability and Risk

The reliability models usually used in a PRA assume that the component is in an operating state or a failed state. These models cannot quantify the benefits of maintenance because they do not consider degraded states of the component. A major benefit of maintenance is to correct degradations before failures occur. Either corrective maintenance or preventative maintenance is beneficial. By not including degraded states in the component reliability models, only the negative effects of maintenance are explicitly quantified in a PRA; these include the downtimes and the human errors associated with maintenances.

* The event codes (in this and later tables) define the events which are involved and are those defined in the reference PRA (the key to the specific event codes are given in Reference 4). For a component failure, the code identifies the specific system, specific component (including its identification number), and the specific mode.

Chapter 3 describes how the usual reliability models used in a PRA can be simply extended to include degraded states of the components. These extended models are termed Markov models. The simplest one considers one degraded state for the component. The chapter presents the equations which need to be applied and the data which are required to use these equations; maintenance data presently existing at plants can be used. The data in the Nuclear Plant Reliability Data System (NPRDS) also can be used.

In addition to being input to PRAs, the Markov component reliability models by themselves can quantify the effectiveness of maintenance actions on a component's reliability and performance. When input to a PRA, the effectiveness of maintenance on system unavailability and plant risk is quantified. By including the benefits of maintenance in detecting and correcting degraded states, as well as its inefficiencies and negative effects, maintenance actions can not only be objectively evaluated for their effectiveness, but can also be optimized from a reliability and risk standpoint.

Figure 1.1 illustrates an application of the models in Chapter 3. In the Figure, the component's operational unavailability is plotted against the maintenance interval for preventative maintenance. The operational unavailability is the probability that the component is not in its designed operational state. The figure shows the significant effects that the maintenance interval can have on the component's unavailability. The usual PRA evaluations cannot give such results. These models can significantly increase the ability to evaluate the effectiveness of maintenance and ensure that preventing failures is appropriately balanced against time out-of-service, as the NRC's Maintenance Rule promotes. Chapter 4 illustrates applications of the models developed in Chapter 3 covering a spectrum of components and degradation conditions.

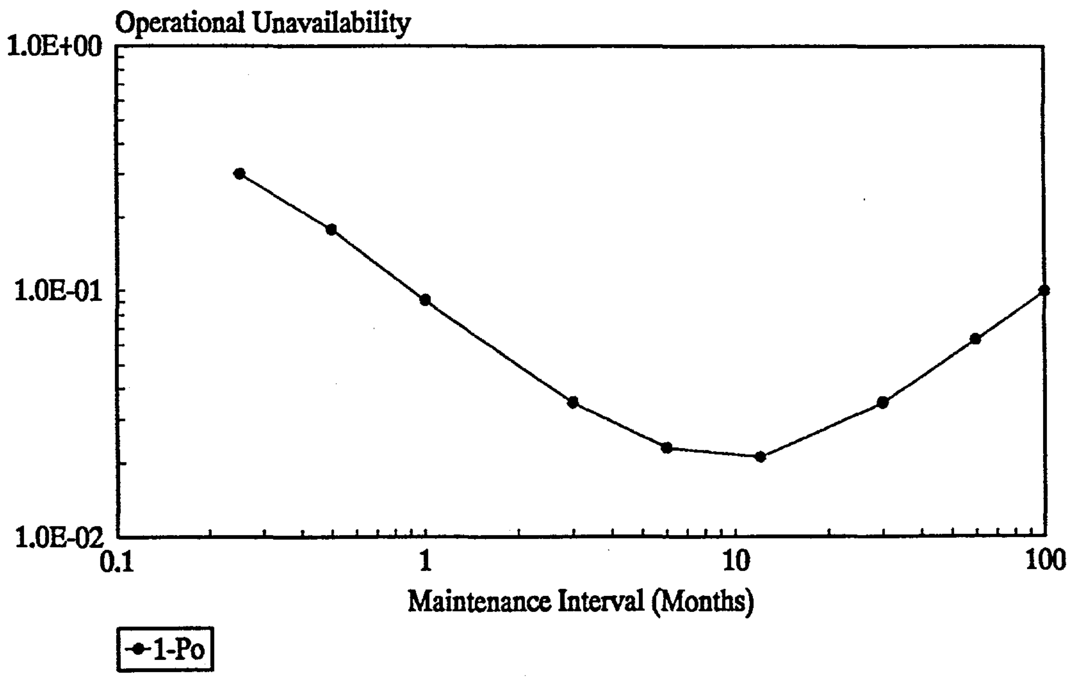


Figure 1.1 Operational unavailability versus maintenance interval

2. PRA IMPORTANCE MEASURES FOR MAINTENANCE PRIORITIZATION APPLICATIONS

Various importance measures are standardly calculated in a Probabilistic Risk Assessment (PRA). Approaches are developed in this chapter for using two of these measures, the minimal cutset contribution and the risk reduction importance, for prioritizing the risk importances of maintenances. One approach prioritizes maintenances based on the risk importance of the associated equipment which is maintained. The second approach prioritizes maintenances based on the risk impact if the maintenance is ineffective. The core damage frequency is used as the risk measure for prioritization. The demonstration studies which are carried out using a reference PRA indicate the two approaches give similar results if appropriate cutoff criteria are used. As an additional evaluation, risk unimportant maintenances are identified using the risk increase importance, or risk achievement worth, calculated in the PRA.

Importance measures are standardly computed in a Probabilistic Risk Assessment (PRA) to identify the important risk contributors and the important risk sensitivities. Various types of importances are calculated, including risk contribution importances, risk reduction importances, and risk increase importances. These importances also go by various names such as the Birnbaum importance, the risk achievement worth, and the Fussell-Vesely importance (ref. 1).

This chapter focuses on PRA importance measures which can be useful for maintenance prioritization applications. Specific importance measures are identified which can be used to identify risk important maintenances as well as risk unimportant maintenances. Two different measures are identified which can be used to determine risk important maintenances. One importance measure determines the risk importance of the maintenance based on the risk importance of the equipment being maintained. The other importance measure determines the importance of the maintenance based on the risk impact that would occur if the maintenance were not carried out effectively. In the demonstrations, both measures gave similar results.

The importance measure which determines those maintenances which are risk unimportant is based on the risk impact which occurs if the component fails. If the risk impact is negligible even when the component fails then maintenance on the component is not important from a risk standpoint since the risk is not sensitive to the proper functioning of the component.

The importance measures which are identified are specific cases of the standard importance measures which are usually calculated in a PRA, which allows for straightforward implementation. The standard importance measures are simply normalized in an appropriate manner for the maintenance applications. The point of this work is to describe a rationale and criteria for the use of specific importance measures for maintenance applications.

2.1 Determining the Risk Contributor Importance of a Maintenance

One way to identify the risk importance of a maintenance is to identify the risk importance of the equipment being maintained. Risk important maintenances can be defined to be those maintenances which are performed on risk important equipment. The measure of the risk importance of the equipment will thus provide the risk importance of the maintenance.

The risk contributions in a PRA are standardly prioritized by prioritizing the minimal cutset contributions. A minimal cutset is a smallest combination of basic events which if they all occur will result in core damage (or other undesired event analyzed by the PRA). For a core damage, which will be our focus for the specific applications, the combination of basic events consists of the initiating event, such as a pipe break, and a combination of component failures or other basic events which result in the loss of necessary safety functions to prevent a core damage.

The core damage frequency (CDF) contribution from a given minimal cutset is quantified by multiplying the frequency of the initiating event in the minimal cutset times the unavailabilities of the basic events in the minimal cutset. The PRA identifies the minimal cutsets for core damage and ranks them in order of their CDF contribution from the largest to smallest, down to some cutoff point. To first order, as generally assumed by the PRA, the sum of the core damage minimal cutset contributions equals the CDF.

The minimal cutset contributions provide a straightforward way of identifying the risk important maintenances. The risk important minimal cutsets are identified and the set of maintenances associated with the basic events in the risk important minimal cutsets can then be defined as the risk important maintenances. We will call this approach for determining the risk important basic events and associated maintenances, the minimal cutset prioritization approach. Note, that the minimal cutset approach is applicable not only for maintenance prioritization but also for all other activities and procedures associated with the basic events in the risk important minimal cutsets.

A criterion is needed to define the risk important minimal cutsets, i.e. to cutoff the risk important minimal cutsets from the marginal and unimportant ones. In terms of relative contributions, the risk important minimal cutsets can be defined to be the collection of top minimal cutsets which contribute a significant percentage to the CDF, such as contributing 90%. The precise cutoff criterion will often not be critical as long as a significant percentage of the total contribution is obtained. Table 2.1 summarizes the minimal cutset maintenance prioritization approach. This approach is also basically the approach described in NUREG/CR-5695 (ref. 2) where it is termed the risk-focused maintenance approach.

Table 2.1 The Minimal Cutset Maintenance Prioritization Approach

1. Rank the minimal cutsets in terms of their contribution to the CDF.

2. Divide each minimal cutset contribution by the total CDF to give the relative minimal cutset contribution.

3. Prepare a running sum of the ranked, relative minimal cutset contributions and cutoff at some significant percentage, such as 90%, to identify the risk important minimal cutsets.

4. Identify the maintainable components and equipment associated with the basic events in the risk important minimal cutsets. The associated maintenances are then the risk important maintenances.

2.2 Determining the Risk Impact Importance of a Maintenance

Another approach for determining the risk importance of a maintenance is to determine the risk impact if the maintenance is assumed not to be carried out effectively. Risk important maintenances are then defined to be those maintenances which if not carried out effectively will have significant risk impacts.

We need to model the impact of an ineffective maintenance on a component in order to determine the associated risk impact. We will assume as a general model that ineffective maintenance will cause the component unavailability to increase by some factor f. From NUREG/CR-5510 (ref. 3) and as shown in Section 2.9, when the component unavailabilities increase by a general factor f the CDF increase ΔC is given by

$$\Delta C = \sum_{i=1}^{n} r_i f + \sum_{i>j} r_{ij} f^2 + ... + \sum_{i_1 > ... > i_k} r_{i_1 ... i_k} f^k \quad (2.1)$$

where

r_i = the risk reduction importance of component i (2.2)

r_{ij} = the joint risk reduction importance of components i and j (2.3)

⋮

$r_{i_1 ... i_k}$ = the joint risk reduction importance of components $i_1....i_k$ (2.4)

and where k is the largest size of the minimal cutsets.* The components are those associated with the basic events defined in the PRA and in the minimal cutsets. If ineffective maintenances on different components result in different factor increases in the unavailabilities, then f can be taken as the maximum factor in which case ΔC is the maximum CDF increase.

The individual risk reduction importances r_i are standardly tabulated in PRAs and the joint risk reductions $r_{ij}, ... r_{i_1 ... i_k}$ are extensions to multiple components. From their definitions, the individual and joint risk reductions can be straightforwardly obtained from the minimal cutset contributions:

r_i = the sum of the contributions from the minimal cutsets, each containing component i (2.5)

r_{ij} = the sum of the contributions from minimal cutsets, each containing both components i and j (2.6)

⋮

$r_{i_1 ... i_k}$ = the sum of the contributions from minimal cutsets, each containing components i_1, i_2....and i_k. (2.7)

The risk reduction terms are so named because they indicate the risk reduction, i.e. the reduction in CDF, if the associated component unavailabilities are reduced to zero.

If we want to identify the significant contributions to ΔC then we need to determine the significant contributions to each of the terms on the right hand side of Equation (2.1) which determines ΔC. We focus on the first term, using the other terms as checks. The first term on the right hand side of Equation (2.1) represents the contribution from individual component degradation impacts:

$\sum_{i=1}^{n} r_i f$ = the contribution to ΔC from individual component degradation impacts due to ineffective maintenances. (2.8)

To obtain the significant portion of the contribution for any impact f, we can obtain the significant portion of $\sum_{i=1}^{n} r_i$, which is the sum of the individual risk reductions. This can be done by first ranking the risk reductions r_i

---

* In the above, the indices i, j and $i_1...i_k$ are a shorthand notation and refer to particular components for which the importances are determined.

from largest to smallest, which most PRAs already do. If we normalize each individual risk reduction by the sum of the individual risk reductions then we can accumulate the top normalized risk reductions in a running sum until the percentage reaches 95% or 99%, or some other high inclusion percentage. The value for the cutoff will again not generally be critical if it is high enough to include the significant portion of the total term. The associated components in the included set are then the risk important components from an impact standpoint. The maintenances on these components can then be defined to be the risk important maintenances which can significantly impact the CDF if not carried out effectively.

The significant contributions from the second and higher order terms in Equation (2.1) can be evaluated in a similar manner to see if any new components and new maintenances enter. These higher order terms represent additional impacts from simultaneous degradations of multiple components due to ineffective maintenances simultaneously being performed on the multiple components. For example, the term $r_{ij}f^2$ represents the CDF impact if ineffective maintenances are performed on both component i and component j resulting in a factor f increase in each component unavailability. These higher order terms thus represent interactions among the maintenance impacts.

The joint risk reductions for a given order (e.g. r_{ij} for the second order term) can be ranked and can be normalized by the respective sum again. A significant percentage (e.g. 95%) of the total sum can be taken and any new components and maintenances identified and added to the list. This can be repeated for each term.

If enough significant contributors are included in the first term using the individual risk reductions r_i then no significant, additional maintenances will be identified from these higher order terms. To help assure this condition, a high inclusion percentage can be used, such as 95% or 99%. As checks on any specific maintenances which are not included, the associated higher order contributions can be calculated using various values for the degradation factors f to determine the sensitivity to these excluded maintenances. Table 2.2 summarizes the risk reduction approach for identifying the risk important maintenances by their risk impacts.

Table 2.2 The Risk Reduction Maintenance Prioritization Approach

1.	Determine the individual risk reductions of the basic events in the PRA.
2.	Rank the individual risk reductions in order of decreasing size.
3.	Normalize the individual risk reductions by dividing by the sum of the risk reductions.
4.	Prepare a running sum of the ranked, relative risk reductions and cutoff at some significant percentage to identify the risk important basic events and associated maintenances.
5.	The joint risk reductions can be checked to determine if any additional maintenances can be important because of interactions.

2.3 Determining the Risk Unimportant Maintenances

Maintenances can be classified into those which are risk important, those which are marginal, and those which are risk unimportant. In addition to those which are risk important, it is useful to identify those maintenances which are risk unimportant. One of the simplest ways to identify risk unimportant maintenances is to identify those components which even if they fail will have little risk impact. If a component fails and has little risk impact then maintenance is not important in maintaining the performance of this component.

The standard measure of the risk impact of a component when it fails is the risk increase importance of the component, which is also called the risk achievement worth and the Birnbaum importance. Using the CDF as the risk measure, the risk increase importance is standardly determined in the PRA by failing the component and determining the increase in the CDF when the component is failed. The risk increase importance is also equal to the sum of the contributions of the minimal cutsets containing the component with the component unavailability set to one, provided sufficient minimal cutsets are obtained by the PRA to contain the component.

The risk increase importances can be determined for the basic events and can be ranked from largest to smallest, as is often standardly done in a PRA. Those basic events which have insignificantly small risk increase importances, such as those which are less than 1% of the CDF, can be identified as being risk unimportant. The associated maintenances done on these components can then be identified as being risk unimportant.

In interpreting risk unimportant results, two issues need to be considered. One is the cumulative CDF increase from multiple components being simultaneously down at the same time. The cumulative CDF increase can be significantly larger than the sum of the individual CDF increases if two or more components are in the same minimal cutset. One must thus assure that the cumulative increase is also small, for example by limiting the components to be in different minimal cutsets or by evaluating the CDF increase by simultaneously failing all the prospective components which are deemed to be unimportant.

The second issue that needs to be considered is related to the first and involves plant configurations which can cause unimportant components to become important. The CDF increase importance as standardly calculated in a PRA assumes average plant conditions, i.e. average component unavailabilities for the other components. If certain other components are actually down then the CDF increase from a normally, risk unimportant component can be significantly larger. The components which can cause these large effects will again be those components in the same minimal cutset as the unimportant component. Thus, there must be assurances that these adverse configurations are controlled and are avoided. Table 2.3 summarizes the risk increase maintenance unimportance identification approach.

Table 2.3 The Risk Increase Maintenance Unimportance Identification Approach

1. Determine the individual risk increases of basic events in the PRA.

2. Rank the risk increases in order of decreasing size and divide each one by the CDF.

3. Identify those components and associated maintenances as being risk unimportant if their risk increase is less than a small percent of the CDF.

4. For implementations, check cumulative effects and configuration effects to assure the CDF increases remain small.

2.4 Demonstration of the Minimal Cutset Prioritization Approach

To demonstrate the minimal cutset approach for identifying the risk important maintenances, a plant-specific PRA is used (ref. 4). The ranked minimal cutset contributions to the CDF as tabulated by the PRA are normalized by dividing by the CDF and multiplying by 100 to convert to percent. The ranked, normalized minimal cutset contributions are then accumulated in a running sum and the unique, basic events in the cutsets are listed. The basic events which are listed are those having potential associated maintenances. (Operator errors were removed before prioritization). These basic events can again be checked by the plant personnel to assure they have maintenance performed on them. The maintenances associated with the basic events in the top contributing minimal cutsets, e.g. the top 90%, are then identified as the risk important maintenances.

Table 2.4 shows the top 42 basic events so identified. Table 2.8 contains a more complete prioritization. The first column in Table 2.4 is the basic event counter and the second column is the rank of the cutset containing the basic event. The third column is the basic event code as defined in the PRA and the fourth column provides a general description of the event. The event code defines the detailed event which is involved; for a component failure, the code identifies the specific system, specific component (by its identification number), and the specific failure mode. Reference 4 contains the key for the event code. Note that different failure modes of the same component are listed separately (e.g. Events 29 and 30) since they may involve different maintenances. These events involving the same component but different failure modes can also be combined into one event for more condensed prioritizations.

The next to last column in Table 2.4 is the cutset frequency, i.e. CDF contribution of the minimal cutset containing the basic event. The last column is the cutset cumulative percentage contribution, which is the running sum of the cutset contributions including the present cutset. There are repeats in the last column, as there are in the second column, since a cutset generally contains several basic events which have associated maintenances.

The prioritization can be continued in the manner shown in Table 2.4 until a significant percentage of the total cutset contribution is obtained, such as 90%. As Table 2.8 shows, to include 90% of the total contribution, 83 basic events are identified. If the coverage is increased to 95% then 16 additional basic events are identified for a total of 99 basic events. The basic events are included in terms of their minimal cutset importance, and hence these last additional events are of much lesser importance than the first events included.

For implementation, the risk important basic events and associated maintenances can be organized in various ways. If maintenance procedures are defined by type of component, then the risk important components of a similar type can be extracted, i.e. the risk important motor operated valves identified, the risk important motor driven pumps identified, etc. If maintenance procedures are defined by system, then the risk important components in given systems can be extracted. The risk important prioritization can thus be used in any way deemed most appropriate for implementation.

2.5 Demonstration of the Risk Reduction Prioritization Approach

The PRA (ref. 4) is again used to demonstrate the risk reduction approach for identifying the risk important maintenances. As was described, the risk reduction approach prioritizes maintenances in terms of their risk impacts if not carried out effectively. The ranked, individual risk reduction importances tabulated by the PRA are normalized by their sum and then a running sum of the relative values is taken to obtain the cumulative relative contribution, as was done for the previous minimal cutset approach. The listing of the associated basic events then gives a prioritization of the events in terms of their CDF impact.

Table 2.5 shows the top 55 basic events prioritized by their risk reduction importance. Table 2.9 contains the more complete prioritization. Only those basic events were ranked which had potential associated maintenances (e.g., operator errors were excluded). These events should again be checked by plant personnel. The first column in Table 2.5 is the event rank and the second column is again the event code as identified in the PRA. The third column is the event description. The fourth column is the CDF risk reduction importance, which again is the sum of the contributions of the minimal cutsets containing the basic event.

The next to last column is the relative risk reduction, which is the individual risk reduction divided by the sum of the risk reductions and multiplied by 100 to convert to percent. The last column is the running sum of the relative risk reductions up through the current basic event. Having constructed the listing, the risk important events can then be identified as those constituting a significant percentage, such as 95%, of the CDF impact as

Table 2.4 Minimal Cutset Prioritization of the Top Potentially Maintainable Basic Events

Event Index	Cutset Rank	Event Code	Event Description	Cutset Freq. (per year)	Cumulative cutset %
1	1	OEP-DGN-FS	Diesel failure	1.17E-06	3.5
2	1	BETA-3DG	Beta for 3 diesels	1.17E-06	3.5
3	1	RCP-LOCA-750-90M	Seal failure	1.17E-06	3.5
4	2	K	Failure to scram	8.43E-07	6.1
5	2	R	Failure to scram	8.43E-07	6.1
6	3	OEP-DGN-FS-DG01	Diesel failure	6.21E-07	8.0
7	3	OEP-DGN-FS-DG02	Diesel failure	6.21E-07	8.0
8	4	OEP-DGN-FS-DG03	Diesel failure	6.21E-07	9.9
9	5	MSS-SRV-OO-ODSRV	Safety relief valve failure	6.09E-07	11.7
10	5	SGTR-SGSRV-ODMD1	Steam generator failure	6.09E-07	11.7
11	6	BETA-2DG	Beta for 2 diesels	5.77E-07	13.5
12	7	SGTR-SGSRV-ODMD2	Steam generator failure	5.18E-07	15.0
13	8	LPR-MOV-FT-1862A	Motor-operated valve failure	4.58E-07	16.4
14	8	BETA-2MOV	Beta for 2 motor-operated valves	4.58E-07	16.4
15	9	QS-SBO	Station blackout event	4.54E-07	17.8
16	10	LPI-MDP-FS	Motor-driven pump failure	4.50E-07	19.2
17	10	BETA-LPI	Beta for 2 motor-driven pumps	4.50E-07	19.2
18	11	LPI-MOV-PG-1890C	Motor-operated valve failure	4.40E-07	20.5
19	15	AFW-PSF-FC-XCONN	UNIT-2 event	3.60E-07	25.2
20	16	OEP-DGN-FR-6HDG1	Diesel failure	3.39E-07	26.2
21	17	OEP-DGN-FR-6HDG3	Diesel failure	3.39E-07	27.3
22	18	OEP-DGN-FR-6HDG2	Diesel failure	3.39E-07	28.3
23	20	ACC-MOV-PG-1865C	Motor-operated valve failure	3.25E-07	30.3
24	21	ACC-MOV-PG-1865B	Motor-operated valve failure	3.25E-07	31.3
25	23	RMT-CCF-FA-MSCAL	Common-cause failure	3.00E-07	33.1
26	24	HPI-MOV-FT	Motor-operated valve failure	2.64E-07	33.9
27	25	LPR-MOV-FT-1860A	Motor-operated valve failure	2.64E-07	34.7
28	26	LPR-MOV-FT-1890A	Motor-operated valve failure	2.64E-07	35.5
29	30	PPS-MOV-FT-1535	Motor-operated valve failure	2.42E-07	38.5
30	30	PPS-MOV-FC-1535	Motor-operated valve failure	2.42E-07	38.5
31	30	PPS-MOV-FC-1536	Motor-operated valve failure	2.42E-07	38.5
32	31	AFW-CCF-LK-STMBD	Common-cause failure	2.40E-07	39.2
33	38	MSS-SOV-OO-ODADV	Solenoid-operated valve failure	2.21E-07	44.0
34	38	SGTR-SGADV-ODMD	Steam generator rupture	2.21E-07	44.0
35	40	RCP-LOCA-467-150	Seal failure	2.19E-07	45.4
36	42	HPI-MOV-FT-1350	Motor-operated valve failure	2.02E-07	46.6
37	57	SBO-PORV-DMD	Station blackout event	1.40E-07	54.1
38	57	PPS-SOV-OO-1456	Solenoid-operated valve failure	1.40E-07	54.1
39	58	PPS-SOV-OO-1455C	Solenoid-operated valve failure	1.40E-07	54.5
40	77	HPI-CKV-FT-CV25	Check valve failure	1.00E-07	61.7
41	78	HPI-CKV-FT-CV225	Check valve failure	1.00E-07	62.0
42	79	HPI-CKV-FT-CV410	Check valve failure	1.00E-07	62.3

Table 2.5 Risk Reduction Prioritization of the Top Potentially Maintainable Basic Events

Rank	Event	Event Description	Risk Reduction (yr^{-1})	% Risk Reduction	Cumulative % Contribution
1	OEP-DGN-FS-DG01	Diesel failure	8.22E-06	11.0	11.0
2	RCP-LOCA-750-90M	Seal failure	5.20E-06	7.0	18.0
3	OEP-DGN-FS	Diesel failure	4.88E-06	6.5	24.5
4	OEP-DGN-FS-DG02	Diesel failure	4.38E-06	5.9	30.4
5	OEP-DGN-FS-DG03	Diesel failure	4.38E-06	5.9	36.2
6	OEP-DGN-FR-6HDG1	Diesel failure	4.08E-06	5.5	41.7
7	QS-SBO	Station blackout event	3.04E-06	4.1	45.7
8	BETA-2MOV	Beta for 2 motor-operated valves	2.72E-06	3.6	49.4
9	BETA-3DG	Beta for 3 diesels	2.66E-06	3.6	52.9
10	OEP-DGN-FR-6HDG3	Diesel failure	2.32E-06	3.1	56.0
11	SBO-PORV-DMD	Station blackout event	2.27E-06	3.0	59.1
12	BETA-2DG	Beta for 2 diesels	2.25E-06	3.0	62.1
13	OEP-DGN-FR-6HDG2	Diesel failure	2.09E-06	2.8	64.9
14	R	Failure to scram	1.51E-06	2.0	66.9
15	K	Failure to scram	1.51E-06	2.0	68.9
16	MCW-CCF-VF-SBO	Common-cause failure	1.38E-06	1.8	70.8
17	MSS-SRV-OO-ODSRV	Safety relief valve failure	1.25E-06	1.7	72.5
18	HPI-MOV-FT	Motor-operated valve failure	1.20E-06	1.6	74.1
19	PPS-SOV-OO-1455C	Solenoid-operated valve failure	1.20E-06	1.6	75.7
20	PPS-SOV-OO-1456	Solenoid-operated valve failure	1.20E-06	1.6	77.3
21	OEP-CRB-FT-15H3	Circuit breaker failure	1.06E-06	1.4	78.7
22	RCP-LOCA-467-150	Seal failure	9.74E-07	1.3	80.0
23	AFW-PSF-FC-XCONN	UNIT-2 event	8.75E-07	1.2	81.2
24	LPR-MOV-FT-1862A	Motor-operated valve failure	7.95E-07	1.1	82.2
25	SGTR-SGSRV-ODMD1	Steam generator failure	6.77E-07	0.9	83.1
26	LPI-MDP-FS	Motor-driven pump failure	6.75E-07	0.9	84.0
27	BETA-LPI	Beta for motor-driven pumps	6.75E-07	0.9	84.9
28	AFW-TDP-FR-2P6HR	Turbine-driven pump failure	6.60E-07	0.9	85.8
29	LPI-MOV-PG-1890C	Motor-operated valve failure	6.60E-07	0.9	86.7
30	AFW-TDP-FS-FW2	Turbine-driven pump failure	6.42E-07	0.9	87.6
31	AFW-CCF-LK-STMBD	Common-cause failure	5.82E-07	0.8	88.3
32	SGTR-SGSRV-ODMD2	Steam generator failure	5.75E-07	0.8	89.1
33	OEP-CRB-FT-15J3	Circuit breaker failure	5.65E-07	0.8	89.9
34	LPR-MOV-FT-1860A	Motor-operated valve failure	4.58E-07	0.6	90.5
35	RMT-CCF-FA-MSCAL	Common-cause failure	4.50E-07	0.6	91.1
36	PPS-MOV-FC-1536	Motor-operated valve failure	4.31E-07	0.6	91.7
37	PPS-MOV-FC-1535	Motor-operated valve failure	4.26E-07	0.6	92.2
38	LPR-MOV-FT-1890A	Motor-operated valve failure	4.09E-07	0.5	92.8
39	PPS-MOV-FT-1535	Motor-operated valve failure	3.87E-07	0.5	93.3
40	ACC-MOV-PG-1865C	Motor-operated valve failure	3.25E-07	0.4	93.7
41	ACC-MOV-PG-1865B	Motor-operated valve failure	3.25E-07	0.4	94.2
42	MSS-SOV-OO-ODADV	Solenoid-operated valve failure	2.54E-07	0.3	94.5
43	SGTR-SGADV-ODMD	Steam generator failure	2.54E-07	0.3	94.8
44	HPI-CKV-FT-CV225	Check valve failure	2.10E-07	0.3	95.1
45	HPI-CKV-FT-CV410	Check valve failure	2.06E-07	0.3	95.4
46	HPI-CKV-FT-CV25	Check valve failure	2.06E-07	0.3	95.7
47	HPI-MOV-FT-1350	Motor-operated valve failure	2.02E-07	0.3	95.9
48	AFW-MDP-FS	Motor-driven pump failure	1.73E-07	0.2	96.2
49	BETA-AFW	Beta for motor-driven pumps	1.73E-07	0.2	96.4
50	PPS-MOV-FT-1536	Motor-operated valve failure	1.45E-07	0.2	96.6
51	AFW-TDP-FR-2P24H	Turbine-driven pump failure	1.26E-07	0.2	96.8
52	RCS-PORV-ODMD	Steam generator event	1.22E-07	0.2	96.9
53	LPR-MOV-FT-1862B	Motor-operated valve failure	1.09E-07	0.1	97.1
54	OEP-DGN-FR-DG01	Diesel failure	1.02E-07	0.1	97.2
55	AFW-MDP-FS-FW3A	Motor-driven pump failure	1.00E-07	0.1	97.4

measured by the sum of the risk reductions. The maintenances associated with the significant risk impacting events can then be identified as the important, risk impacting maintenances.

2.6 Comparison of the Minimal Cutset and Risk Reduction Prioritization Procedures

Table 2.6 compares the percentage level at which a basic event enters using the risk reduction approach versus the level at which it enters using the minimal cutset approach. A more comprehensive table is given in Table 2.10. Figure 2.1 shows an analogous comparison of the cutoff percentage versus the number of basic events included for the minimal cutset and risk reduction approaches.

As Table 2.6 and Figure 2.1 show, a basic event generally enters at a higher percentage level using the risk reduction approach than using the minimal cutset approach. This behavior was also found in applications using other PRAs. The demonstrations therefore indicate that a higher percentage should be used for the risk reduction approach as for the minimal cutset approach to obtain the same set of basic events and associated maintenances. For example, Table 2.6 or Figure 2.1 indicates that using a 99% cutoff percentage for the risk reduction approach will yield essentially the same set of basic events as a 90% cutoff percentage for the minimal cutset approach.

Since the risk reduction approach is generally easier to apply than the minimal cutset approach, the use of a higher cutoff percentage should cause little extra work. The risk reductions are already standardly computed and ranked in the PRA, while the minimal cutset approach involves sorting of the basic events in the cutsets. Relatively few additional components and maintenances are added using a higher cutoff percentage which should also cause relatively little extra burden for the added assurance. Finally, as previously discussed, using a higher cutoff percentage in the risk reduction approach provides assurance that interaction effects from maintenances are included in the prioritization.

2.7 Demonstration of the Risk Increase Approach for Determining Unimportances

To determine the risk unimportant maintenances, the PRA is used and the risk increases with regard to the CDF, normalized by the CDF, are ranked. Table 2.7 shows the basic events with the smallest risk increases. Table 2.11 gives a more complete prioritization according to the risk increase. The maintenances associated with the basic events having insignificant risk increases (e.g. less than 10% or less than 5%) are identified as the risk unimportant maintenances.

Some of the events of low risk increase importance in Table 2.7 were previously identified as events of high risk reduction importance in Table 2.5. Examples of such "low-high" events include turbine driven pump failure (rank 130), diesel failure (rank 136), and steam generator failures (ranks 143 and 144). These events which have low risk increase importance and high risk reduction importance are generally events having relatively high unavailability and high functional performance. Because the (normal) unavailability is already high, if the component goes down, a relatively small risk increase will occur because of the relative small unavailability change. However, because the component is functionally important, reductions in the unavailability will significantly increase the performance of the component and cause significant risk reductions. Hence, maintenance should focus on reducing the unavailability of these components, not simply maintaining it. This illustrates how the risk importance results need to be carefully considered in guiding maintenance.

2.8 Conclusion

Using either the minimal cutsets or the risk reduction importances, the basic events and their associated maintenances can be prioritized for their risk importances. Both the minimal cutsets and the risk reductions are standardly tabulated in a PRA so application of the approaches is straightforward. The risk reduction approach is somewhat simpler to use as it does not involve sorting out the basic events which is required in using the minimal cutset approach. However, the minimal cutset approach is still reasonable to implement.

Table 2.6 Comparison of the Top Risk Reduction and Minimal Cutset Prioritizations

Rank Based on Risk Reduction	Event Code	Cumulative % Contribution (Risk Reduction)	Cutset % at which Event Enters
1	OEP-DGN-FS-DGO1	11.0	8.0
2	RCP-LOCA-750-90M	18.0	3.5
3	OEP-DGN-FS	24.5	3.5
4	OEP-DGN-FS-DGO2	30.4	8.0
5	OEP-DGN-FS-DGO3	36.2	9.9
6	OEP-DGN-FR-6HDG1	41.7	26.2
7	QS-SBO	45.7	17.8
8	BETA-2MOV	49.4	16.4
9	BETA-3DG	52.9	3.5
10	OEP-DGN-FR-6HDG3	56.0	27.3
11	SBO-PORV-DMD	59.1	54.1
12	BETA-2DG	62.1	13.5
13	OEP-DGN-FR-6HDG2	64.9	28.3
14	R	66.9	6.1
15	K	68.9	6.1
16	MCW-CCF-VF-SBO	70.8	64.9
17	MSS-SRV-OO-ODSRV	72.5	11.7
18	HPI-MOV-FT	74.1	33.9
19	PPS-SOV-OO-1455C	75.7	54.5
20	PPS-SOV-OO-1456	77.3	54.1
21	OEP-CRB-FT-15H3	78.7	65.4
22	RCP-LOCA-467-150	80.0	45.4
23	AFW-PSF-FC-XCONN	81.2	25.2
24	LPR-MOV-FT-1862A	82.2	16.4
25	SGTR-SGSRV-ODMD1	83.1	11.7
26	LPI-MDP-FS	84.0	19.2
27	BETA-LPI	84.9	19.2
28	AFW-TDP-FR-2P6HR	85.8	74.8
29	LPI-MOV-PG-1890C	86.7	20.5
30	AFW-TDP-FS-FW2	87.6	72.3
31	AFW-CCF-LK-STMBD	88.3	39.2
32	SGTR-SGSRV-ODMD2	89.1	15.0
33	OEP-CRB-FT-15J3	89.9	65.9
34	LPR-MOV-FT-1860A	90.5	34.7
35	RMT-CCF-FA-MSCAL	91.1	33.1
36	PPS-MOV-FC-1536	91.7	38.5
37	PPS-MOV-FC-1535	92.2	38.5
38	LPR-MOV-FT-1890A	92.8	35.5
39	PPS-MOV-FT-1535	93.3	38.5
40	ACC-MOV-PG-1865C	93.7	30.3
41	ACC-MOV-PG-1865B	94.2	31.3
42	MSS-SOV-OO-ODADV	94.5	44.0
43	SGTR-SGADV-ODMD	94.8	44.0
44	HPI-CKV-FT-CV225	95.1	62.0
45	HPI-CKV-FT-CV410	95.4	62.3

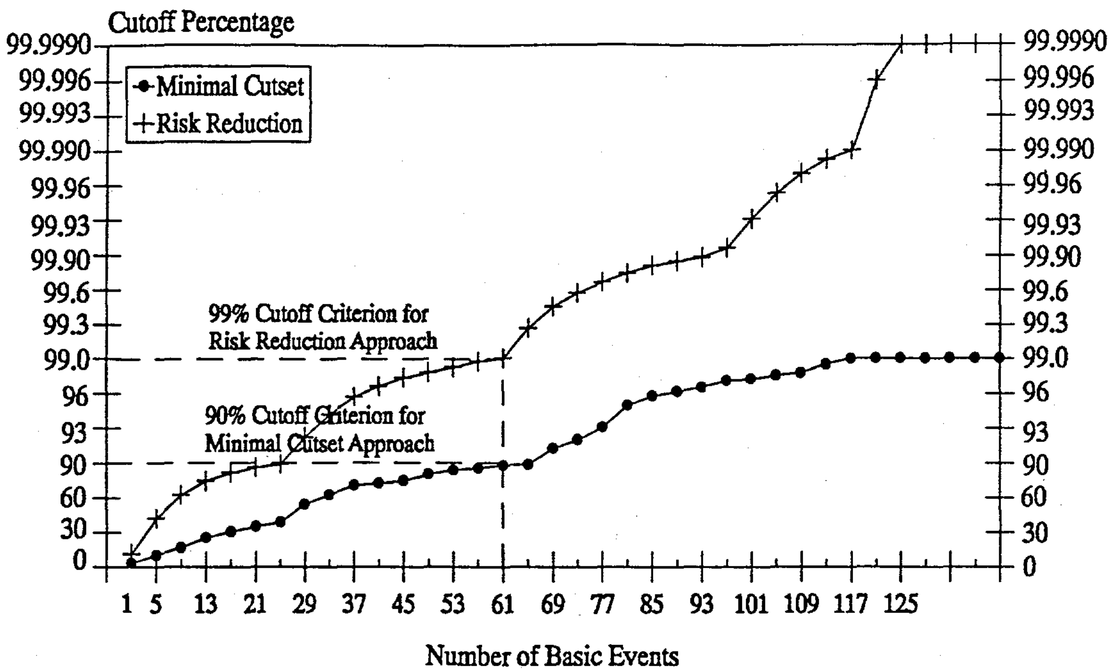


Figure 2.1 Cutoff percentage versus number of included basic events

In the demonstrations, both the minimal cutset approach and the risk reduction approach give similar results providing a higher cutoff is used for the risk reduction approach. Since the risk reduction importance involves a summation of pertinent minimal cutset contributions, it is not surprising that both give consistent results. The interaction terms in the risk reduction approach can be used to check for additional impacts from ineffective maintenances being performed on multiple components.

Using the risk increase importances standardly tabulated in the PRA, risk unimportant basic events and unimportant maintenances can also be identified. In implementations involving the risk unimportant findings, assurances are needed that cumulative effects and configuration effects are controlled.

2.9 The General Risk Sensitivity Formula

The general minimal cutset formula for the core damage frequency C (or for any other appropriate risk result) is

$$C = \sum_{i=1}^{N} Q_i \tag{2.9}$$

where

Q_i = the ith minimal cutset contribution (2.10)

Table 2.7 Lowest Risk Increases for the Basic Events

Rank	Event	Event Description	Risk Increase	% Risk Increase
94	HPI-MOV-FT-1115E	Motor-operated valve failure	5.63E-06	14.0
95	HPI-MOV-FT-1115D	Motor-operated valve failure	5.63E-06	14.0
96	HPI-MOV-FT-1115C	Motor-operated valve failure	5.63E-06	14.0
97	AFW-CKV-FT-CV157	Check valve failure	5.40E-06	13.5
98	AFW-CKV-FT-CV172	Check valve failure	5.40E-06	13.5
99	AFW-XVM-PG-XV168	Manual valve failure	5.40E-06	13.5
100	AFW-XVM-PG-XV183	Manual valve failure	5.40E-06	13.5
101	PPS-SOV-FT	Solenoid-operated valve failure	4.71E-06	11.7
102	RCP-LOCA-750-90M	Seal failure	4.61E-06	11.5
103	LPI-CKV-OO-CV58	Check valve failure	4.50E-06	11.2
104	LPI-CKV-OO-CV50	Check valve failure	4.50E-06	11.2
105	LPR-MOV-FT-1890B	Motor-operated valve failure	4.49E-06	11.2
106	MSS-CKV-FT-SGDHR	Check valve failure	4.05E-06	10.1
107	HPI-MDP-FR-1A6HR	Motor-driven pump failure	4.00E-06	10.0
108	BETA-LPI	Beta for motor-driven pumps	3.83E-06	9.6
109	HPI-MOV-FT-1867D	Motor-operated valve failure	3.57E-06	8.9
110	RCP-LOCA-183-90	Seal failure	3.49E-06	8.7
111	RCP-LOCA-183-150	Seal failure	3.49E-06	8.7
112	RCP-LOCA-183-210	Seal failure	3.49E-06	8.7
113	PPS-MOV-FT-1536	Motor-operated valve failure	3.48E-06	8.7
114	SGTR-SGSRV-ODMD2	Steam generator failure	3.26E-06	8.1
115	BETA-AFW	Beta for motor-driven pumps	2.92E-06	7.3
116	CPC-MDP-FR-CCA24	Motor-driven pump failure	2.86E-06	7.1
117	SBO-PORV-DMD	Station blackout event	2.77E-06	6.9
118	RMT-ACT-FA-RMTSA	Actuator failure	2.73E-06	6.8
119	RMT-ACT-FA-RMTSB	Actuator failure	2.73E-06	6.8
120	PPS-MOV-FC-OPER	Motor-operated valve failure	2.41E-06	6.0
121	CPC-CKV-OO-CV113	Check valve failure	2.17E-06	5.4
122	AFW-TDP-FS-U2FW2	Turbine-driven pump failure	1.96E-06	4.9
123	PPS-MOV-OO-1536	Motor-operated valve failure	1.39E-06	3.5
124	PPS-MOV-OO-1535	Motor-operated valve failure	1.39E-06	3.5
125	AFW-TDP-FR-6HRU2	Turbine-driven pump failure	1.16E-06	2.9
126	CPC-MDP-FR-SWA24	Motor-driven pump failure	1.04E-06	2.6
127	PPS-MOV-FT	Motor-operated valve failure	1.01E-06	2.5
128	PPS-MOV-FC-1536	Motor-operated valve failure	1.01E-06	2.5
129	PPS-MOV-FC-1535	Motor-operated valve failure	9.93E-07	2.5
130	AFW-TDP-FR-2P24H	Turbine-driven pump failure	9.21E-07	2.3
131	HPI-MOV-FT-1867C	Motor-operated valve failure	7.42E-07	1.9
132	CPC-MDP-FS-SW10B	Motor-driven pump failure	7.16E-07	1.8
133	CON-VFC-RP-COREM	Containment event	4.93E-07	1.2
134	CPC-MDP-FS-CC2B	Motor-driven pump failure	4.11E-07	1.0
135	HPI-MDP-FS	Motor-driven pump failure	1.91E-07	0.5
136	OEP-DGN-FC-DG3U2	Diesel failure	1.54E-07	0.4
137	CPC-MDP-FR-SWB24	Motor-driven pump failure	1.52E-07	0.4
138	RCS-PORV-ODMD	Steam generator event	1.22E-07	0.3
139	BETA-STR	Beta for strainers	9.36E-08	0.2
140	BETA-SRV	Beta for safety relief valves	6.26E-08	0.2
141	UNIT2-LOW-POWER	UNIT-2 event	2.40E-08	0.060
142	BETA-HPI	Beta for motor-driven pumps	2.89E-09	0.007
143	SGTR-SGADV-ODMD	Steam generator failure	ε	ε
144	SGTR-SGSRV-ODMD1	Steam generator failure	ε	ε
145	MSS-SRV-OO-ODSRV	Safety relief valve failure	ε	ε
146	MSS-SOV-OO-ODADV	Solenoid-operated valve failure	ε	ε

and where there are N total minimal cutsets. As previously discussed, the minimal cutset contribution Q_i generally consists of the frequency of an initiating event times the product of the unavailabilities of the basic events in the cutsets.

Assume the individual unavailabilities of the maintainable components are increased because of ineffective maintenances. To be general, assume the new unavailability is a factor of 1+f times the original unavailability, where f is a general factor increase. The new cutset contribution $Q_i^{'}$ is thus

$$Q_i^{'} = Q_i(1+f)^{n_i} \tag{2.11}$$

where n_i is the number of maintainable components in cutset i. Expanding Equation (2.11) as a power series gives

$$Q_i^{'} = Q_i\left(1 + n_i f + \binom{n_i}{2} f^2 + \ldots + f^{n_i}\right). \tag{2.12}$$

Now, when $Q_i^{'}$ is summed over all the cutsets to obtain the new core damage frequency using Equation (2.9), the first term on the right hand side of Equation (2.12) gives the original value C. For each maintainable component, the second term will give $Q_i f$ for each cutset containing the component. For each pair of maintainable components, the third term will yield $Q_i f^2$ for each cutset containing the pair. Hence we may write the expression for the new core damage frequency C' as

$$C' = C + \sum_{i=1}^{n} r_i f + \sum_{i>j} r_{ij} f^2 + \ldots + \sum_{i_1 > \ldots > i_k} r_{i_1 \ldots i_k} f^k, \tag{2.13}$$

or

$$\Delta C = \sum_{i=1}^{n} r_i f + \sum_{i>j} r_{ij} f^2 + \ldots + \sum_{i_1 > \ldots > i_k} r_{i_1 \ldots i_k} f^k, \tag{2.14}$$

where r_i is the sum of the minimal cutset contributions containing component i, r_{ij} is the sum of minimal cutset contributions each containing components i and j, etc.

2.10 Detailed Minimal Cutset Prioritizations and Risk Reduction Prioritizations

Tables 2.8 and 2.9 give the detailed minimal cutset prioritizations and risk reduction prioritizations, respectively, using the plant-specific PRA (ref. 4). These tables give perspectives on the numbers and types of contributors required for different total percentage coverages. The tables are also useful in providing perspectives on the prioritization levels at which given contributors enter.

Table 2.8 Minimal Cutset Prioritization of the Potentially Maintainable Basic Events

Event Index	Cutset Rank	Event Code	Event Description	Cutset Freq. (per year)	Cumulative cutset %
1	1	OEP-DGN-FS	Diesel failure	1.17E-06	3.5
2	1	BETA-3DG	Beta for 3 diesels	1.17E-06	3.5
3	1	RCP-LOCA-750-90M	Seal failure	1.17E-06	3.5
4	2	K	Failure to scram	8.43E-07	6.1
5	2	R	Failure to scram	8.43E-07	6.1
6	3	OEP-DGN-FS-DG01	Diesel failure	6.21E-07	8.0
7	3	OEP-DGN-FS-DG02	Diesel failure	6.21E-07	8.0
8	4	OEP-DGN-FS-DG03	Diesel failure	6.21E-07	9.9
9	5	MSS-SRV-OO-ODSRV	Safety relief valve failure	6.09E-07	11.7
10	5	SGTR-SGSRV-ODMD1	Steam generator failure	6.09E-07	11.7
11	6	BETA-2DG	Beta for 2 diesels	5.77E-07	13.5
12	7	SGTR-SGSRV-ODMD2	Steam generator failure	5.18E-07	15.0
13	8	LPR-MOV-FT-1862A	Motor-operated valve failure	4.58E-07	16.4
14	8	BETA-2MOV	Beta for 2 motor-operated valves	4.58E-07	16.4
15	9	QS-SBO	Station blackout event	4.54E-07	17.8
16	10	LPI-MDP-FS	Motor-driven pump failure	4.50E-07	19.2
17	10	BETA-LPI	Beta for 2 motor-driven pumps	4.50E-07	19.2
18	11	LPI-MOV-PG-1890C	Motor-operated valve failure	4.40E-07	20.5
19	15	AFW-PSF-FC-XCONN	UNIT-2 event	3.60E-07	25.2
20	16	OEP-DGN-FR-6HDG1	Diesel failure	3.39E-07	26.2
21	17	OEP-DGN-FR-6HDG3	Diesel failure	3.39E-07	27.3
22	18	OEP-DGN-FR-6HDG2	Diesel failure	3.39E-07	28.3
23	20	ACC-MOV-PG-1865C	Motor-operated valve failure	3.25E-07	30.3
24	21	ACC-MOV-PG-1865B	Motor-operated valve failure	3.25E-07	31.3
25	23	RMT-CCF-FA-MSCAL	Common-cause failure	3.00E-07	33.1
26	24	HPI-MOV-FT	Motor-operated valve failure	2.64E-07	33.9
27	25	LPR-MOV-FT-1860A	Motor-operated valve failure	2.64E-07	34.7
28	26	LPR-MOV-FT-1890A	Motor-operated valve failure	2.64E-07	35.5
29	30	PPS-MOV-FT-1535	Motor-operated valve failure	2.42E-07	38.5
30	30	PPS-MOV-FC-1535	Motor-operated valve failure	2.42E-07	38.5
31	30	PPS-MOV-FC-1536	Motor-operated valve failure	2.42E-07	38.5
32	31	AFW-CCF-LK-STMBD	Common-cause failure	2.40E-07	39.2
33	38	MSS-SOV-OO-ODADV	Solenoid-operated valve failure	2.21E-07	44.0
34	38	SGTR-SGADV-ODMD	Steam generator rupture	2.21E-07	44.0
35	40	RCP-LOCA-467-150	Seal failure	2.19E-07	45.4
36	42	HPI-MOV-FT-1350	Motor-operated valve failure	2.02E-07	46.6
37	57	SBO-PORV-DMD	Station blackout event	1.40E-07	54.1
38	57	PPS-SOV-OO-1456	Solenoid-operated valve failure	1.40E-07	54.1
39	58	PPS-SOV-OO-1455C	Solenoid-operated valve failure	1.40E-07	54.5
40	77	HPI-CKV-FT-CV25	Check valve failure	1.00E-07	61.7
41	78	HPI-CKV-FT-CV225	Check valve failure	1.00E-07	62.0
42	79	HPI-CKV-FT-CV410	Check valve failure	1.00E-07	62.3
43	88	MCW-CCF-VF-SBO	Common-cause failure	8.48E-08	64.9
44	90	OEP-CRB-FT-15H3	Circuit breaker failure	8.47E-08	65.4
45	92	OEP-CRB-FT-15J3	Circuit breaker failure	8.47E-08	65.9

Table 2.8 Minimal Cutset Prioritization of the Potentially Maintainable Basic Events (Continued)

Event Index	Cutset Rank	Event Code	Event Description	Cutset Freq. (per year)	Cumulative cutset %
46	113	BETA-AFW	Beta for motor-driven pumps	6.30E-08	70.4
47	113	AFW-TDP-FR-2P24H	Turbine-driven pump failure	6.30E-08	70.4
48	113	AFW-MDP-FS	Motor-driven pump failure	6.30E-08	70.4
49	120	PPS-MOV-FT-1536	Motor-operated valve failure	6.09E-08	71.8
50	123	AFW-TDP-FS-FW2	Turbine-driven pump failure	5.62E-08	72.3
51	134	ACC-CKV-FT-CV130	Check valve failure	5.00E-08	74.0
52	135	ACC-CKV-FT-CV147	Check valve failure	5.00E-08	74.2
53	136	ACC-CKV-FT-CV128	Check valve failure	5.00E-08	74.3
54	137	LPR-CCF-PG-SUMP	Common-cause failure	5.00E-08	74.5
55	138	ACC-CKV-FT-CV145	Check valve failure	5.00E-08	74.6
56	139	AFW-TDP-FR-2P6HR	Turbine-driven pump failure	4.95E-08	74.8
57	160	HPI-XVM-PG-XV24	Manual valve failure	4.00E-08	77.7
58	178	RWT-TNK-LF-RWST	Insufficient water in tank	3.51E-08	79.7
59	181	AFW-MDP-FS-FW3B	Motor-driven pump failure	3.40E-08	80.0
60	182	AFW-MDP-FS-FW3A	Motor-driven pump failure	3.40E-08	80.1
61	210	LPR-MOV-FT-1862B	Motor-operated valve failure	2.70E-08	82.7
62	217	AFW-CKV-OO-CV142	Check valve failure	2.64E-08	83.3
63	220	PPS-MOV-OO-1536	Motor-operated valve failure	2.61E-08	83.5
64	220	RCS-PORV-ODMD	Steam generator event	2.61E-08	83.5
65	221	PPS-MOV-OO-1535	Motor-operated valve failure	2.61E-08	83.6
66	231	BETA-STR	Beta for strainers	2.37E-08	84.3
67	231	CPC-STR-PG-3HR	Strainer plugged	2.37E-08	84.3
68	243	PPS-MOV-FT	Motor-operated valve failure	2.13E-08	85.2
69	245	HPI-MDP-FR-1A24H	Motor-driven pump failure	2.08E-08	85.3
70	245	HPI-CKV-OO-CV258	Check valve failure	2.08E-08	85.3
71	291	LPI-MDP-FS-SI1B	Motor-driven pump failure	1.56E-08	87.8
72	292	LPI-MDP-FS-SI1A	Motor-driven pump failure	1.56E-08	87.8
73	293	LPR-MOV-FT-1860B	Motor-operated valve failure	1.56E-08	87.9
74	302	AFW-CKV-OO-CV157	Check valve failure	1.51E-08	88.3
75	303	AFW-CKV-OO-CV172	Check valve failure	1.51E-08	88.3
76	306	IAS-CCF-LF-INAIR	Common-cause failure	1.47E-08	88.5
77	307	RCP-LOCA-1440-90	Seal failure	1.44E-08	88.5
78	332	RCP-LOCA-183-210	Seal failure	1.28E-08	89.6
79	333	RCP-LOCA-183-150	Seal failure	1.28E-08	89.6
80	334	OEP-DGN-FR-DG01	Diesel failure	1.27E-08	89.6
81	335	OEP-DGN-FR-DG03	Diesel failure	1.27E-08	89.7
82	338	OEP-DGN-FR-DG02	Diesel failure	1.27E-08	89.8
83	367	RCP-LOCA-183-90	Seal failure	1.12E-08	90.8
84	380	SIS-ACT-FA-SISA	Actuator failure	1.02E-08	91.3
85	380	SIS-ACT-FA-SISB	Actuator failure	1.02E-08	91.3
86	406	HPI-MOV-FT-1115E	Motor-operated valve failure	9.00E-09	92.0
87	406	HPI-MOV-FT-1115C	Motor-operated valve failure	9.00E-09	92.0
88	407	LPR-MOV-FT-1890B	Motor-operated valve failure	9.00E-09	92.0
89	411	HPI-MOV-FT-1115D	Motor-operated valve failure	9.00E-09	92.2
90	411	HPI-MOV-FT-1115B	Motor-operated valve failure	9.00E-09	92.2

Table 2.8 Minimal Cutset Prioritization of the Potentially Maintainable Basic Events (Continued)

Event Index	Cutset Rank	Event Code	Event Description	Cutset Freq. (per year)	Cumulative cutset %
91	433	MSS-CKV-FT-SGDHR	Check valve failure	8.12E-09	92.3
92	448	CPC-STR-PG-24H	Strainer plugged	5.58E-09	93.1
93	454	RCP-LOCA-561-150	Seal failure	7.34E-09	93.2
94	503	ACP-BAC-ST-1H1-2	AC bus failure	6.06E-09	94.2
95	504	ACP-BAC-ST-4KV1H	AC bus failure	6.06E-09	94.2
96	505	ACP-BAC-ST-1H1	AC bus failure	6.06E-09	94.2
97	550	PPS-SOV-FT-1455C	Solenoid-operated valve failure	5.08E-09	95.0
98	551	PPS-SOV-FT-1456	Solenoid-operated valve failure	5.08E-09	95.0
99	568	PPS-SOV-FT	Solenoid-operated valve failure	4.71E-09	95.2
100	568	BETA-SRV	Beta for safety relief valves	4.71E-09	95.2
101	609	OEP-CRB-FT-25H3	Circuit breaker failure	4.82E-09	95.8
102	615	AFW-TDP-FR-6HRU2	Turbine-driven pump failure	4.02E-09	95.9
103	620	CPC-MDP-FS-SW10B	Motor-driven pump failure	3.84E-09	95.9
104	620	CPC-MDP-FR-SWA3H	Motor-driven pump failure	3.84E-09	95.9
105	643	HPI-MOV-FT-1867D	Motor-operated valve failure	3.51E-09	96.2
106	673	LPI-MDP-FR-B21HR	Motor-driven pump failure	3.28E-09	96.5
107	674	LPI-MDP-FR-A21HR	Motor-driven pump failure	3.28E-09	96.5
108	676	AFW-ACT-FA-PMP3A	Actuator failure	3.24E-09	96.5
109	677	AFW-ACT-FA-PMP3B	Actuator failure	3.24E-09	96.5
110	705	CON-VFC-RP-COREM	Containment event	3.02E-09	96.8
111	705	SWS-CCF-FT-3ABCD	Common-cause failure	3.02E-09	96.8
112	708	LPI-CKV-OO-CV50	Check valve failure	3.00E-09	96.8
113	709	LPI-CKV-OO-CV58	Check valve failure	3.00E-09	96.8
114	741	ACP-TFM-NO-1H1	Transformer failure	2.69E-09	97.1
115	742	HPI-MOV-PG-1350	Motor-operated valve failure	2.69E-09	97.1
116	753	RMT-ACT-FA-RMTSB	Actuator failure	2.56E-09	97.2
117	753	RMT-ACT-FA-RMTSA	Actuator failure	2.56E-09	97.2
118	759	OEP-DGN-FC-DG3U2	Diesel failure	2.54E-09	97.3
119	767	AFW-TNK-VF-CST	Insufficient water in tank	2.40E-09	97.3
120	781	DCP-BDC-ST-BUS1B	DC bus failure	2.30E-09	97.4
121	782	DCP-BDC-ST-BUS1A	DC bus failure	2.30E-09	97.4
122	800	CPC-CKV-OO-CV113	Check valve failure	2.17E-09	97.5
123	800	CPC-MDP-FR-SWA24	Motor-driven pump failure	2.17E-09	97.5
124	810	CVC-MDP-FR-2A1HR	Motor-driven pump failure	2.02E-09	97.6
125	842	LPI-MDP-FR-B24HR	Motor-driven pump failure	1.87E-09	97.8
126	843	LPI-MDP-FR-A24HR	Motor-driven pump failure	1.87E-09	97.8
127	863	PPS-MOV-FC-OPER	Motor-operated valve failure	1.76E-09	97.9
128	876	UNIT2-LOW-POWER	UNIT-2 event	1.71E-09	97.9
129	895	AFW-TDP-FS-U2FW2	Turbine-driven pump failure	1.67E-09	98.0
130	916	HPI-MDP-FR-1A6HR	Motor-driven pump failure	1.60E-09	98.1
131	993	HPI-MOV-FT-1867C	Motor-operated valve failure	1.34E-09	98.5
132	1038	CPC-MDP-FS-CC2B	Motor-driven pump failure	1.24E-09	98.7
133	1038	CPC-MDP-FR-CCA24	Motor-driven pump failure	1.24E-09	98.7
134	1123	CPC-STR-PG-6HR	Strainer plugged	1.03E-09	99.0
135	1132	AFW-MDP-FR-3B6HR	Motor-driven pump failure	9.72E-10	99.0
136	1131	AFW-MDP-FR-3A6HR	Motor-driven pump failure	9.72E-10	99.0

Table 2.9 Risk Reduction Prioritization of the Potentially Maintainable Basic Events

Rank	Event	Event Description	Risk Reduction (yr^{-1})	% Risk Reduction	Cumulative % Contribution
1	OEP-DGN-FS-DG01	Diesel failure	8.22E-06	11.0	11.0
2	RCP-LOCA-750-90M	Seal failure	5.20E-06	7.0	18.0
3	OEP-DGN-FS	Diesel failure	4.88E-06	6.5	24.5
4	OEP-DGN-FS-DG02	Diesel failure	4.38E-06	5.9	30.4
5	OEP-DGN-FS-DG03	Diesel failure	4.38E-06	5.9	36.2
6	OEP-DGN-FR-6HDG1	Diesel failure	4.08E-06	5.5	41.7
7	QS-SBO	Station blackout event	3.04E-06	4.1	45.7
8	BETA-2MOV	Beta for 2 motor-operated valves	2.72E-06	3.6	49.4
9	BETA-3DG	Beta for 3 diesels	2.66E-06	3.6	52.9
10	OEP-DGN-FR-6HDG3	Diesel failure	2.32E-06	3.1	56.0
11	SBO-PORV-DMD	Station blackout event	2.27E-06	3.0	59.1
12	BETA-2DG	Beta for 2 diesels	2.25E-06	3.0	62.1
13	OEP-DGN-FR-6HDG2	Diesel failure	2.09E-06	2.8	64.9
14	R	Failure to scram	1.51E-06	2.0	66.9
15	K	Failure to scram	1.51E-06	2.0	68.9
16	MCW-CCF-VF-SBO	Common-cause failure	1.38E-06	1.8	70.8
17	MSS-SRV-OO-ODSRV	Safety relief valve failure	1.25E-06	1.7	72.5
18	HPI-MOV-FT	Motor-operated valve failure	1.20E-06	1.6	74.1
19	PPS-SOV-OO-1455C	Solenoid-operated valve failure	1.20E-06	1.6	75.7
20	PPS-SOV-OO-1456	Solenoid-operated valve failure	1.20E-06	1.6	77.3
21	OEP-CRB-FT-15H3	Circuit breaker failure	1.06E-06	1.4	78.7
22	RCP-LOCA-467-150	Seal failure	9.74E-07	1.3	80.0
23	AFW-PSF-FC-XCONN	UNIT-2 event	8.75E-07	1.2	81.2
24	LPR-MOV-FT-1862A	Motor-operated valve failure	7.95E-07	1.1	82.2
25	SGTR-SGSRV-ODMD1	Steam generator failure	6.77E-07	0.9	83.1
26	LPI-MDP-FS	Motor-driven pump failure	6.75E-07	0.9	84.0
27	BETA-LPI	Beta for motor-driven pumps	6.75E-07	0.9	84.9
28	AFW-TDP-FR-2P6HR	Turbine-driven pump failure	6.60E-07	0.9	85.8
29	LPI-MOV-PG-1890C	Motor-operated valve failure	6.60E-07	0.9	86.7
30	AFW-TDP-FS-FW2	Turbine-driven pump failure	6.42E-07	0.9	87.6
31	AFW-CCF-LK-STMBD	Common-cause failure	5.82E-07	0.8	88.3
32	SGTR-SGSRV-ODMD2	Steam generator failure	5.75E-07	0.8	89.1
33	OEP-CRB-FT-15J3	Circuit breaker failure	5.65E-07	0.8	89.9
34	LPR-MOV-FT-1860A	Motor-operated valve failure	4.58E-07	0.6	90.5
35	RMT-CCF-FA-MSCAL	Common-cause failure	4.50E-07	0.6	91.1
36	PPS-MOV-FC-1536	Motor-operated valve failure	4.31E-07	0.6	91.7
37	PPS-MOV-FC-1535	Motor-operated valve failure	4.26E-07	0.6	92.2
38	LPR-MOV-FT-1890A	Motor-operated valve failure	4.09E-07	0.5	92.8
39	PPS-MOV-FT-1535	Motor-operated valve failure	3.87E-07	0.5	93.3
40	ACC-MOV-PG-1865C	Motor-operated valve failure	3.25E-07	0.4	93.7
41	ACC-MOV-PG-1865B	Motor-operated valve failure	3.25E-07	0.4	94.2
42	MSS-SOV-OO-ODADV	Solenoid-operated valve failure	2.54E-07	0.3	94.5
43	SGTR-SGADV-ODMD	Steam generator failure	2.54E-07	0.3	94.8
44	HPI-CKV-FT-CV225	Check valve failure	2.10E-07	0.3	95.1
45	HPI-CKV-FT-CV410	Check valve failure	2.06E-07	0.3	95.4
46	HPI-CKV-FT-CV25	Check valve failure	2.06E-07	0.3	95.7
47	HPI-MOV-FT-1350	Motor-operated valve failure	2.02E-07	0.3	95.9
48	AFW-MDP-FS	Motor-driven pump failure	1.73E-07	0.2	96.2
49	BETA-AFW	Beta for motor-driven pumps	1.73E-07	0.2	96.4
50	PPS-MOV-FT-1536	Motor-operated valve failure	1.45E-07	0.2	96.6
51	AFW-TDP-FR-2P24H	Turbine-driven pump failure	1.26E-07	0.2	96.8

Table 2.9 Risk Reduction Prioritization of the Potentially Maintainable Basic Events (Continued)

Rank	Event	Event Description	Risk Reduction (yr^{-1})	% Risk Reduction	Cumulative % Contribution
52	RCS-PORV-ODMD'	Steam generator event	1.22E-07	0.2	96.9
53	LPR-MOV-FT-1862B	Motor-operated valve failure	1.09E-07	0.1	97.1
54	OEP-DGN-FR-DG01	Diesel failure	1.02E-07	0.1	97.2
55	AFW-MDP-FS-FW3A	Motor-driven pump failure	1.00E-07	0.1	97.4
56	AFW-MDP-FS-FW3B	Motor-driven pump failure	9.93E-08	0.1	97.5
57	HPI-XVM-PG-XV24	Manual valve failure	8.23E-08	0.1	97.6
58	LPR-CCF-PG-SUMP	Common-cause failure	7.75E-08	0.1	97.7
59	LPI-MDP-FS-SI1B	Motor-driven pump failure	7.41E-08	0.1	97.8
60	LPI-MDP-FS-SI1A	Motor-driven pump failure	7.41E-08	0.1	97.9
61	RCP-LOCA-1440-90	Seal failure	6.40E-08	0.09	98.0
62	LPR-MOV-FT-1860B	Motor-operated valve failure	6.24E-08	0.08	98.1
63	AFW-CKV-OO-CV142	Check valve failure	6.10E-08	0.08	98.1
64	PPS-MOV-OO-1536	Motor-operated valve failure	5.78E-08	0.08	98.2
65	PPS-MOV-OO-1535	Motor-operated valve failure	5.78E-08	0.08	98.3
66	RCP-LOCA-183-210	Seal failure	5.70E-08	0.08	98.4
67	RCP-LOCA-183-150	Seal failure	5.70E-08	0.08	98.5
68	RWT-TNK-LF-RWST	Insufficient water in tank	5.27E-08	0.07	98.5
69	OEP-DGN-FR-DG02	Diesel failure	5.13E-08	0.07	98.6
70	AFW-CKV-OO-CV172	Check valve failure	5.09E-08	0.07	98.7
71	OEP-DGN-FR-DG03	Diesel failure	5.06E-08	0.07	98.7
72	ACC-CKV-FT-CV145	Check valve failure	5.00E-08	0.07	98.8
73	ACC-CKV-FT-CV128	Check valve failure	5.00E-08	0.07	98.9
74	ACC-CKV-FT-CV130	Check valve failure	5.00E-08	0.07	98.9
75	ACC-CKV-FT-CV147	Check valve failure	5.00E-08	0.07	99.0
76	RCP-LOCA-183-90	Seal failure	4.96E-08	0.07	99.1
77	PPS-MOV-FT	Motor-operated valve failure	4.22E-08	0.06	99.1
78	IAS-CCF-LF-INAIR	Common-cause failure	3.72E-08	0.05	99.2
79	AFW-TDP-FR-6HRU2	Turbine-driven pump failure	3.58E-08	0.05	99.2
80	BETA-STR	Beta for strainers	3.34E-08	0.05	99.3
81	RCP-LOCA-561-150	Seal failure	3.27E-08	0.04	99.3
82	SIS-ACT-FA-SISA	Actuator failure	2.86E-08	0.04	99.3
83	SIS-ACT-FA-SISB	Actuator failure	2.86E-08	0.04	99.4
84	AFW-CKV-OO-CV157	Check valve failure	2.56E-08	0.03	99.4
85	OEP-CRB-FT-25H3	Circuit breaker failure	2.46E-08	0.03	99.5
86	CPC-STR-PG-3HR	Strainer plugged	2.37E-08	0.03	99.5
87	HPI-CKV-OO-CV258	Check valve failure	2.24E-08	0.03	99.5
88	AFW-TDP-FS-U2FW2	Turbine-driven pump failure	2.18E-08	0.03	99.5
89	HPI-MDP-FR-1A24H	Motor-driven pump failure	2.16E-08	0.03	99.6
90	HPI-MOV-FT-1115B	Motor-operated valve failure	1.92E-08	0.03	99.6
91	HPI-MOV-FT-1115E	Motor-operated valve failure	1.69E-08	0.02	99.6
92	HPI-MOV-FT-1115D	Motor-operated valve failure	1.69E-08	0.02	99.6
93	HPI-MOV-FT-1115C	Motor-operated valve failure	1.69E-08	0.02	99.7
94	LPR-MOV-FT-1890B	Motor-operated valve failure	1.35E-08	0.02	99.7
95	UNIT2-LOW-POWER	UNIT-2 event	1.29E-08	0.02	99.7
96	ACP-BAC-ST-4KV1H	AC bus failure	1.18E-08	0.02	99.7
97	HPI-MOV-FT-1867D	Motor-operated valve failure	1.07E-08	0.01	99.7
98	PPS-SOV-FT-1456	Solenoid-operated valve failure	1.07E-08	0.01	99.7
99	PPS-SOV-FT-1455C	Solenoid-operated valve failure	1.07E-08	0.01	99.8
100	ACP-BAC-ST-1H1	AC bus failure	1.06E-08	0.01	99.8
101	CON-VFC-RP-COREM	Containment event	1.01E-08	0.01	99.8

Table 2.9 Risk Reduction Prioritization of the Potentially Maintainable Basic Events (Continued)

Rank	Event	Event Description	Risk Reduction (yr^{-1})	% Risk Reduction	Cumulative % Contribution
102	LPI-MDP-FR-B21HR	Motor-driven pump failure	8.32E-09	0.01	99.8
103	LPI-MDP-FR-A21HR	Motor-driven pump failure	8.32E-09	0.01	99.8
104	MSS-CKV-FT-SGDHR	Check valve failure	8.12E-09	0.01	99.8
105	CPC-STR-PG-24H	Strainer plugged	7.58E-09	0.01	99.8
106	SWS-CCF-FT-3ABCD	Common-cause failure	7.56E-09	0.01	99.8
107	PPS-MOV-FC-OPER	Motor-operated valve failure	6.52E-09	0.009	99.8
108	ACP-BAC-ST-1H1-2	AC bus failure	6.06E-09	0.008	99.9
109	CPC-MDP-FS-SW10B	Motor-driven pump failure	5.78E-09	0.008	99.9
110	AFW-ACT-FA-PMP3B	Actuator failure	5.51E-09	0.007	99.9
111	AFW-ACT-FA-PMP3A	Actuator failure	5.51E-09	0.007	99.9
112	OEP-DGN-FC-DG3U2	Diesel failure	5.42E-09	0.007	99.9
113	CPC-MDP-FR-SWA3H	Motor-driven pump failure	4.80E-09	0.006	99.9
114	LPI-MDP-FR-B24HR	Motor-driven pump failure	4.75E-09	0.006	99.90
115	LPI-MDP-FR-A24HR	Motor-driven pump failure	4.75E-09	0.006	99.91
116	BETA-SRV	Beta for safety relief valves	4.71E-09	0.006	99.91
117	PPS-SOV-FT	Solenoid-operated valve failure	4.71E-09	0.006	99.92
118	LPI-CKV-OO-CV58	Check valve failure	4.50E-09	0.006	99.93
119	LPI-CKV-OO-CV50	Check valve failure	4.50E-09	0.006	99.93
120	RMT-ACT-FA-RMTSB	Actuator failure	4.37E-09	0.006	99.94
121	RMT-ACT-FA-RMTSA	Actuator failure	4.37E-09	0.006	99.94
122	ACP-TFM-NO-1H1	Transformer failure	4.25E-09	0.006	99.95
123	CPC-MDP-FR-SWA24	Motor-driven pump failure	3.97E-09	0.005	99.95
124	DCP-BDC-ST-BUS1B	DC bus failure	3.52E-09	0.005	99.96
125	DCP-BDC-ST-BUS1A	DC bus failure	3.52E-09	0.005	99.96
126	AFW-TNK-VF-CST	Insufficient water in tank	2.76E-09	0.004	99.97
127	HPI-MOV-PG-1350	Motor-operated valve failure	2.69E-09	0.004	99.97
128	HPI-MOV-FT-1867C	Motor-operated valve failure	2.23E-09	0.003	99.97
129	CPC-CKV-OO-CV113	Check valve failure	2.17E-09	0.003	99.98
130	CPC-MDP-FR-CCA24	Motor-driven pump failure	2.06E-09	0.003	99.98
131	CVC-MDP-FR-2A1HR	Motor-driven pump failure	2.02E-09	0.003	99.98
132	AFW-MDP-FR-3B6HR	Motor-driven pump failure	1.65E-09	0.002	99.98
133	AFW-MDP-FR-3A6HR	Motor-driven pump failure	1.65E-09	0.002	99.99
134	CPC-STR-PG-6HR	Strainer plugged	1.61E-09	0.002	99.99
135	HPI-MDP-FR-1A6HR	Motor-driven pump failure	1.60E-09	0.002	99.99
136	CPC-MDP-FS-CC2B	Motor-driven pump failure	1.24E-09	0.002	99.99
137	ACP-BAC-ST-4KV1J	AC bus failure	1.18E-09	0.002	99.99
138	BETA-HPI	Beta for motor-driven pumps	7.69E-10	0.001	99.99
139	HPI-MDP-FS	Motor-driven pump failure	7.69E-10	0.001	100.00
140	CPC-STR-PG-2A3HR	Strainer plugged	7.20E-10	0.001	100.00
141	CPC-MDP-FR-SWB24	Motor-driven pump failure	5.78E-10	0.001	100.00
142	AFW-CKV-FT-CV157	Check valve failure	5.40E-10	0.001	100.00
143	AFW-CKV-FT-CV172	Check valve failure	5.40E-10	0.001	100.00
144	CPC-STR-PG-1HR	Strainer plugged	5.31E-10	0.001	100.00
145	AFW-XVM-PG-XV183	Manual valve failure	2.16E-10	0.000	100.00
146	AFW-XVM-PG-XV168	Manual valve failure	2.16E-10	0.000	100.00

2.11 Comparison of Risk Reduction and Minimal Cutset Prioritizations

Table 2.10 presents a detailed comparison of risk reduction prioritizations and minimal cutset prioritizations using the plant-specific PRA. The table can be used to gain a more detailed perspective on the level at which a given contributor enters under the different prioritizations. As previously indicated, the relative levels at which different contributors enter are similar for the two prioritizations with a given contributor generally entering at a lower level for the minimal cutset prioritization.

Table 2.10 Comparison of the Risk Reduction and Minimal Cutset Prioritizations

Rank Based on Risk Reduction	Event Code	Cumulative % Contribution (Risk Reduction)	Cutset % at which Event Enters
1	OEP-DGN-FS-DGO1	11.0	8.0
2	RCP-LOCA-750-90M	18.0	3.5
3	OEP-DGN-FS	24.5	3.5
4	OEP-DGN-FS-DGO2	30.4	8.0
5	OEP-DGN-FS-DGO3	36.2	9.9
6	OEP-DGN-FR-6HDG1	41.7	26.2
7	QS-SBO	45.7	17.8
8	BETA-2MOV	49.4	16.4
9	BETA-3DG	52.9	3.5
10	OEP-DGN-FR-6HDG3	56.0	27.3
11	SBO-PORV-DMD	59.1	54.1
12	BETA-2DG	62.1	13.5
13	OEP-DGN-FR-6HDG2	64.9	28.3
14	R	66.9	6.1
15	K	68.9	6.1
16	MCW-CCF-VF-SBO	70.8	64.9
17	MSS-SRV-OO-ODSRV	72.5	11.7
18	HPI-MOV-FT	74.1	33.9
19	PPS-SOV-OO-1455C	75.7	54.5
20	PPS-SOV-OO-1456	77.3	54.1
21	OEP-CRB-FT-15H3	78.7	65.4
22	RCP-LOCA-467-150	80.0	45.4
23	AFW-PSF-FC-XCONN	81.2	25.2
24	LPR-MOV-FT-1862A	82.2	16.4
25	SGTR-SGSRV-ODMD1	83.1	11.7
26	LPI-MDP-FS	84.0	19.2
27	BETA-LPI	84.9	19.2
28	AFW-TDP-FR-2P6HR	85.8	74.8
29	LPI-MOV-PG-1890C	86.7	20.5
30	AFW-TDP-FS-FW2	87.6	72.3
31	AFW-CCF-LK-STMBD	88.3	39.2
32	SGTR-SGSRV-ODMD2	89.1	15.0
33	OEP-CRB-FT-15J3	89.9	65.9
34	LPR-MOV-FT-1860A	90.5	34.7
35	RMT-CCF-FA-MSCAL	91.1	33.1
36	PPS-MOV-FC-1536	91.7	38.5
37	PPS-MOV-FC-1535	92.2	38.5
38	LPR-MOV-FT-1890A	92.8	35.5
39	PPS-MOV-FT-1535	93.3	38.5
40	ACC-MOV-PG-1865C	93.7	30.3
41	ACC-MOV-PG-1865B	94.2	31.3
42	MSS-SOV-OO-ODADV	94.5	44.0
43	SGTR-SGADV-ODMD	94.8	44.0
44	HPI-CKV-FT-CV225	95.1	62.0

Table 2.10 Comparison of the Risk Reduction and Minimal Cutset Prioritizations (Continued)

Rank Based on Risk Reduction	Event Code	Cumulative % Contribution (Risk Reduction)	Cutset % at which Event Enters
45	HPI-CKV-FT-CV410	95.4	62.3
46	HPI-CKV-FT-CV25	95.7	61.7
47	HPI-MOV-FT-1350	95.9	46.6
48	AFW-MDP-FS	96.2	70.4
49	BETA-AFW	96.4	70.4
50	PPS-MOV-FT-1536	96.6	71.8
51	AFW-TDP-FR-2P24H	96.8	70.4
52	RCS-PORV-ODMD	96.9	83.5
53	LPR-MOV-FT-1862B	97.1	82.7
54	OEP-DGN-FR-DG01	97.2	89.6
55	AFW-MDP-FS-FW3A	97.4	80.1
56	AFW-MDP-FS-FW3B	97.5	80.0
57	HPI-XVM-PG-XV24	97.6	77.7
58	LPR-CCF-PG-SUMP	97.7	74.5
59	LPI-MDP-FS-SI1B	97.8	87.8
60	LPI-MDP-FS-SI1A	97.9	87.8
61	RCP-LOCA-1440-90	98.0	88.5
62	LPR-MOV-FT-1860B	98.1	87.9
63	AFW-CKV-OO-CV142	98.1	83.3
64	PPS-MOV-OO-1536	98.2	83.5
65	PPS-MOV-OO-1535	98.3	83.6
66	RCP-LOCA-183-210	98.4	89.6
67	RCP-LOCA-183-150	98.5	89.6
68	RWT-TNK-LF-RWST	98.5	79.7
69	OEP-DGN-FR-DG02	98.6	89.8
70	AFW-CKV-OO-CV172	98.7	88.3
71	OEP-DGN-FR-DGO3	98.7	89.7
72	ACC-CKV-FT-CV145	98.8	74.6
73	ACC-CKV-FT-CV128	98.9	74.3
74	ACC-CKV-FT-CV130	98.9	74.0
75	ACC-CKV-FT-CV147	99.0	74.2
76	RCP-LOCA-183-90	99.1	90.8
77	PPS-MOV-FT	99.1	85.2
78	IAS-CCF-LF-INAIR	99.2	88.5
79	AFW-TDP-FR-6HRU2	99.2	95.9
80	BETA-STR	99.3	84.3
81	RCP-LOCA-561-150	99.3	93.2
82	SIS-ACT-FA-SISA	99.3	91.3
83	SIS-ACT-FA-SISB	99.4	91.3
84	AFW-CKV-OO-CV157	99.4	88.3
85	OEP-CRB-FT-25H3	99.5	95.8
86	CPC-STR-PG-3HR	99.5	84.3
87	HPI-CKV-OO-CV258	99.5	85.3
88	AFW-TDP-FS-U2FW2	99.5	98.0
89	HPI-MDP-FR-1A24H	99.6	85.3
90	HPI-MOV-FT-1115B	99.6	92.2
91	HPI-MOV-FT-1115E	99.6	92.0
92	HPI-MOV-FT-1115D	99.6	92.2
93	HPI-MOV-FT-1115C	99.7	92.0
94	LPR-MOV-FT-1890B	99.7	92.0
95	UNIT2-LOW-POWER	99.7	97.9
96	ACP-BAC-ST-4KV1H	99.7	94.2
97	HPI-MOV-FT-1867D	99.7	96.2
98	PPS-SOV-FT-1456	99.7	95.0
99	PPS-SOV-FT-1455C	99.8	95.0

Table 2.10 Comparison of the Risk Reduction and Minimal Cutset Prioritizations (Continued)

Rank Based on Risk Reduction	Event Code	Cumulative % Contribution (Risk Reduction)	Cutset % at which Event Enters
100	ACP-BAC-ST-1H1	99.8	94.2
101	CON-VFC-RP-COREM	99.8	96.8
102	LPI-MDP-FR-B21HR	99.8	96.5
103	LPI-MDP-FR-A21HR	99.8	96.5
104	MSS-CKV-FT-SGDHR	99.8	92.3
105	CPC-STR-PG-24H	99.8	93.1
106	SWS-CCF-FT-3ABCD	99.8	96.8
107	PPS-MOV-FC-OPER	99.8	97.9
108	ACP-BAC-ST-1H1-2	99.9	94.2
109	CPC-MDP-FS-SW10B	99.9	95.9
110	AFW-ACT-FA-PMP3B	99.9	96.5
111	AFW-ACT-FA-PMP3A	99.9	96.5
112	OEP-DGN-FC-DG3U2	99.9	97.3
113	CPC-MDP-FR-SWA3H	99.9	95.9
114	LPI-MDP-FR-B24HR	99.90	97.8
115	LPI-MDP-FR-A24HR	99.91	97.8
116	BETA-SRV	99.91	95.2
117	PPS-SOV-FT	99.92	95.2
118	LPI-CKV-OO-CV58	99.93	96.8
119	LPI-CKV-OO-CV50	99.93	96.8
120	RMT-ACT-FA-RMTSB	99.94	97.2
121	RMT-ACT-FA-RMTSA	99.94	97.2
122	ACP-TFM-NO-1H1	99.95	97.1
123	CPC-MDP-FR-SWA24	99.95	97.5
124	DCP-BDC-ST-BUS1B	99.96	97.4
125	DCP-BDC-ST-BUS1A	99.96	97.4
126	AFW-TNK-VF-CST	99.97	97.3
127	HPI-MOV-PG-1350	99.97	97.1
128	HPI-MOV-FT-1867C	99.97	98.5
129	CPC-CKV-OO-CV113	99.98	97.5
130	CPC-MDP-FR-CCA24	99.98	98.7
131	CVC-MDP-FR-2A1HR	99.98	97.6
132	AFW-MDP-FR-3B6HR	99.98	99.0
133	AFW-MDP-FR-3A6HR	99.99	99.0
134	CPC-STR-PG-6HR	99.99	99.0
135	HPI-MDP-FR-1A6HR	99.99	98.1
136	CPC-MDP-FS-CC2B	99.99	98.7

2.12 Detailed Risk Increase Prioritizations

Table 2.11 presents the detailed increase prioritizations for the basic events in the plant-specific PRA. The risk increase is the increase in the core damage frequency when the event is assumed to occur.

Table 2.11 Risk Increase Prioritization of the Basic Events

Rank	Event	Event Description	Risk Increase
1	K	Failure to scram	2.52E-02
2	RWT-TNK-LF-RWST	Insufficient water in tank	1.95E-02
3	AFW-PSF-FC-XCONN	UNIT-2 event	5.83E-03
4	AFW-CCF-LK-STMBD	Common-cause failure	5.82E-03
5	AFW-TNK-VF-CST	Insufficient water in tank	2.76E-03
6	HPI-CKV-FT-CV225	Check valve failure	2.10E-03
7	HPI-CKV-FT-CV410	Check valve failure	2.06E-03
8	HPI-CKV-FT-CV25	Check valve failure	2.06E-03
9	HPI-XVM-PG-XV24	Manual valve failure	2.06E-03
10	LPR-CCF-PG-SUMP	Common-cause failure	1.55E-03
11	LPI-MOV-PG-1890C	Motor-operated valve failure	1.50E-03
12	RMT-CCF-FA-MSCAL	Common-cause failure	1.50E-03
13	IAS-CCF-LF-INAIR	Common-cause failure	1.38E-03
14	ACC-CKV-FT-CV145	Check valve failure	5.00E-04
15	ACC-CKV-FT-CV130	Check valve failure	5.00E-04
16	ACC-MOV-PG-1865B	Motor-operated valve failure	5.00E-04
17	ACC-CKV-FT-CV147	Check valve failure	5.00E-04
18	ACC-MOV-PG-1865C	Motor-operated valve failure	5.00E-04
19	ACC-CKV-FT-CV128	Check valve failure	5.00E-04
20	HPI-MOV-FT	Motor-operated valve failure	3.98E-04
21	OEP-DGN-FS-DGO1	Diesel failure	3.65E-04
22	OEP-CRB-FT-15H3	Circuit breaker failure	3.54E-04
23	OEP-DGN-FR-6HDG1	Diesel failure	3.36E-04
24	CPC-STR-PG-3HR	Strainer plugged	2.63E-04
25	LPI-MDP-FS	Motor-driven pump failure	2.24E-04
26	OEP-DGN-FS	Diesel failure	2.17E-04
27	OEP-DGN-FS-DGO2	Diesel failure	1.95E-04
28	OEP-DGN-FS-DGO3	Diesel failure	1.95E-04
29	OEP-DGN-FR-6HDG3	Diesel failure	1.91E-04
30	OEP-CRB-FT-15J3	Circuit breaker failure	1.88E-04
31	OEP-DGN-FR-6HDG2	Diesel failure	1.72E-04
32	LPR-MOV-FT-1860A	Motor-operated valve failure	1.52E-04
33	LPR-MOV-FT-1862A	Motor-operated valve failure	1.52E-04
34	BETA-3DG	Beta for 3 diesels	1.45E-04
35	LPR-MOV-FT-1890A	Motor-operated valve failure	1.36E-04
36	ACP-BAC-ST-4KV1H	AC bus failure	1.31E-04
37	ACP-BAC-ST-1H1	AC bus failure	1.18E-04
38	ACP-TFM-NO-1H1	Transformer failure	1.06E-04

Table 2.11 Risk Increase Prioritization of the Basic Events (Continued)

Rank	Event	Event Description	Risk Increase
39	HPI-MOV-PG-1350	Motor-operated valve failure	6.73E-05
40	ACP-BAC-ST-1H1-2	AC bus failure	6.73E-05
41	CVC-MDP-FR-2A1HR	Motor-driven pump failure	6.73E-05
42	HPI-MOV-FT-1350	Motor-operated valve failure	6.71E-05
43	AFW-CKV-OO-CV142	Check valve failure	6.09E-05
44	AFW-TDP-FS-FW2	Turbine-driven pump failure	5.77E-05
45	BETA-2DG	Beta for 2 diesels	5.69E-05
46	OEP-DGN-FR-DG01	Diesel failure	5.10E-05
47	AFW-CKV-OO-CV172	Check valve failure	5.09E-05
48	DCP-BDC-ST-BUS1A	DC bus failure	3.91E-05
49	DCP-BDC-ST-BUS1B	DC bus failure	3.91E-05
50	PPS-SOV-OO-1456	Solenoid-operated valve failure	3.87E-05
51	PPS-SOV-OO-1455C	Solenoid-operated valve failure	3.87E-05
52	BETA-2MOV	Beta for 2 motor-operated valves	2.82E-05
53	AFW-MDP-FS	Motor-driven pump failure	2.74E-05
54	OEP-DGN-FR-DG02	Diesel failure	2.56E-05
55	AFW-CKV-OO-CV157	Check valve failure	2.55E-05
56	OEP-DGN-FR-DGO3	Diesel failure	2.53E-05
57	LPI-MDP-FS-SI1A	Motor-driven pump failure	2.46E-05
58	LPI-MDP-FS-SI1B	Motor-driven pump failure	2.46E-05
59	HPI-CKV-OO-CV258	Check valve failure	2.24E-05
60	MCW-CCF-VF-SBO	Common-cause failure	2.16E-05
61	AFW-TDP-FR-2P6HR	Turbine-driven pump failure	2.13E-05
62	LPR-MOV-FT-1862B	Motor-operated valve failure	2.08E-05
63	LPR-MOV-FT-1860B	Motor-operated valve failure	2.07E-05
64	SIS-ACT-FA-SISB	Actuator failure	1.79E-05
65	SIS-ACT-FA-SISA	Actuator failure	1.79E-05
66	CPC-STR-PG-1HR	Strainer plugged	1.77E-05
67	AFW-MDP-FS-FW3A	Motor-driven pump failure	1.58E-05
68	AFW-MDP-FS-FW3B	Motor-driven pump failure	1.57E-05
69	RCP-LOCA-1440-90	Seal failure	1.48E-05
70	HPI-MDP-FR-1A24H	Motor-driven pump failure	1.35E-05
71	LPI-MDP-FR-B21HR	Motor-driven pump failure	1.32E-05
72	LPI-MDP-FR-A21HR	Motor-driven pump failure	1.32E-05
73	ACP-BAC-ST-4KV1J	AC bus failure	1.31E-05
74	SWS-CCF-FT-3ABCD	Common-cause failure	1.20E-05
75	PPS-SOV-FT-1455C	Solenoid-operated valve failure	1.07E-05
76	PPS-SOV-FT-1456	Solenoid-operated valve failure	1.07E-05
77	CPC-STR-PG-24H	Strainer plugged	1.05E-05
78	CPC-MDP-FR-SWA3H	Motor-driven pump failure	1.00E-05
79	PPS-MOV-FT-1535	Motor-operated valve failure	9.30E-06
80	AFW-MDP-FR-3A6HR	Motor-driven pump failure	9.18E-06
81	AFW-MDP-FR-3B6HR	Motor-driven pump failure	9.18E-06
82	AFW-ACT-FA-PMP3B	Actuator failure	9.17E-06
83	AFW-ACT-FA-PMP3A	Actuator failure	9.17E-06

Table 2.11 Risk Increase Prioritization of the Basic Events (Continued)

Rank	Event	Event Description	Risk Increase
84	CPC-STR-PG-6HR	Strainer plugged	8.95E-06
85	QS-SBO	Station blackout event	8.21E-06
86	OEP-CRB-FT-25H3	Circuit breaker failure	8.19E-06
87	RCP-LOCA-561-150	Seal failure	8.14E-06
88	CPC-STR-PG-2A3HR	Strainer plugged	8.00E-06
89	R	Failure to scram	7.37E-06
90	RCP-LOCA-467-150	Seal failure	6.70E-06
91	LPI-MDP-FR-B24HR	Motor-driven pump failure	6.60E-06
92	LPI-MDP-FR-A24HR	Motor-driven pump failure	6.60E-06
93	HPI-MOV-FT-1115B	Motor-operated valve failure	6.37E-06
94	HPI-MOV-FT-1115E	Motor-operated valve failure	5.63E-06
95	HPI-MOV-FT-1115D	Motor-operated valve failure	5.63E-06
96	HPI-MOV-FT-1115C	Motor-operated valve failure	5.63E-06
97	AFW-CKV-FT-CV157	Check valve failure	5.40E-06
98	AFW-CKV-FT-CV172	Check valve failure	5.40E-06
99	AFW-XVM-PG-XV168	Manual valve failure	5.40E-06
100	AFW-XVM-PG-XV183	Manual valve failure	5.40E-06
101	PPS-SOV-FT	Solenoid-operated valve failure	4.71E-06
102	RCP-LOCA-750-90M	Seal failure	4.61E-06
103	LPI-CKV-OO-CV58	Check valve failure	4.50E-06
104	LPI-CKV-OO-CV50	Check valve failure	4.50E-06
105	LPR-MOV-FT-1890B	Motor-operated valve failure	4.49E-06
106	MSS-CKV-FT-SGDHR	Check valve failure	4.05E-06
107	HPI-MDP-FR-1A6HR	Motor-driven pump failure	4.00E-06
108	BETA-LPI	Beta for motor-driven pumps	3.83E-06
109	HPI-MOV-FT-1867D	Motor-operated valve failure	3.57E-06
110	RCP-LOCA-183-90	Seal failure	3.49E-06
111	RCP-LOCA-183-150	Seal failure	3.49E-06
112	RCP-LOCA-183-210	Seal failure	3.49E-06
113	PPS-MOV-FT-1536	Motor-operated valve failure	3.48E-06
114	SGTR-SGSRV-ODMD2	Steam generator failure	3.26E-06
115	BETA-AFW	Beta for motor-driven pumps	2.92E-06
116	CPC-MDP-FR-CCA24	Motor-driven pump failure	2.86E-06
117	SBO-PORV-DMD	Station blackout event	2.77E-06
118	RMT-ACT-FA-RMTSA	Actuator failure	2.73E-06
119	RMT-ACT-FA-RMTSB	Actuator failure	2.73E-06
120	PPS-MOV-FC-OPER	Motor-operated valve failure	2.41E-06
121	CPC-CKV-OO-CV113	Check valve failure	2.17E-06
122	AFW-TDP-FS-U2FW2	Turbine-driven pump failure	1.96E-06
123	PPS-MOV-OO-1536	Motor-operated valve failure	1.39E-06
124	PPS-MOV-OO-1535	Motor-operated valve failure	1.39E-06
125	AFW-TDP-FR-6HRU2	Turbine-driven pump failure	1.16E-06
126	CPC-MDP-FR-SWA24	Motor-driven pump failure	1.04E-06
127	PPS-MOV-FT	Motor-operated valve failure	1.01E-06
128	PPS-MOV-FC-1536	Motor-operated valve failure	1.01E-06

Table 2.11 Risk Increase Prioritization of the Basic Events (Continued)

Rank	Event	Event Description	Risk Increase
129	PPS-MOV-FC-1535	Motor-operated valve failure	9.93E-07
130	AFW-TDP-FR-2P24H	Turbine-driven pump failure	9.21E-07
131	HPI-MOV-FT-1867C	Motor-operated valve failure	7.42E-07
132	CPC-MDP-FS-SW10B	Motor-driven pump failure	7.16E-07
133	CON-VFC-RP-COREM	Containment event	4.93E-07
134	CPC-MDP-FS-CC2B	Motor-driven pump failure	4.11E-07
135	HPI-MDP-FS	Motor-driven pump failure	1.91E-07
136	OEP-DGN-FC-DG3U2	Diesel failure	1.54E-07
137	CPC-MDP-FR-SWB24	Motor-driven pump failure	1.52E-07
138	RCS-PORV-ODMD	Steam generator event	1.22E-07
139	BETA-STR	Beta for strainers	9.36E-08
140	BETA-SRV	Beta for safety relief valves	6.26E-08
141	UNIT2-LOW-POWER	UNIT-2 event	2.40E-08
142	BETA-HPI	Beta for motor-driven pumps	2.89E-09
143	SGTR-SGADV-ODMD	Steam generator failure	ε
144	SGTR-SGSRV-ODMD1	Steam generator failure	ε
145	MSS-SRV-OO-ODSRV	Safety relief valve failure	ε
146	MSS-SOV-OO-ODADV	Solenoid-operated valve failure	ε

3. QUANTIFYING MAINTENANCE EFFECTS ON UNAVAILABILITY AND RISK USING MARKOV MODELING

A Markov approach is presented for quantifying the effects of maintenance on unavailability and risk. The maintenance particularly modeled is preventative maintenance according to the EPRI definition on page 1-1. Markov modeling is standard, however what is new is the new applications that are presented, including the relations which are developed for the required transition rates to allow practical implementations of the model. Maintenance effects are quantified by defining a degraded state for the component in addition to an operational state and a failed state. The Markov maintenance model which is developed is a natural extension of the standard models used in Probabilistic Risk Assessments (PRAs) and simplifies to the PRA models when the degraded state is not differentiated from the operational state. Identification of a degraded state allows the benefits of maintenance to be explicitly evaluated and allows optimal maintenance intervals to be determined. The component unavailabilities which are determined can be subsequently used in a PRA to evaluate the risk effectiveness of maintenance. Applications of the model are demonstrated. The demonstrations indicate that maintenance effects on component unavailability can be significant in certain situations.

Standard reliability approaches and standard probabilistic risk assessments (PRAs) assume two states for each component, a success state and a failed state. Because of these assumptions, only the negative aspects of maintenance can be explicitly quantified, which include the effects of maintenance downtime and possible maintenance related errors. The benefits of maintenance cannot be explicitly quantified since a principle benefit of maintenance is to prevent and correct degradations before failure occurs. Degraded component conditions are not considered in standard reliability and PRA modeling, and hence the benefit of maintenance in correcting degraded conditions is not explicitly considered. A straightforward approach for considering component degraded conditions is to utilize Markov models. The objective of this chapter is to show how Markov modeling can be used to quantify maintenance effectiveness on component unavailability which explicitly quantifies both the positive and negative effects of maintenance. Markov models incorporating maintenance effects have been reported in literature (refs. 5, 6, 7, 8, and 9). What is new in this work is the new application approaches which are developed including relationships which are developed for the transition rates which allow the rates to be determined from engineering data and engineering knowledge. This work is an extension of the work reported in Reference 10.

The presented Markov maintenance model can be directly used to identify optimal maintenance intervals from a component reliability and performance standpoint using plant maintenance data. The Markov model can also be applied to component pieceparts to optimize maintenances at the piecepart level. The Markov maintenance model can thus be a potentially powerful tool for monitoring maintenance effectiveness, for supplementing reliability centered maintenance applications, and for carrying out predictive maintenance functions. The component unavailabilities which are obtained from the Markov maintenance model can furthermore be input into PRAs to explicitly evaluate the risk effectiveness of maintenance.

3.1 The Four State Markov Maintenance Model

To explicitly evaluate the benefit of maintenance in correcting degradations, at least one degraded state needs to be considered for the component (or component piecepart). The simplest Markov model is to thus consider one degraded state for the component in addition to the operational state and the failed state. When in the degraded state, the component will still be functional but will be in a degraded mode. The degraded state of a component occurs when the component's performance degrades below some threshold value defining normal designed performance. A standard PRA lumps the degraded state with the operational state. To quantify maintenance effectiveness the degraded state needs to be separated.

The operating, degraded, and failed states partition the range of performance of the component and can be defined in various ways which are consistent with available information. The states can be defined based on explicit performance criteria such as pump flow rates or diesel load times. Alternatively, the states can be defined based on the type of maintenance required and its urgency. The Nuclear Plant Reliability Data System (NPRDS) (ref. 11) defines component degraded states based on a combination of performance considerations and maintenance considerations.

In addition to the normal operational state, the degraded state, and the functionally failed state, we will also define a maintenance down state for the component. The maintenance down state exists when the component is down for maintenance and measures a negative aspect of maintenance. We will further assume the component is a standby component and is periodically tested. We will assume that any test downtime required for testing is negligible. We include in the failed state definition the component being in an undetected failed state or being in a repair state when the failure has been detected. We could define a separate repair state and test state for the component if we wanted to separate out these contributions. We could also define more than one degraded state if we wanted to track the progression of degradations. The definition of an operational state, one degraded state, a maintenance state, and a failed state is, however, sufficient to quantify maintenance effectiveness.

We thus have a total of four states for the component which we denote by o, d, m, and f:

o: the component operational state reflecting normal designed performance (3.1)

d: the component degraded state reflecting degraded, but functional performance (3.2)

m: the component maintenance state in which the component is down for maintenance (3.3)

and

f: the component failed state in which the component is functionally failed. (3.4)

If a component piecepart instead of a component is the focus of maintenance then the above state definitions apply to the specific piecepart.

Given the four performance states (o, d, m, f) we need to define the transition rates between states. The relevant transition rates are shown in the transition matrix below:

	o	d	m	f
o	-	λ_{od}	λ_{om}	λ_{of}
d	-	-	λ_{dm}	λ_{df}
m	λ_{mo}	λ_{md}	-	λ_{mf}
f	λ_{fo}	λ_{fd}	-	-

The initial state consists of the rows of the matrix and the succeeding state consists of the columns of the matrix. The missing values are disallowed transitions and can be treated as having a transition rate value of zero. As is standard, we do not consider one-step transitions from one state to the same state since they do not constitute state changes. We do not consider a transition from a degraded state directly to an operating state (d→o) since a maintenance state must first exist. We also do not consider a transition from a failed state directly to a maintenance state (f→m) assuming repair has precedence over maintenance. The nonzero transition rates are defined below:

λ_{od} = the transition rate from an operational state to a degraded state, i.e. *the component degradation rate** (3.5)

λ_{om} = the transition rate from an operational state to a maintenance state, i.e. *the maintenance frequency when the component is operational* (3.6)

λ_{of} = the transition rate from an operational state directly to a failed state, i.e. *the catastrophic failure rate* (3.7)

λ_{dm} = the transition rate from a degraded state to a maintenance state, i.e. *the maintenance frequency when the component is degraded* (3.8)

λ_{df} = the transition rate from a degraded state to a failed state, i.e. *the failure rate when the component is degraded* (3.9)

λ_{mo} = the transition rate from a maintenance state to an operational state, i.e. *the maintenance restoration rate* (3.10)

λ_{md} = the transition rate from a maintenance state to a degraded state, i.e. *the maintenance degradation rate* (3.11)

λ_{mf} = the transition rate from a maintenance state to a failed state, i.e. *the maintenance failure rate* (3.12)

λ_{fo} = the transition rate from a failed state to an operational state, i.e. *the failure restoration rate* (3.13)

and

λ_{fd} = the transition rate from a failed state to a degraded state, i.e. *the failure degradation rate.* (3.14)

The definitions in italics express the rates in reliability oriented terminology and assist in their determination from data and test and maintenance procedures. The transition rates are treated as being constant to obtain the steady state maintenance characteristics.

3.2 Performance State Probabilities for the Four State Model

For the four state model, the associated performance state probabilities are:

p_o = the probability that the component is in the operational state (o) at a given time (3.15)

p_d = the probability that the component is in the degraded state (d) at a given time (3.16)

p_m = the probability that the component is in the maintenance state (m) at a given time (3.17)

---

* Note that the degradation rate as defined here is a rate of transition to a degraded state and is not the differential, or rate of decrease, of a performance characteristic.

and

p_f = the probability that the component is in the failed state (f) at a given time. (3.18)

The steady state solutions for p_o, p_d, p_m, p_f give the steady state reliability performance of the component. All reliability characteristics of the component are obtainable from the performance state probabilities, which include:

p_f = *the component unavailability due to failures* (3.19)

p_m = *the component unavailability due to being in maintenance* (3.20)

p_o = *the designed, operational availability* (3.21)

p_d = *the degraded availability* (3.22)

$p_o\lambda_{od}$ = *the observed degradation rate* (3.23)

$p_d\lambda_{df}$ = *the observed failure frequency from degradations* (3.24)

$p_o\lambda_{of}$ = *the observed catastrophic failure frequency* (3.25)

Maintenance effectiveness is obtained from these performance characteristics, and maintenance can be scheduled to optimize one or more of these characteristics.

The time dependent solution for the performance state probabilities for the four state maintenance model is addressed in Reference 10. We focus here on the steady state solutions to give the average measures of maintenance effectiveness. The standard steady state equations for p_o, p_d, p_m, and p_f are (see for example Reference 12 or Reference 13):

$$p_o(\lambda_{od} + \lambda_{om} + \lambda_{of}) = p_m\lambda_{mo} + p_f\lambda_{fo} \quad (3.26)$$

$$p_d(\lambda_{dm} + \lambda_{df}) = p_o\lambda_{od} + p_m\lambda_{md} + p_f\lambda_{fd} \quad (3.27)$$

$$p_m(\lambda_{mo} + \lambda_{md} + \lambda_{mf}) = p_o\lambda_{om} + p_d\lambda_{dm} \quad (3.28)$$

$$p_f(\lambda_{fo} + \lambda_{fd}) = p_o\lambda_{of} + p_d\lambda_{df} + p_m\lambda_{mf}. \quad (3.29)$$

These steady state equations are solved for p_o, p_d, p_m, and p_f using the constraint

$$p_o + p_d + p_m + p_f = 1. \quad (3.30)$$

One solution approach is to solve for the ratios of the performance probabilities and then determine the probabilities from the ratios. This approach worked efficiently for the applications that have been carried out. Assuming p_o is greater than zero, otherwise the component would never be operational, let:

$$r_d = \frac{p_d}{p_o} \quad (3.31)$$

$$r_m = \frac{p_m}{p_o} \quad (3.32)$$

and

$$r_f = \frac{p_f}{p_o} \tag{3.33}$$

Then the steady state equations are solved to yield:

$$r_d = \frac{\frac{\lambda_m}{\lambda_{dm}}\left(\lambda_{od} + \frac{\lambda_{fd}\lambda_o}{\lambda_{fo}} + \frac{\lambda_d\lambda_{om}}{\lambda_{dm}}\right)}{\frac{\lambda_d\lambda_m}{\lambda_{dm}} + \frac{\lambda_{fd}\lambda_{mo}}{\lambda_{fo}} - \lambda_{md}} - \frac{\lambda_{om}}{\lambda_{dm}} \tag{3.34}$$

$$r_m = \frac{\lambda_{od} + \frac{\lambda_{fd}\lambda_o}{\lambda_{fo}} + \frac{\lambda_d\lambda_{om}}{\lambda_{dm}}}{\frac{\lambda_d\lambda_m}{\lambda_{dm}} + \frac{\lambda_{fd}\lambda_{mo}}{\lambda_{fo}} - \lambda_{md}} \tag{3.35}$$

and

$$r_f = \frac{\lambda_o}{\lambda_{fo}} - \frac{\lambda_{mo}}{\lambda_{fo}} \frac{\left(\lambda_{od} + \frac{\lambda_{fd}\lambda_o}{\lambda_{fo}} + \frac{\lambda_d\lambda_{om}}{\lambda_{dm}}\right)}{\left(\frac{\lambda_d\lambda_m}{\lambda_{dm}} + \frac{\lambda_{fd}\lambda_{mo}}{\lambda_{fo}} - \lambda_{md}\right)} \tag{3.36}$$

where

$$\lambda_o = \lambda_{od} + \lambda_{om} + \lambda_{of} \tag{3.37}$$

$$\lambda_d = \lambda_{dm} + \lambda_{df} \tag{3.38}$$

$$\lambda_m = \lambda_{mo} + \lambda_{md} + \lambda_{mf} \tag{3.39}$$

$$\lambda_f = \lambda_{fo} + \lambda_{fd}. \tag{3.40}$$

The state probabilities are subsequently determined from the equations:

$$p_o = \frac{1}{1 + r_d + r_m + r_f} \tag{3.41}$$

$$p_d = \frac{r_d}{1 + r_d + r_m + r_f} \tag{3.42}$$

$$p_m = \frac{r_m}{1 + r_d + r_m + r_f} \tag{3.43}$$

and

$$p_f = \frac{r_f}{1 + r_d + r_m + r_f}. \qquad (3.44)$$

Through algebraic manipulations, other alternative expressions can be obtained for r_d, r_m, and r_f which do not contain specific transition rates in the denominator which allows these transition rates to go to zero.

3.3 Parametric Relationships for the Transition Rates

To determine the performance state probabilities for a given application we need to determine specific values for the transition rates. This is often a problem for application of the Markov modeling approach. When there is sufficient maintenance and failure data, then the transition rates can be directly estimated from the data using appropriate statistical estimation techniques (ref. 14). However, oftentimes detailed data are not available. To make the Markov maintenance model practically applicable, we have found it useful to express the transition rates in terms of basic test and maintenance parameters and component failure rates which are more readily estimated based on PRA data and engineering knowledge. Sensitivity studies can also be more easily carried out in terms of these basic parameters. The relationships which are developed in this section are examples of relationships which are important in making the Markov approach a practical tool for applications.

The Component Catastrophic Failure Rate λ_{of}

Let λ be the component constant failure rate from all causes as standardly defined in PRAs:

$$\lambda \quad = \quad \text{the constant component failure rate.} \qquad (3.45)$$

We have found it useful to relate relevant component transition rates to the constant component failure rate since constant component failure rates are standardly available. Since λ contains both catastrophic failures and failures passing through degradation, the catastrophic failure rate λ_{of} can be expressed as a fraction f_{of} of the component failure rate:

$$\lambda_{of} \quad = \quad f_{of}\lambda \qquad (3.46)$$

where

$$f_{of} \quad = \quad \text{the catastrophic failure fraction.} \qquad (3.47)$$

Note that f_{of} is not the fraction of transitions from o to f, but the fraction of all failures which are catastrophic. Knowing λ, λ_{of} can be determined by determining f_{of}. A small value of f_{of} (e.g. $f_{of} = 0.1$) represents a small fraction of catastrophic failures which do not pass through a degraded state.

The Component Degradation Rate λ_{od}

The component degradation rate λ_{od} can also be related to the component failure rate λ using the expression,

$$\lambda_{od} = r_{od}\lambda \qquad (3.48)$$

where

$$r_{od} \quad = \quad \text{the degradation ratio.} \qquad (3.49)$$

With λ used as a reference, determination of r_{od} such as based on data from NPRDS will thus determine λ_{od}. Since r_{od} is a relative factor, it can be less sensitive to uncertainties. Small values of r_{od} (e.g. $1< r_{od} \leq 3$) represent slow degradation rates while large values (e.g. $r_{od} \geq 10$) represent rapid degradation rates.

The Degraded Failure Rate λ_{df}

We have developed two alternative expressions for the degraded failure rate λ_{df}. Others can also be developed. One expression is obtained by relating λ_{df} to λ:

$$\lambda_{df} = r_{df}\lambda \tag{3.50}$$

where

r_{df} = the failure rate ratio. (3.51)

The failure rate ratio gives the relative increase in the failure rate when the component is degraded. The failure rate ratio r_{df} is thus similar to the degradation ratio r_{od}.

To obtain an alternative expression for the degraded failure rate λ_{df}, consider mean times to occurrences of events. Let

T_{od} = the mean transition time from an operational state to a degraded state (3.52)

T_{df} = the mean transition time from a degraded to failed state (3.53)

and

T_{odf} = the mean transition time from an operational state to a failed state passing through a degraded state. (3.54)

By their definitions

$$T_{odf} = T_{od} + T_{df}. \tag{3.55}$$

The transition rates λ_{od} and λ_{df} are the inverses of the corresponding mean transition times:

$$\lambda_{od} = \frac{1}{T_{od}} \tag{3.56}$$

$$\lambda_{df} = \frac{1}{T_{df}} \tag{3.57}$$

Also define

$$\lambda_{odf} = \frac{1}{T_{odf}}, \tag{3.58}$$

where λ_{odf} is the failure rate through a degraded state.

Now, the total component failure rate λ is the sum of contributions from catastrophic failures and from failures passing through a degraded state. Therefore,

$$\lambda = \lambda_{of} + \lambda_{odf}, \tag{3.59}$$

or in terms of mean transition times

$$\lambda = \frac{1}{T_{of}} + \frac{1}{T_{odf}}. \tag{3.60}$$

Equation (3.59) can be considered as the defining equation for λ in terms of the Markov-related transition rates.

Expressing Equation (3.55) in terms of transition rates

$$\frac{1}{\lambda_{odf}} = \frac{1}{\lambda_{od}} + \frac{1}{\lambda_{df}} \tag{3.61}$$

Now from Equations (3.46) and (3.59) we have

$$\lambda_{odf} = (1 - f_{of})\lambda, \tag{3.62}$$

where f_{of} is again the catastrophic failure fraction.

Finally, substituting Equation (3.62) and Equation (3.48) for λ_{od} into Equation (3.61), we have

$$\frac{1}{(1-f_{of})\lambda} = \frac{1}{r_{od}\lambda} + \frac{1}{\lambda_{df}}, \tag{3.63}$$

which can be solved for λ_{df} giving

$$\lambda_{df} = \lambda \frac{r_{od}(1-f_{of})}{r_{od} - (1-f_{of})}. \tag{3.64}$$

This expression does not contain any additional parameters such as the failure rate ratio r_{df}, however the transition rates are constrained by Equation (3.59).

The Maintenance Completion Rates λ_{mo}, λ_{md}, λ_{mf}

The maintenance completion rates λ_{mo}, λ_{md}, and λ_{mf} may be expressed as:

$$\lambda_{mo} = \frac{p_{mo}}{d_m} \tag{3.65}$$

$$\lambda_{md} = \frac{p_{md}}{d_m} \tag{3.66}$$

and

$$\lambda_{mf} = \frac{p_{mf}}{d_m} \tag{3.67}$$

where

d_m	=	the average maintenance duration	(3.68)
p_{mo}	=	the fraction of maintenances resulting in the component being in an operational state	(3.69)
p_{md}	=	the fraction of maintenances resulting in the component being in a degraded state	(3.70)
p_{mf}	=	the fraction of maintenances resulting in the component being in a failed state	(3.71)

and where

$$p_{mo} + p_{md} + p_{mf} = 1. \tag{3.72}$$

Equations (3.65)-(3.67) are a particular application of the general transition rate relationship,

$$\lambda_{ij} = \frac{p_{ij}}{L_i} \tag{3.73}$$

where λ_{ij} is the transition rate from state i to j, p_{ij} the transition probability, and L_i the average sojourn time in state i (ref. 15). Equations (3.65)-(3.67) are useful since they allow the transition rates to be determined from the maintenance downtime d_m and the maintenance efficiencies p_{mo}, p_{md}, p_{mf}.

The Repair Completion Rates λ_{fo}, λ_{fd}

The repair completion rates λ_{fo} and λ_{fd} may similarly be expressed as

$$\lambda_{fo} = \frac{p_{fo}}{d_f} \tag{3.74}$$

and

$$\lambda_{fd} = \frac{p_{fd}}{d_f} \tag{3.75}$$

where

d_f	=	the average failure duration time	(3.76)
p_{fo}	=	the fraction of failures which are restored to an operational state	(3.77)

and

p_{fd} = the fraction of failures which are partially restored to a degraded state. (3.78)

where

$$p_{fo} + p_{fd} = 1. \tag{3.79}$$

If a failure is most likely to be detected by a surveillance test as opposed to a maintenance then

$$d_f = \frac{1}{2}T + r \quad : \text{negligible failure detection by maintenance} \tag{3.80}$$

where

T = the surveillance test interval (3.81)

and

r = the average repair time. (3.82)

Equation (3.80) is an accurate approximation when the maintenance interval is significantly larger than the surveillance test interval. Equation (3.80) can also be an accurate approximation when maintenances do not carry out operational testing to detect component failures.

When the possibility of failure detection by maintenance is also to be incorporated then the following expression can be used for d_f:

$$d_f = \frac{T}{2}\left(1 - \frac{1}{3}\frac{T}{T_m}\right) + r \tag{3.83}$$

where

T_m = the average time between maintenances, (3.84)

and where T_m is assumed to be larger than T. Equation (3.83) is obtained by assuming a maintenance can be carried out uniformly throughout the test interval with probability proportional to $1/T_m$. Appendix A presents the derivation.

The Maintenance Frequency When Operational λ_{om}

Using the general transition rate relationship, the maintenance frequency λ_{om} when the component is operational can be expressed as

$$\lambda_{om} = \frac{p_{om}}{L_o} \tag{3.85}$$

where

p_{om} = the transition probability from the operational state(o) to the maintenance state(m) (3.86)

and

L_o = the average duration (sojourn) in the operational state before a transition. (3.87)

Consider an operational state existing after a maintenance. The next transition can result in a maintenance state if there is no degradation occurrence and no catastrophic failure occurrence to the next time of maintenance, at an interval T_m. Hence

$$p_{om} = \exp(-\lambda_{ofd} T_m) \quad ; \text{ given an o state after maintenance} \tag{3.88}$$

where

$$\lambda_{ofd} = \lambda_{of} + \lambda_{od} \tag{3.89}$$

The average duration is accordingly

$$L_o = T_m \exp(-\lambda_{ofd} T_m) + \int_0^{T_m} t \exp(-\lambda_{ofd} t) \lambda_{ofd} \, dt \tag{3.90}$$

$$= T_m \exp(-\lambda_{ofd} T_m) + \frac{1}{\lambda_{ofd}} \left(1 - \exp(-\lambda_{ofd} T_m)(1 + \lambda_{odf} T_m)\right). \tag{3.91}$$

When λ_{ofd} T_m<<1 then

$$L_o \cong T_m. \tag{3.92}$$

The derivation of this limiting expression is given in Appendix B. The transition rate λ_{om} is then obtained by substituting Equations (3.88) and (3.91) in Equation (3.85). An additional correction term can be added to p_{om} and L_o to consider a failure occurring after maintenance and being repaired to achieve the operational state before the next maintenance, however this correction term is generally small.

The Maintenance Frequency When Degraded λ_{dm}

The maintenance frequency when the component is degraded λ_{dm} may be expressed as

$$\lambda_{dm} = \frac{p_{dm}}{L_d} \tag{3.93}$$

where

p_{dm} = the transition probability from the degraded state (d) to the maintenance state (m) (3.94)

and

L_d = the average duration in the degraded state before a transition. (3.95)

Again, assume the component is in an operational state after a maintenance. If a degraded state occurs between maintenances then on the average it will occur at one half the interval between maintenances because of the assumption of a constant degradation rate λ_{od}.

Hence,

$$p_{dm} = \exp\left(-\lambda_{df}\frac{T_m}{2}\right) \tag{3.96}$$

and

$$L_d = \left(\frac{T_m}{2}\right)\exp\left(-\lambda_{df}\frac{T_m}{2}\right) + \int_0^{\frac{T_m}{2}} t\exp(-\lambda_{df}t)\lambda_{df}dt \tag{3.97}$$

or

$$L_d = \left(\frac{T_m}{2}\right)\exp\left(-\lambda_{df}\frac{T_m}{2}\right) + \frac{1}{\lambda_{df}}\left(1 - \exp\left(-\lambda_{df}\frac{T_m}{2}\right)\left(1 + \lambda_{df}\frac{T_m}{2}\right)\right). \tag{3.98}$$

When λ_{df} is small such that $\lambda_{df}\,T_m << 1$ then $L_d \cong \frac{T_m}{2}$. Since Equation (3.98) is similar in form to Equation (3.91) the derivation of this limiting expression is similar and is given in Appendix B. An additional correction term can be added to p_{dm} and L_d to account for a degraded state existing immediately after maintenance but this correction term is generally small. Appendix C also presents an alternative method of determining λ_{df} which is consistent with a given failure rate value used in a PRA.

3.4 Applications

As a demonstration of the preceding methodology consider a standby component with the following failure rate, test interval, and repair downtime data which could serve as input data to a PRA:

$$\lambda = 1 \times 10^{-6}\ hr^{-1} \tag{3.99}$$

$$T = 730\ \text{hrs (1 month)} \tag{3.100}$$

$$d = 72\ \text{hrs.} \tag{3.101}$$

Assume however, we want now to explicitly include the effects of maintenance in calculating the component reliability and unavailability characteristics. Using the Markov four state model and parametric expressions for the transition rates including Equation (3.64) and assuming maintenance and repair are effective, we need the following additional data:

f_{of} = the catastrophic failure fraction (3.102)

r_{od} = the degradation ratio (3.103)

T_m = the average interval between maintenances (3.104)

and

$$d_m \quad = \quad \text{the average maintenance duration time} \qquad (3.105)$$

If the values are not known then sensitivity studies can be performed to evaluate ranges of impacts and to evaluate ranges of optimal maintenance intervals.

For our evaluations we will use the following values:

$$f_{of} \quad = \quad 0.1 \qquad (3.106)$$

$$r_{od} \quad = \quad 3 \qquad (3.107)$$

and

$$d_m \quad = \quad 72 \text{ hours.} \qquad (3.108)$$

We will allow the maintenance interval T_m to vary to determine the effectiveness of different maintenance intervals:

$$T_m \quad = \quad \text{variable.} \qquad (3.109)$$

Figure 3.1 illustrates the steady state performance state probabilities which are obtained. Table 3.1 tabulates the corresponding state probabilities depicted in Figure 3.1. Figure 3.1 shows $1-p_o$ instead of p_o for better resolution since p_o is near unity. The term $1-p_o$ may be called the operational unavailability.

Figure 3.1 indicates that component performance can be significantly affected by maintenance and the interval at which the maintenance is carried out. All that is being varied is the maintenance interval; the surveillance test interval, repair and maintenance downtimes, component failure rate, and component degradation characteristics are not changed. As the maintenance interval increases from 1 wk to 8 1/3 yrs, the operational unavailability $1 - p_o$ varies from a high of 3.0E-1 at a 1 week maintenance interval to a low of 2.1E-02 at a 1 year maintenance interval, a factor change of more than 14. As the maintenance interval increases, the degraded unavailability p_d increases by more than a factor of 500 and the maintenance unavailability p_m decreases by more than factor of 300. Also the failed unavailability p_f increases by more than a factor of 3.

Figure 3.2 and Table 3.2 show the component performance state probabilities for a degradation ratio r_{od} of 10; all other data is the same as in Figure 3.1 and Table 3.1. A degradation ratio of 10 represents a faster degradation rate. The performance of the component shows similar behaviors except now the operational unavailability $1 - p_o$ is higher, particularly at larger maintenance intervals. The degraded unavailability p_d is also significantly higher, and the failed probability p_f is also higher at larger maintenance intervals.

To identify the optimal maintenance interval, Figure 3.3 focuses on the operational unavailability $1 - p_o$ versus maintenance interval T_m for a degradation ratio r_{od} of 3. Figure 3.3 identifies the optimal maintenance interval for the component to be approximately 12 months. The optimal interval region is fairly broad, being between approximately 3 months and 24 months for the unavailability to be within a factor of 2 of the optimal value. What is especially important from an operational standpoint is that the maintenance interval not be on the tails of the curve. For too small of a maintenance interval, the operational unavailability is high because of the dominance of the maintenance downtime contribution. For too large of a maintenance interval, the operational unavailability is high because degradations are not being corrected frequently enough. Thus, the Markov maintenance modeling is able to quantify maintenance effectiveness and to identify optimal maintenance guidelines.

Table 3.1 Performance State Probabilities Versus Maintenance Interval for a Degradation Ratio of 3

T_m	p_o	p_d	p_m	p_f
1 wk	7.00E-01	1.76E-04	3.00E-01	3.07E-05
2 wk	8.23E-01	4.15E-04	1.76E-01	3.62E-05
1 mo	9.09E-01	9.96E-04	8.97E-02	4.03E-05
3 mo	9.65E-01	3.17E-03	3.17E-02	4.40E-05
6 mo	9.77E-01	6.42E-03	1.61E-02	4.63E-05
1 yr	9.79E-01	1.29E-02	8.04E-03	5.00E-05
2.5 yrs	9.65E-01	3.17E-02	3.17E-03	6.00E-05
5 yrs	9.37E-01	6.15E-02	1.54E-03	7.55E-05
8.33 yrs	9.01E-01	9.85E-02	8.94E-04	9.47E-05

$\lambda = 1.0E\text{-}06\ hr^{-1}$ T = 730 hrs   d = 72 hrs

$r_{od} = 3$ $f_{of} = 0.1$ $d_m = 72$ hrs

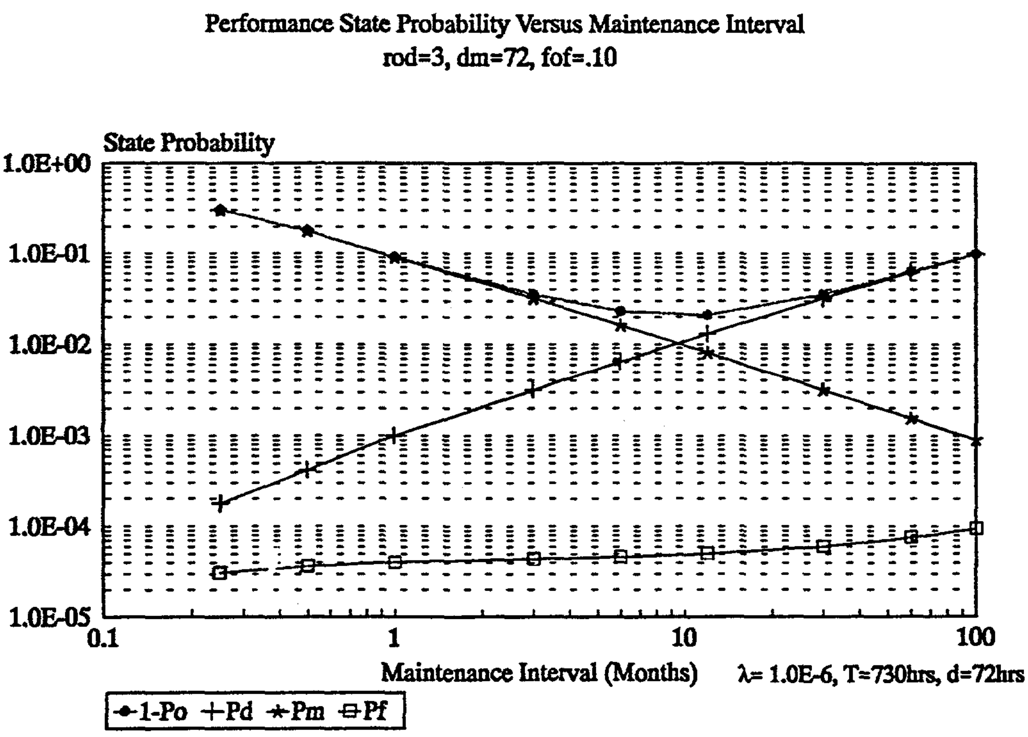


Figure 3.1 Effects of maintenance interval on component performance for a degradation ratio of 3

Table 3.2 Performance State Probabilities Versus Maintenance Interval for a Degradation Ratio of 10

T_m	p_o	p_d	p_m	p_f
1 wk	7.00E-01	5.88E-04	3.00E-01	3.08E-05
2 wk	8.22E-01	1.38E-03	1.76E-01	3.65E-05
1 mo	9.07E-01	3.31E-03	8.95E-02	4.11E-05
3 mo	9.58E-01	1.05E-02	3.15E-02	4.64E-05
6 mo	9.63E-01	2.11E-02	1.58E-02	5.12E-05
1 yr	9.50E-01	4.16E-02	7.83E-03	5.95E-05
2.5 yrs	8.99E-01	9.84E-02	3.01E-03	8.18E-05
5 yrs	8.19E-01	1.79E-01	1.44E-03	1.13E-04
8.33 yrs	7.32E-01	2.67E-01	8.53E-04	1.47E-04
	$\lambda = 1.0E\text{-}06\ hr^{-1}$		$T = 730$ hrs	$d = 72$ hrs
	$r_{od} = 10$		$f_{of} = 0.1$	$d_m = 72$ hrs

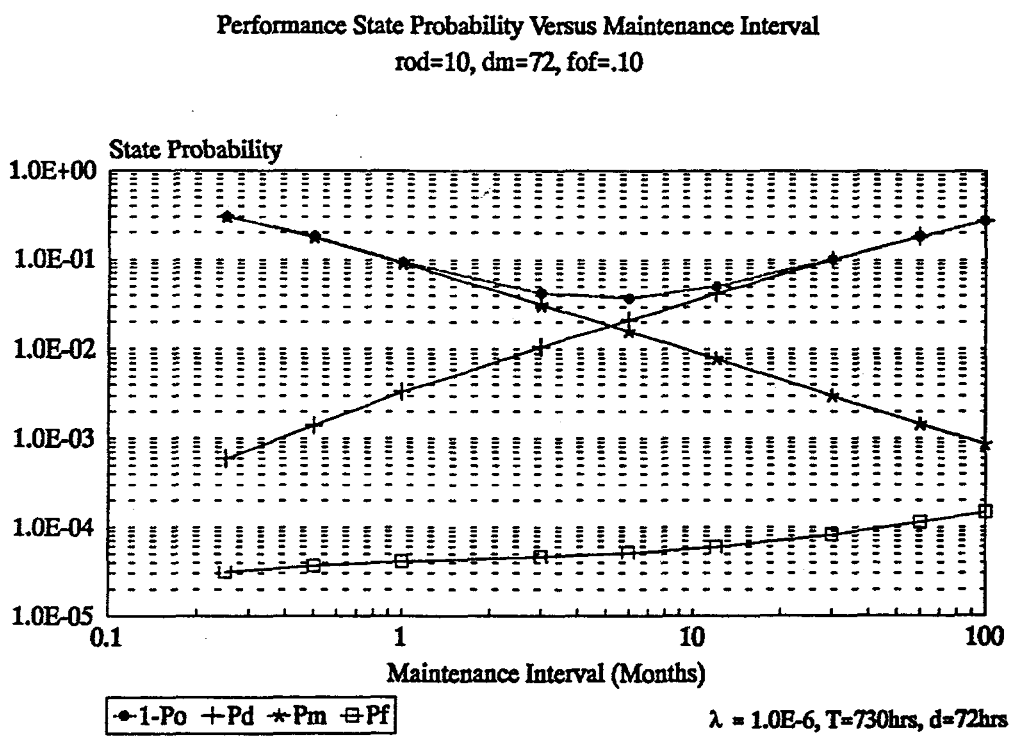


Figure 3.2 Effects of maintenance interval on component performance for a degradation ratio of 10

Operational Unavailability Versus Maintenance Interval
rod=3, dm=72, fof=.10

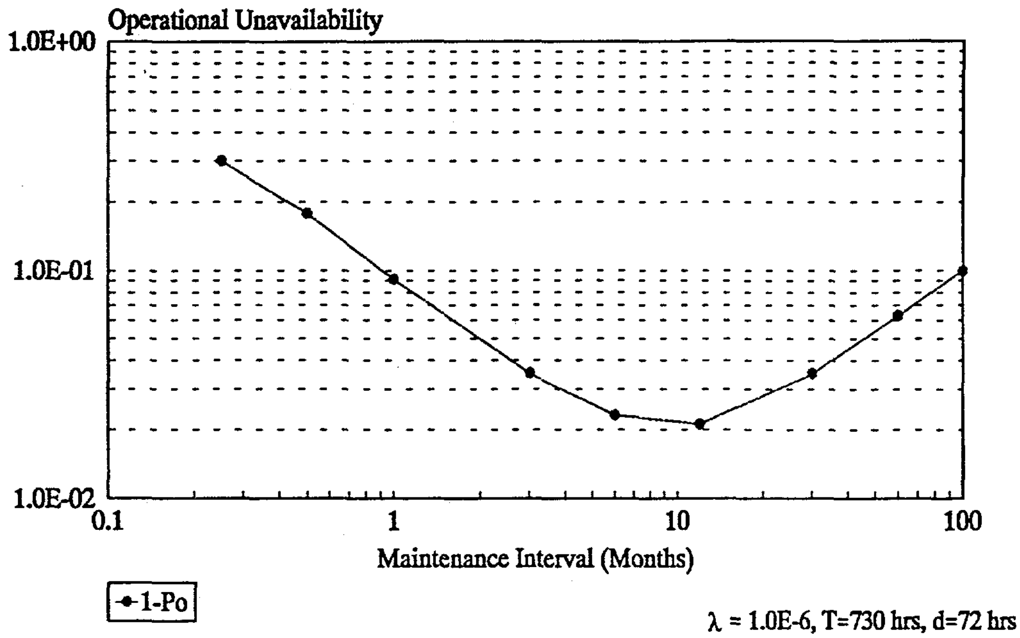


Figure 3.3 Operational unavailability versus maintenance interval for a degradation ratio of 3

4. EVALUATIONS OF COMPONENT UNAVAILABILITY VERSUS MAINTENANCE INTERVAL

The previous chapter presented a methodology for quantifying the unavailability and risk effects of maintenance programs. To illustrate component level applications of this methodology, this chapter presents evaluations of the component unavailability versus maintenance interval for scheduled maintenance actions. The evaluations are carried out for different component degradation rates and failure rates. The values for the degradation rates and failure rates are selected to be representative of various nuclear plant components in different environments. For a particular application, the values for the appropriate degradation rate and failure rate for a component can be obtained from plant maintenance and failure logs using data analysis techniques similar to those now used in PRAs to estimate failure rates. The degradation rates and failure rates in the Nuclear Plant Reliability Data System (NPRDS) could also be used if they are assessed to be applicable for the given application.

4.1 Plots and Tables of Component Unavailability Versus Maintenance Interval

Appendix D shows sixteen (16) plots of the operational unavailability (q_o) and the failed plus maintenance unavailability (q_f+q_m) versus maintenance interval. The operational unavailability (q_o) is the probability of not being in the designed operating state, i.e. being in the degraded state, the maintenance state, or the failed state. The operational unavailability is thus the performance unavailability. The failed plus maintenance unavailability (q_f+q_m) is the functional unavailability used in the PRA. The functional unavailability is thus the probability that the component will not be able to function at all and is what the PRA calls simply the component unavailability.

Each of the 16 plots is for a given component degradation rate (λ_{od}) and a given failure rate from the degraded state (λ_{df}). The rates are in units of per hour. As observed from the calculated unavailabilities in the plots, the values of the degradation rate and degraded failure rate which are used cover behaviors exhibited by active components in nuclear plants, including diesels, motor operated valves, and pumps. For the calculations, all failures are assumed to be preceded by degradation. All plots assume a monthly test interval (730 hours) and a downtime of 72 hours for maintenance or repair. The test interval and downtime are not varied so the variations in component operational and functional unavailability are due only to the maintenance interval. Maintenance and test-caused error probabilities are assumed to be negligible. The associated tables which give the calculated values shown on the plots are given after the plots.

4.2 Observations on the Component Unavailability Evaluations

Observations from the plots are the following:

1. The maintenance interval can have a significant impact on both the operational unavailability and the functional unavailability. In some cases the unavailability varies by two orders of magnitude. These are individual component effects. System and plant effects need to be separately evaluated.

2. The optimal maintenance interval which minimizes operational unavailability is generally smaller than the optimal maintenance interval which minimizes functional unavailability. In extreme cases where the degraded failure rate is very high, which occurs when the component quickly fails after becoming degraded, the optimal functional maintenance interval is basically the same as the optimal operational maintenance interval. This is shown in plots #1 and #10.

3. If the maintenance interval is selected to minimize the functional unavailability then the component can most likely be in a degraded state if called upon. This is shown for example in plot #8. Thus, minimizing functional unavailability can sacrifice performance.

4. The functional unavailability and the optimal functional maintenance interval depends on the surveillance interval. This does not show in the plots since only one test interval is used, however the underlying equations show this dependency. Hence, there is an interaction between maintenance and testing with regard to functional unavailability effects.

5. The maintenance intervals which minimize system unavailability either from an operational or functional standpoint can be different from those which optimize component unavailability. The optimal interval to minimize system unavailability will depend on the scheduling of the maintenances, e.g. not allowing components to be down at the same time for maintenance.

6. Maintenance intervals can also affect the component reliability, e.g. the component failure frequency. We have not carried out these evaluations but the underlying equations show this dependency.

7. Various strategies can be used to optimize maintenance programs. For example, performance can be maximized (i.e. operational unavailability can be minimized) while constraining the functional unavailability to be acceptable and to be below a given value. Alternatively, functional unavailability can be the focus, i.e. functional unavailability can be minimized while constraining the operational unavailability to be acceptable. The exploratory evaluations show large potential benefits in terms of risk reduction and burden reduction.

8. Only the maintenance interval has been varied in the plots. Different types of maintenance and different maintenances on component pieceparts can also be evaluated and can have significant effects.

9. Implications for monitoring maintenance effectiveness are interesting. The effects of maintenance can be significant. Maintenance has significant effects at the component level and thus component level evaluations are useful. By analyzing data on component degradations, maintenance effectiveness can be monitored and maintenance can be optimized using approaches such as these to provide substantial risk and plant benefits.

10. Implications for PRAs are also interesting. PRAs presently do not explicitly model maintenance effects other than the downtime and possible associated errors. It is generally argued that the failure rate data incorporate the effects of maintenance. The effects on the failure rate data, however, are averaged out and are difficult to resolve. The evaluations performed here indicate risk effects can be significant if maintenance is more explicitly evaluated in the PRA and this implies maintenance needs to be more explicitly evaluated.

4.3 Summary and Recommendations

Application of a simple Markov methodology has been presented for quantifying maintenance effectiveness. One degraded state is defined for the component in addition to the designed operating state and the functionally failed state. The equations for the steady state component performance probabilities explicitly incorporate the benefits of maintenance as well as its negative effects. The performance probabilities (e.g. the failed probabilities) with maintenance effects explicitly included can be used in place of the component unavailabilities now used in the PRA. The performance state equations can also be used to determine optimal maintenance intervals for the components. Optimal maintenance intervals can be determined to optimize various performance characteristics, including the operational unavailability, failed probability, or the reliability.

To apply the Markov methodology, transition rates between states are required. This means, first of all, that degraded states need to be defined for maintainable components. Formulations were presented which express the transition rates in terms of parameters which can be more readily estimated from engineering information.

These parameters can also be varied for sensitivity evaluations. Further work is needed in identifying other expressions for specific applications, and in utilizing statistical approaches, including Bayesian approaches, for estimating the transition rates and their uncertainties from plant maintenance log data.

This work assumes that the transition rates are constant, which is a standard assumption for maintenance systems as the references describe. For specific applications, the transition rates can vary with the age of the component. For any application the assumption of constant transition rates needs to be validated. Reference 10 addresses the aging case, but further work is needed to develop specific expressions for age-dependent transition rates.

If the Markov models are to be consistent with the PRA models, then the Markov transition rates need to be calibrated with the PRA data. The expressions which were developed for the transition rates were one step in this direction in that the constant failure rate λ was used as a reference parameter. However, there were constraints assumed in these expressions, particularly in the expression for λ_{df} which was obtained by equating λ to the sum of catastrophic and degradation related transition rates. Appendix C presents another approach for calibrating the degraded failure rate λ_{df} with the total component failure rate λ. Other means of calibrating the Markov models with PRA models need to be investigated.

The Markov models can be used in two ways with the PRA. The component unavailability p_f due to failures and the component unavailability p_m due to maintenance can be used in the PRA as they are now used. The only difference is that the Markov equations are used to calculate p_f and p_m to account explicitly for the effects of maintenance. Optimization of maintenance schedules may then be carried out by varying the maintenance intervals T_m and redetermining p_f and p_m.

Alternatively, the Markov models can be used to transform the PRA from a two state model covering failed and success states to a multi-state model covering failed, degraded, and operational states. Probabilities of safety systems being in various degraded states can be determined to obtain system degraded unavailabilities in order to further resolve and differentiate system and risk performance. Multi-state methodologies have been developed for system models and PRAs (refs. 16, 17, 18), however the importance of evaluating the effects of maintenance and the need to consider degraded states imply that multi-state approaches may need to be given a new look for PRA applications.

5. REFERENCES

1. W. E. Vesely and T. C. Davis, "Evaluations and Utilizations of Risk Importances", NUREG/CR-4377, August 1985.

2. E. V. Lofgren, S. E. Cooper, R. E. Kurth, and L. B. Phillips, "A Process for Risk-Focused Maintenance", NUREG/CR-5695, February 1991.

3. W. E. Vesely, R. E. Kurth, and S. M. Scalzo, "Evaluations of Core Melt Frequency Effects Due to Component Aging and Maintenance", NUREG/CR-5510, June 1990.

4. R. C. Bertucio and J. A Julius, "Analysis of Core Damage Frequency: Surry, Unit 1", NUREG/CR-4550, April 1990.

5. S. H. Sim and J. Endrenyi, "Optimal Preventive Maintenance with Repair", IEEE Trans. on Reliability, Vol. 37, No. 1, April 1988, pp. 92-96.

6. N. M. Khan and A. Gupta, "New Models for Maintenance of Series and Parallel Systems", IEEE Trans. on Reliability, Vol. R-35, No. 1, April 1986, pp. 68-75.

7. S.K. Singh, R. P. Singh, and S. Shukla, "Cost Benefit Analysis of a 2-Unit Priority-Standby System with Patience-Time for Repair", IEEE Trans. on Reliability, Vol. 40, No. 1, April 1991, pp. 11-15.

8. Y. Hatoyama, "On Markov Maintenance Problems", IEEE Trans. on Reliability, Vol. R-33, No. 4, Oct. 1984, pp. 280-284.

9. A. D. Chambardel, "Why Markovian Techniques Were Used in EDF's PSA of Palvel", in Probabilistic Safety Assessment and Management, ed. by G. Apostolakis, Elsevier Publishing Co., New York, 1991, pp. 1425-1431.

10. P. K. Samanta, W. E. Vesely, F. Hsu, and M. Subudhi, "Degradation Modeling with Application to Aging and Maintenance Effectiveness", NUREG/CR-5612, March 1991.

11. R. L. Simard, "Nuclear Plant Reliability Data System: Program Description", INPO Report 86-010, February 1986.

12. D. Dyer, "Unification of Reliability / Availability / Repairability Models for Markov Systems", IEEE Trans. on Reliability, Vol. 38, No. 2, June 1989, pp. 246-253.

13. D. T. Gillespie, Markov Processes, Academic Press, New York, 1992.

14. I. W. Basawa and B. L. S. Prakasa Rao, Statistical Inference for Stochastic Processes, Academic Press, New York, 1980.

15. P. Whittle, Systems in Stochastic Equilibrium, John Wiley and Sons, New York, 1986.

16. S. Garribba, E. Guagnini, and P. Mussio, "Multi-Valued Logic Trees: Meaning and Prime Implicants", IEEE Trans. on Reliability, Vol. R-34, No. 5, December 1985, pp. 463-473.

17. A.P. Wood, "Multi-State Block Diagrams and Fault Trees", IEEE Trans. on Reliability, Vol. R-34, No. 3, August 1985, pp. 236-241.

18. A. Bossche, "Calculation of Critical Importance for Multi-State Components", IEEE Trans. on Reliability, Vol. R-36, No. 2, June 1987, pp. 247-250.

APPENDIX A DERIVATION OF d_f CONSIDERING MAINTENANCE CONTRIBUTIONS

Assume the maintenance interval T_m is larger than the test interval T (otherwise reverse the maintenance and test intervals in the derivation). Now, assume a failure occurs at a time t_f between two successive tests, $0 \le t_f \le T$. The failure will be detected if a maintenance occurs between the time of the failure and the time of the next test. Assuming a maintenance can uniformly occur within an interval, the average duration d_1 to failure detection is

$$d_1 = \int_{t_f}^{T} (t_m - t_f)\frac{dt_m}{T_m}, \tag{A.1}$$

$$= \frac{1}{T_m}\left(\frac{T^2}{2} - Tt_f + \frac{t_f^2}{2}\right). \tag{A.2}$$

Assuming the failure time t_f is uniformly distributed between the test intervals (which is an accurate approximation for the mean time to failure being significantly larger than the test interval), the overall average duration time $\overline{d}_1$ is then

$$\overline{d}_1 = \int_0^T d_1 \frac{dt_f}{T} \tag{A.3}$$

$$= \frac{1}{6}\frac{T}{T_m}T. \tag{A.4}$$

If a maintenance does not occur between t_f and T then the duration time to detection will be the interval to the next test. This average overall duration $\overline{d}_2$ is

$$\overline{d}_2 = \int_0^T \left(1 - \frac{(T - t_f)}{T_m}\right)(T - t_f)\frac{dt_f}{T}, \tag{A.5}$$

where the first term in parentheses is the probability of the maintenance not occurring between t_f and T. Hence,

$$\overline{d}_2 = \frac{1}{2}T - \frac{1}{3}\frac{T}{T_m}T \tag{A.6}$$

Adding $\overline{d}_1 + \overline{d}_2$ gives the total duration to failure detection. We must also add the repair time r to obtain the total failure duration. Hence

$$d_f = \frac{1}{6}\frac{T}{T_m}T + \frac{1}{2}T - \frac{1}{3}\frac{T}{T_m}T + r \tag{A.7}$$

$$= \frac{1}{2}T - \frac{1}{6}\frac{T}{T_m}T + r, \tag{A.8}$$

or

$$d_f = \frac{T}{2}\left(1 - \frac{1}{3}\frac{T}{T_m}\right) + r. \tag{A.9}$$

APPENDIX B DERIVATION OF THE LIMITING EXPRESSIONS FOR L_0 AND L_d

The equation for L_o, Equation (3.91), can be expressed in the general form as:

$$L_o = L\exp(-x) + \frac{1}{r}\left(1 - \exp(-x)(1+x)\right) \tag{B.1}$$

where

$$L = T_m \tag{B.2}$$

$$x = \lambda_{ofd} T_m \tag{B.3}$$

and

$$r = \lambda_{ofd}. \tag{B.4}$$

The equation for L_d, Equation (3.98), is also given by Equation (A.1) with

$$L = \frac{T_m}{2} \tag{B.5}$$

$$x = \lambda_{df} \frac{T_m}{2} \tag{B.6}$$

and

$$r = \lambda_{df}. \tag{B.7}$$

Expanding the exponentials to second order gives

$$L_o \cong L\left(1 - x + \frac{x^2}{2}\right) + \frac{1}{r}\left(1 - \left(1 - x + \frac{x^2}{2}\right)(1+x)\right) \tag{B.8}$$

$$\cong L\left(1 - x + \frac{x^2}{2}\right) + \frac{1}{r}\left(1 - 1 + x - \frac{x^2}{2} - x + x^2 - \frac{x^3}{2}\right) \tag{B.9}$$

$$\cong L\left(1 - x + \frac{x^2}{2}\right) + \frac{1}{r}\left(\frac{x^2}{2} - \frac{x^3}{2}\right). \tag{B.10}$$

Ignoring first order corrections,

$$L_o \cong L. \tag{B.11}$$

Because of the cancellations, the exponents need to be expanded to second order to obtain the proper first order and zeroth order expressions.

APPENDIX C AN ALTERNATIVE DERIVATION OF λ_{df} TO PROVIDE CONSISTENCY WITH THE PRA FAILURE RATE λ

For the four state Markov model, the total failure frequency w_f for the component is

$$w_f = p_o\lambda_{of} + p_d\lambda_{df} \tag{C.1}$$

where p_o and p_d are the component operational state and degraded state probabilities, respectively. We can define the average component failure rate $\overline{\lambda}_f$ as

$$\overline{\lambda}_f = \frac{p_o\lambda_{of} + p_d\lambda_{df}}{p_o + p_d}. \tag{C.2}$$

If we equate $\overline{\lambda}_f$ to a specified total component failure rate λ such as the failure rate used in a PRA then we can determine λ_{df} so that the same failure rate λ is produced:

$$\lambda = \frac{p_o\lambda_{of} + p_d\lambda_{df}}{p_o + p_d}. \tag{C.3}$$

Solving for λ_{df}

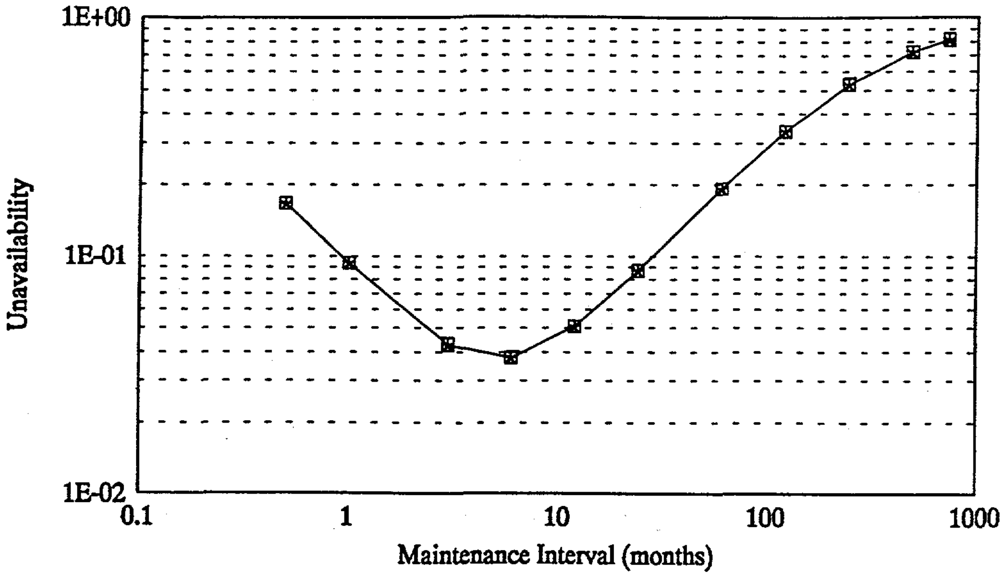
$$\lambda_{df} = \frac{p_d\lambda + p_o(\lambda - \lambda_{of})}{p_d} \tag{C.4}$$

or

$$\lambda_{df} = \lambda + \frac{p_o}{p_d}(\lambda - \lambda_{of}). \tag{C.5}$$

If λ and λ_{of} are given, then to determine λ_{df} using the above expression, values for p_o and p_d need to be estimated, or equivalently a value for p_o/p_d needs to be estimated. A value for p_d can be estimated from an initial Markov model such as given in previous sections. Alternatively, p_o/p_d can be estimated from plant maintenance logs as the relative fraction of time the component is operational to the fraction of time it is degraded. The λ_{df} value determined by the above expression will then result in the Markov total failure rate for the component, given by Equation (C.2), being equal to the PRA total component failure rate λ.

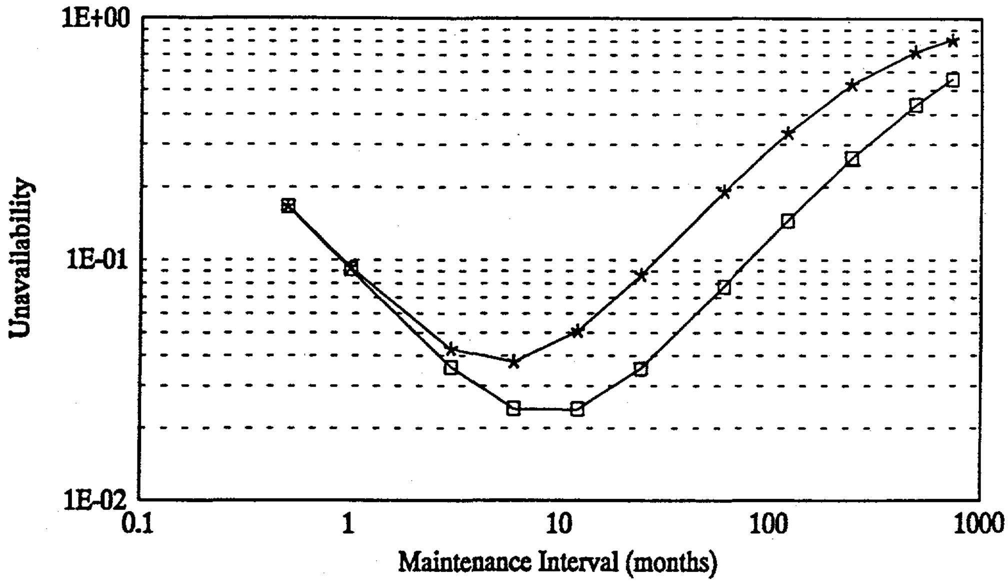
APPENDIX D DETERMINATIONS OF COMPONENT UNAVAILABILITY VERSUS MAINTENANCE INTERVAL FOR DIFFERENT COMPONENT DEGRADATION CHARACTERISTICS



* q_o = performance unavailability

□ $q_r + q_m$ = functional unavailability

Figure D.1 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-2}$ per hour



* q_o = performance unavailability

□ $q_r + q_m$ = functional unavailability

Figure D.2 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-3}$ per hour

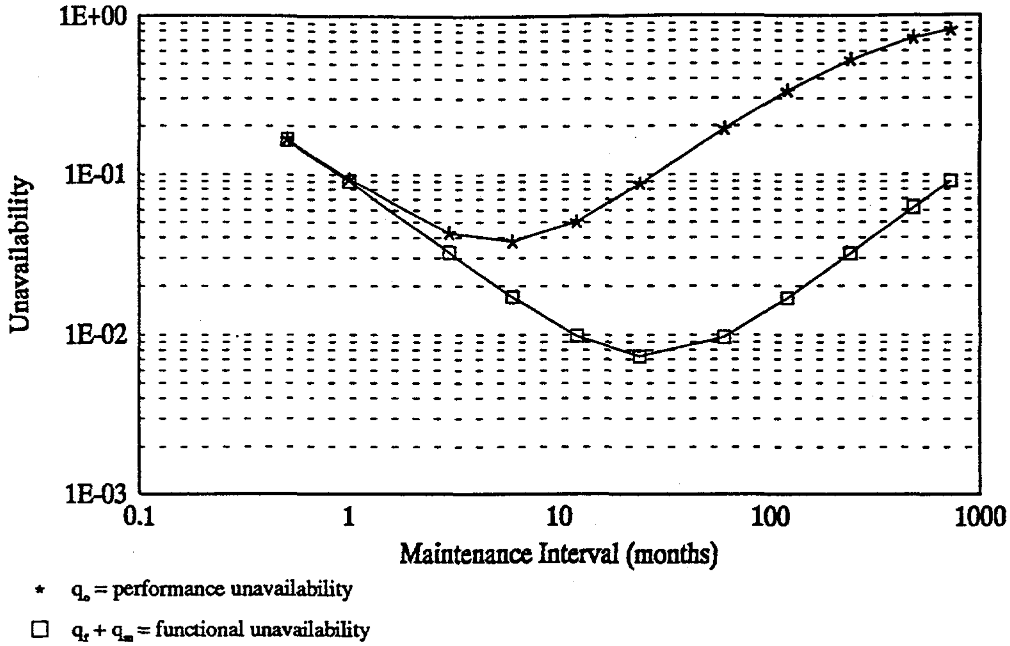


Figure D.3 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour

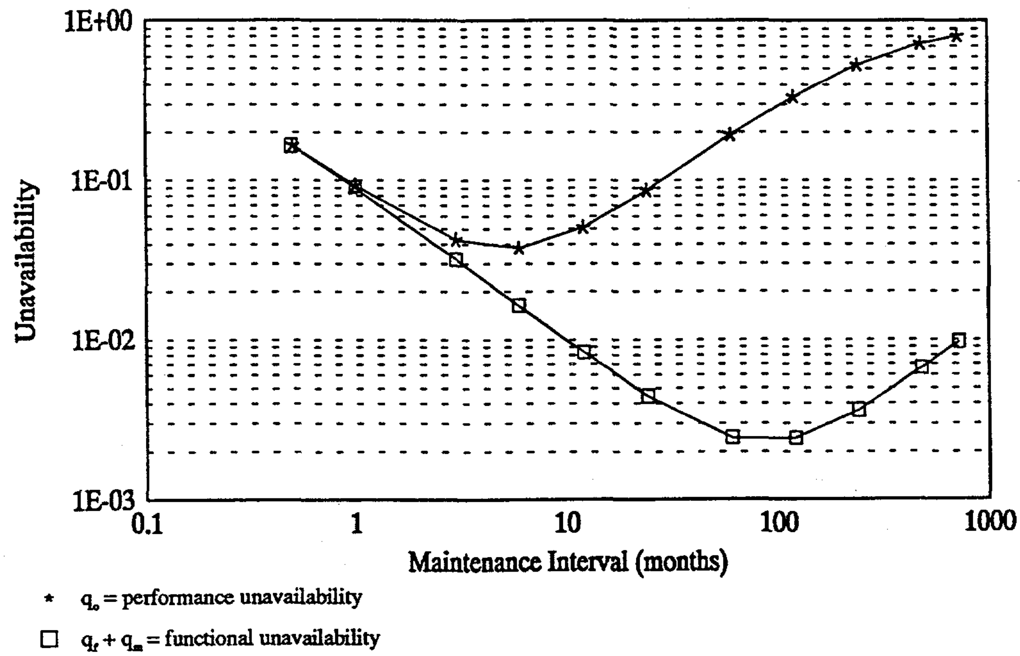
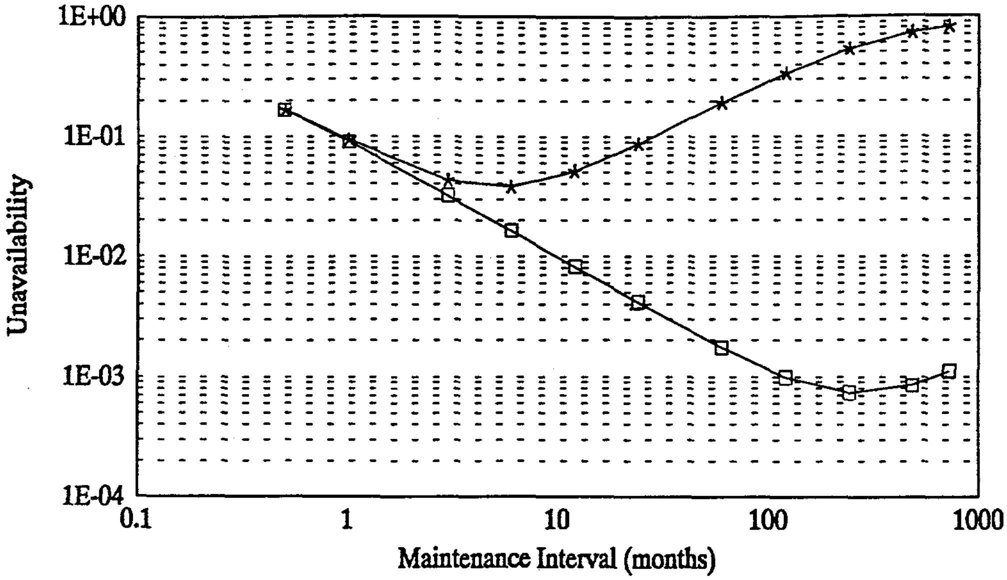


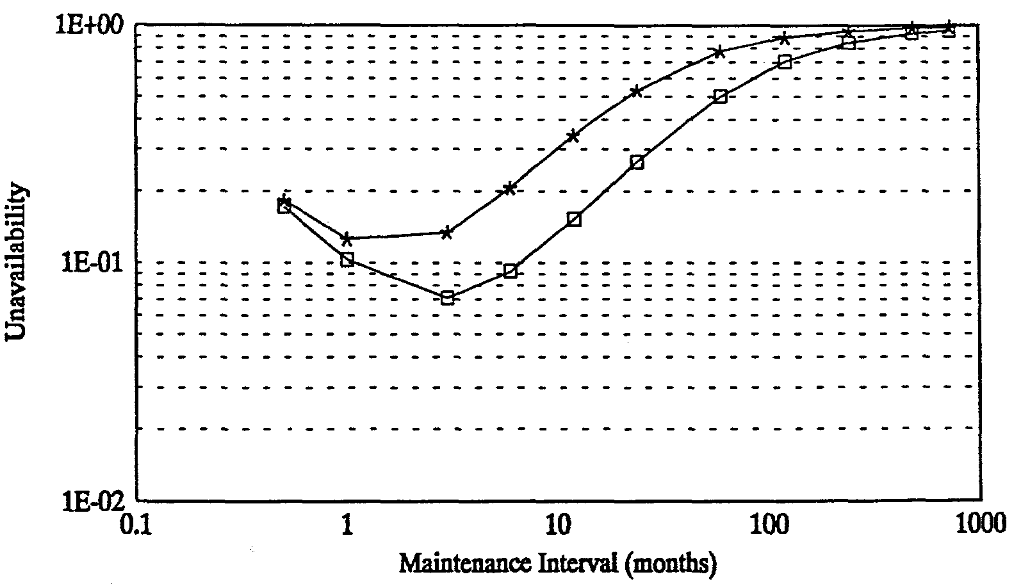
Figure D.4 Component perfor.nance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour



* q_o = performance unavailability

□ $q_r + q_m$ = functional unavailability

Figure D.5 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-6}$ per hour



* q_o = performance unavailability

□ $q_r + q_m$ = functional unavailability

Figure D.6 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-3}$ per hour

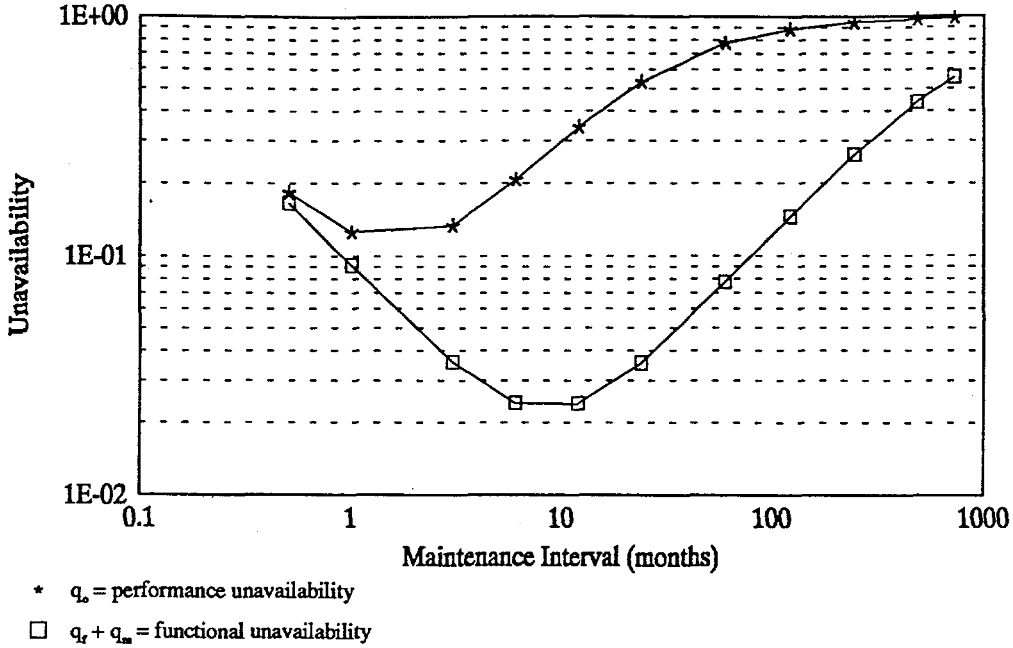


Figure D.7 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour

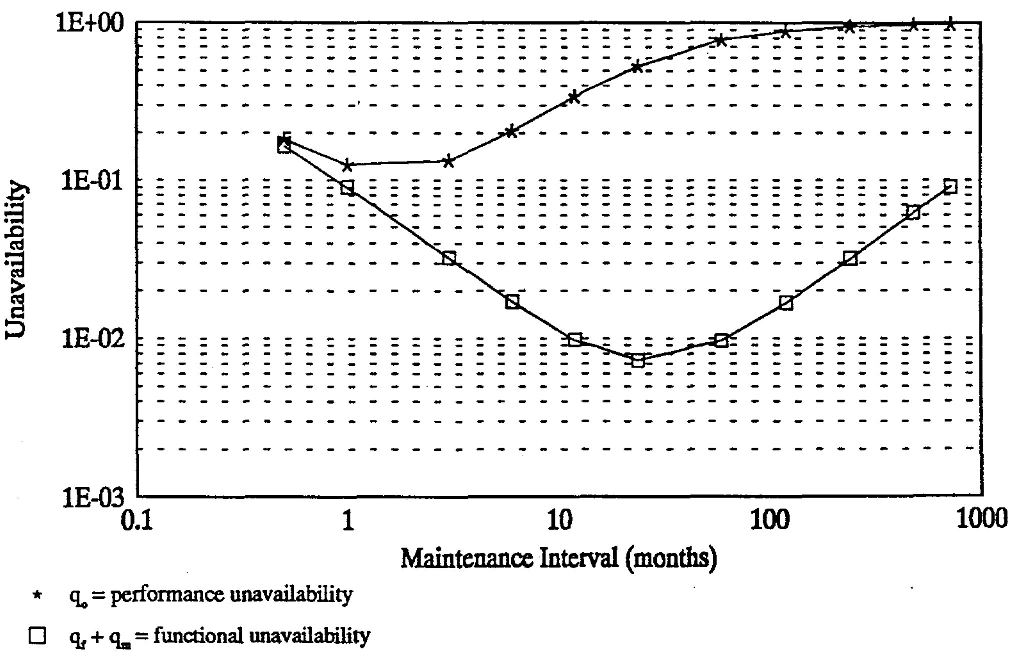


Figure D.8 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour

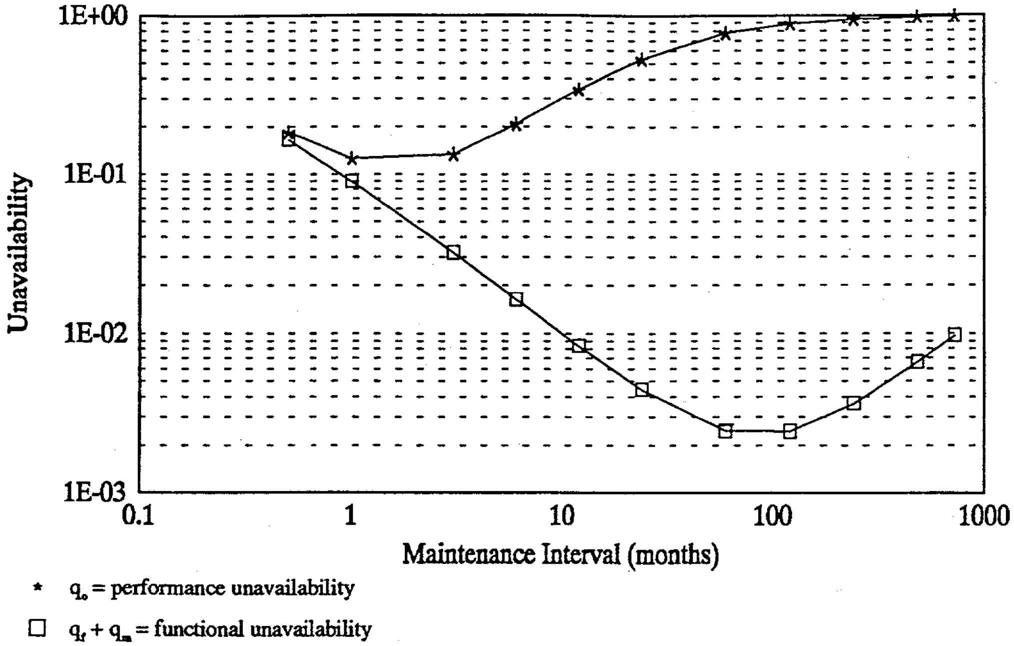


Figure D.9 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-6}$ per hour

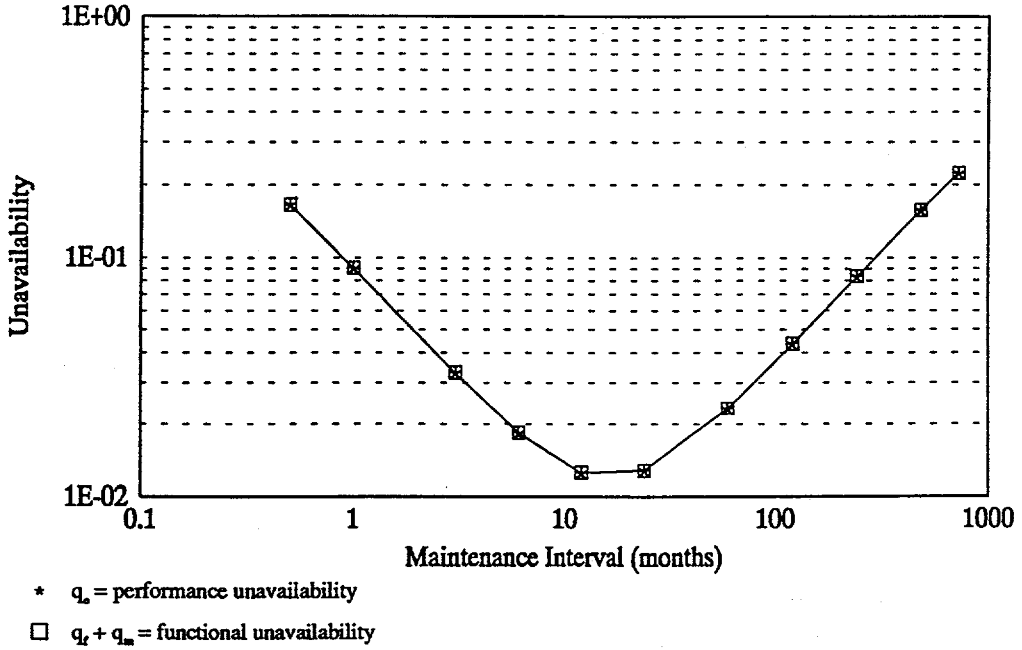


Figure D.10 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-2}$ per hour

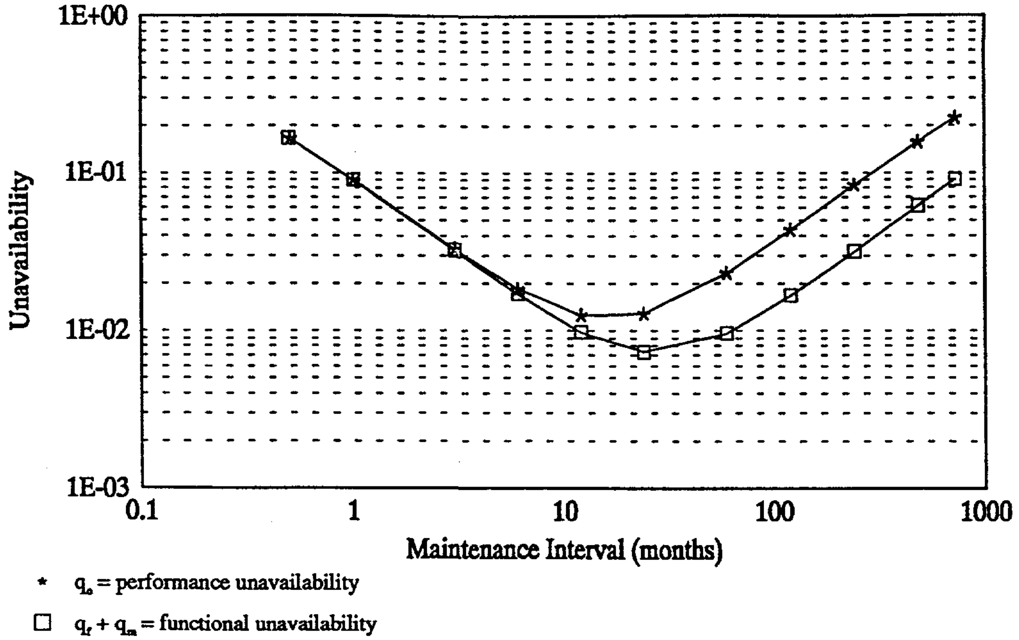


Figure D.11 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-3}$ per hour

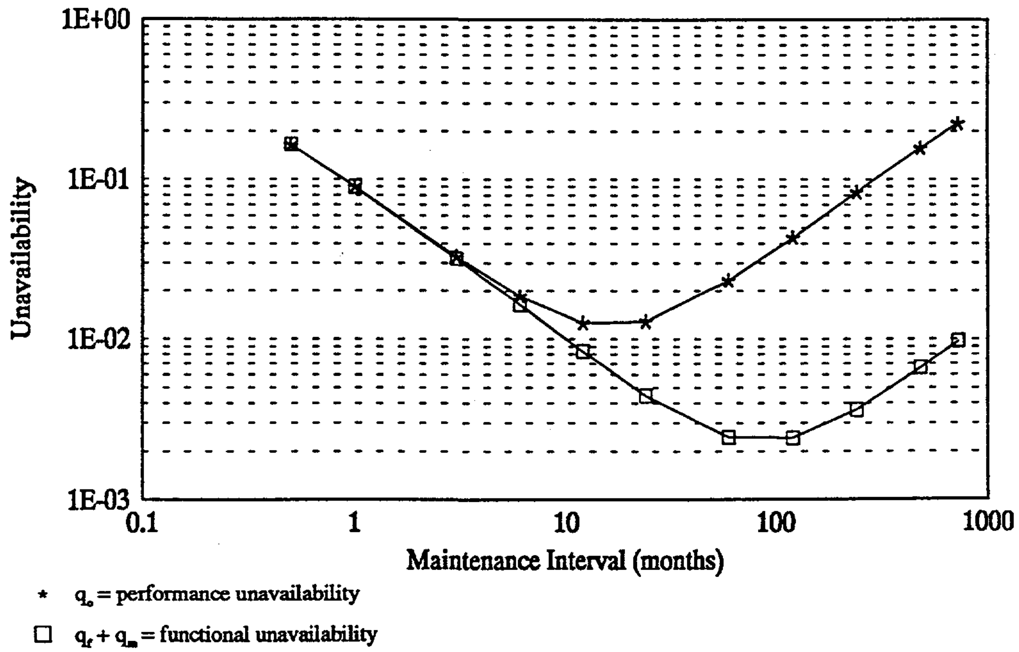


Figure D.12 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour

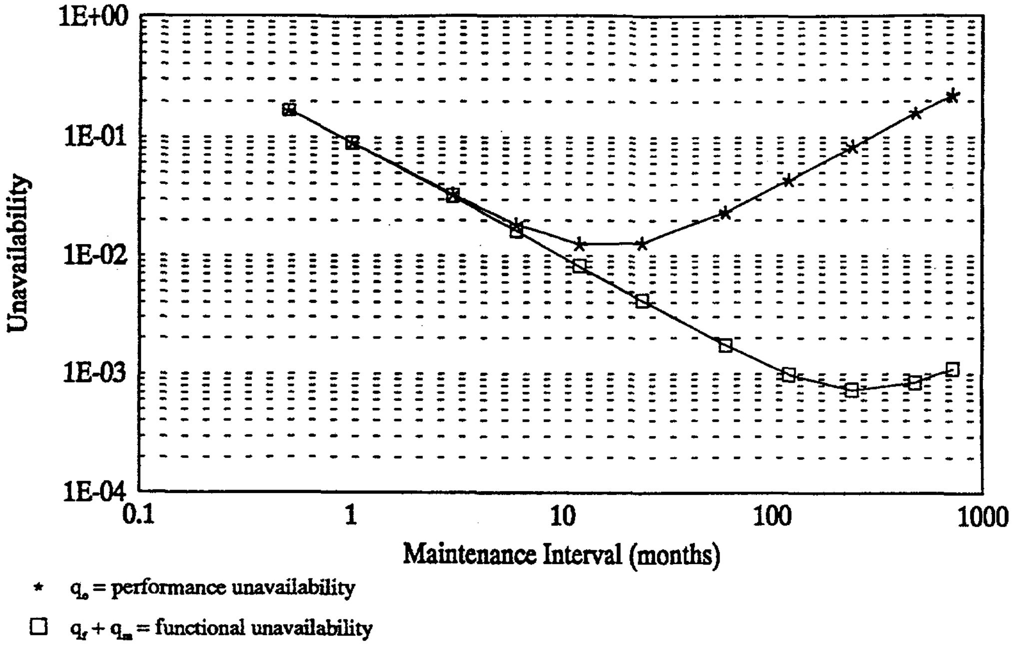


Figure D.13 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour

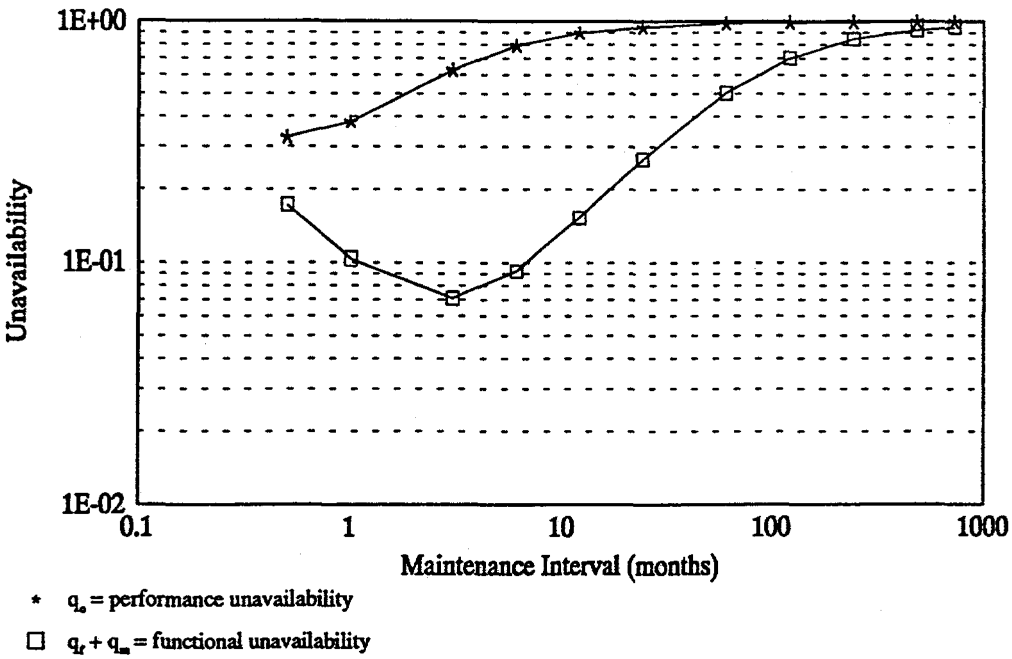
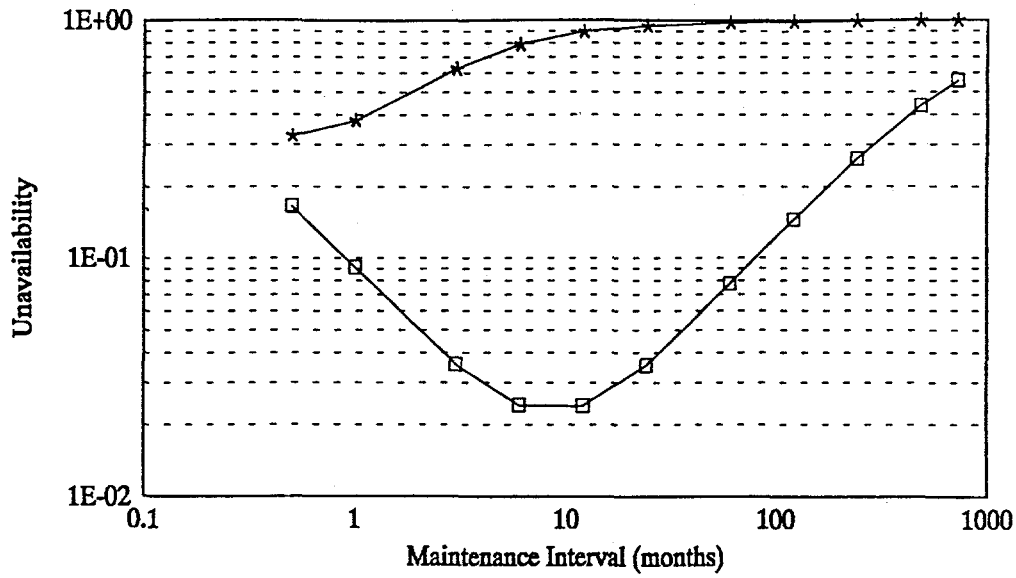


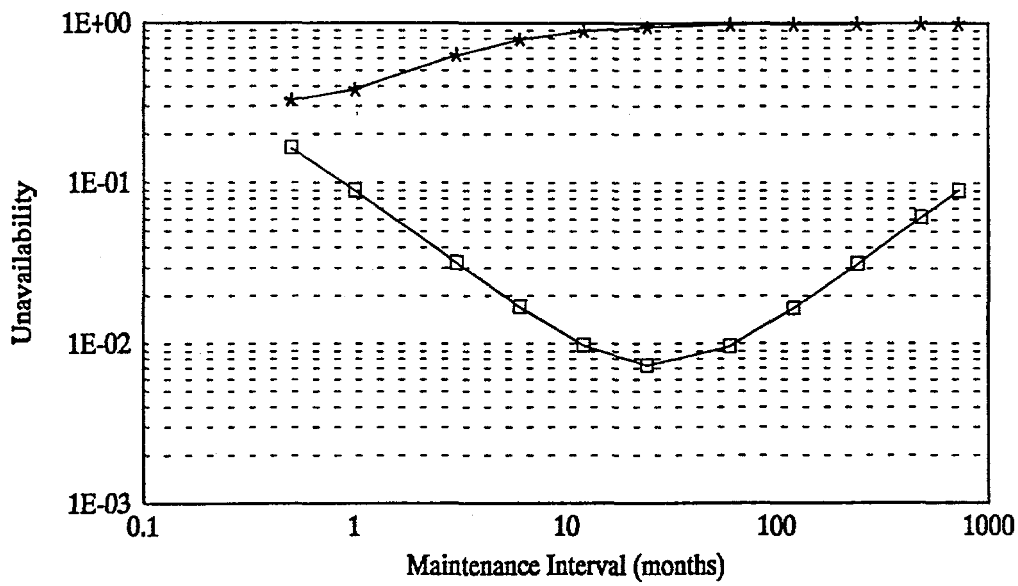
Figure D.14 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-3}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour



* q_o = performance unavailability

□ $q_f + q_m$ = functional unavailability

Figure D.15 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-3}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour



* q_o = performance unavailability

□ $q_f + q_m$ = functional unavailability

Figure D.16 Component performance and functional unavailability versus maintenance interval: $\lambda_{od} = 1\times10^{-3}$ per hour; $\lambda_{df} = 1\times10^{-6}$ per hour

Table D.1 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-2}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1665825	0.1665825
1	0.0934167	0.0934167
3	0.0427007	0.0427007
6	0.0377562	0.0377562
12	0.0507007	0.0507007
24	0.0867934	0.0867934
60	0.1918827	0.1918827
120	0.3346630	0.3346630
240	0.5286224	0.5286224
480	0.7234009	0.7234009
720	0.8108706	0.8108706

Table D.2 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-3}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1665825	0.1654256
1	0.0934167	0.0911066
3	0.0427007	0.0358164
6	0.0377562	0.0241236
12	0.0507007	0.0239701
24	0.0867934	0.0353960
60	0.1918827	0.0774814
120	0.3346630	0.1449316
240	0.5286224	0.2616335
480	0.7234009	0.4359396
720	0.8108706	0.5554193

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

Table D.3 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1665825	0.1648263
1	0.0934167	0.0899088
3	0.0427007	0.0322298
6	0.0377562	0.0169714
12	0.0507007	0.0097492
24	0.0867934	0.0072834
60	0.1918827	0.0095922
120	0.3346630	0.0166392
240	0.5286224	0.0317140
480	0.7234009	0.0615122
720	0.8108706	0.0902082

Table D.4 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1665825	0.1647664
1	0.0934167	0.0897889
3	0.0427007	0.0318702
6	0.0377562	0.0162524
12	0.0507007	0.0083120
24	0.0867934	0.0044124
60	0.1918827	0.0024401
120	0.3346630	0.0024182
240	0.5286224	0.0036014
480	0.7234009	0.0065731
720	0.8108706	0.0096681

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

Table D.5 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-5}$ per hour; $\lambda_{df} = 1\times10^{-6}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1665825	0.1647604
1	0.0934167	0.0897769
3	0.0427007	0.0318342
6	0.0377562	0.0161805
12	0.0507007	0.0081682
24	0.0867934	0.0041247
60	0.1918827	0.0017211
120	0.3346630	0.0009811
240	0.5286224	0.0007305
480	0.7234009	0.0008446
720	0.8108706	0.0010956

Table D.6 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-3}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1827897	0.1713915
1	0.1254034	0.1029805
3	0.1337559	0.0707538
6	0.2064140	0.0920127
12	0.3419939	0.1522626
24	0.5323044	0.2653155
60	0.7761903	0.5025851
120	0.8866839	0.7008489
240	0.9433332	0.8442949
480	0.9716666	0.9220171
720	0.9811111	0.9480113

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

Table D.7 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1827897	0.1654256
1	0.1254034	0.0911066
3	0.1337559	0.0358164
6	0.2064140	0.0241236
12	0.3419939	0.0239701
24	0.5323044	0.0353960
60	0.7761903	0.0774814
120	0.8866839	0.1449316
240	0.9433332	0.2616335
480	0.9716666	0.4359396
720	0.9811111	0.5554193

Table D.8 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1827897	0.1648263
1	0.1254034	0.0899088
3	0.1337559	0.0322298
6	0.2064140	0.0169714
12	0.3419939	0.0097492
24	0.5323044	0.0072834
60	0.7761903	0.0095922
120	0.8866839	0.0166392
240	0.9433332	0.0317140
480	0.9716666	0.0615122
720	0.9811111	0.0902082

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

Table D.9 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-4}$ per hour; $\lambda_{df} = 1\times10^{-6}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1827897	0.1647664
1	0.1254034	0.0897889
3	0.1337559	0.0318702
6	0.2064140	0.0162524
12	0.3419939	0.0083120
24	0.5323044	0.0044124
60	0.7761903	0.0024401
120	0.8866839	0.0024182
240	0.9433332	0.0036014
480	0.9716666	0.0065731
720	0.9811111	0.0096681

Table D.10 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-2}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1649422	0.1649422
1	0.0901405	0.0901405
3	0.0329244	0.0329244
6	0.0183593	0.0183593
12	0.0125194	0.0125194
24	0.0128018	0.0128018
60	0.0232249	0.0232249
120	0.0433698	0.0433698
240	0.0831114	0.0831114
480	0.1566160	0.1566160
720	0.2223602	0.2223602

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

Table D.11 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-3}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1649422	0.1648263
1	0.0901405	0.0899088
3	0.0329244	0.0322298
6	0.0183593	0.0169714
12	0.0125194	0.0097492
24	0.0128018	0.0072834
60	0.0232249	0.0095922
120	0.0433698	0.0166392
240	0.0831114	0.0317140
480	0.1566160	0.0615122
720	0.2223602	0.0902082

Table D.12 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1649422	0.1647664
1	0.0901405	0.0897889
3	0.0329244	0.0318702
6	0.0183593	0.0162524
12	0.0125194	0.0083120
24	0.0128018	0.0044124
60	0.0232249	0.0024401
120	0.0433698	0.0024182
240	0.0831114	0.0036014
480	0.1566160	0.0065731
720	0.2223602	0.0096681

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

Table D.13 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-6}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.1649422	0.1647604
1	0.0901405	0.0897769
3	0.0329244	0.0318342
6	0.0183593	0.0161805
12	0.0125194	0.0081682
24	0.0128018	0.0041247
60	0.0232249	0.0017211
120	0.0433698	0.0009811
240	0.0831114	0.0007305
480	0.1566160	0.0008446
720	0.2223602	0.0010956

Table D.14 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-3}$ per hour; $\lambda_{df} = 1\times10^{-4}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.3269423	0.1713915
1	0.3800618	0.1029805
3	0.6263128	0.0707538
6	0.7907217	0.0920127
12	0.8940148	0.1522626
24	0.9470151	0.2653155
60	0.9788101	0.5025851
120	0.9894057	0.7008489
240	0.9947030	0.8442949
480	0.9973516	0.9220171
720	0.9982344	0.9480113

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

Table D.15 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-3}$ per hour; $\lambda_{df} = 1\times10^{-5}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.3269423	0.1654256
1	0.3800618	0.0911066
3	0.6263128	0.0358164
6	0.7907217	0.0241236
12	0.8940148	0.0239701
24	0.9470151	0.0353960
60	0.9788101	0.0774814
120	0.9894057	0.1449316
240	0.9947030	0.2616335
480	0.9973516	0.4359396
720	0.9982344	0.5554193

Table D.16 Component Performance and Functional Unavailability Versus Maintenance Interval: $\lambda_{od} = 1\times10^{-3}$ per hour; $\lambda_{df} = 1\times10^{-6}$ per hour

T_m (months)	q_o	q_f+q_m
0.5	0.3269423	0.1648263
1	0.3800618	0.0899088
3	0.6263128	0.0322298
6	0.7907217	0.0169714
12	0.8940148	0.0097492
24	0.9470151	0.0072834
60	0.9788101	0.0095922
120	0.9894057	0.0166392
240	0.9947030	0.0317140
480	0.9973516	0.0615122
720	0.9982344	0.0902082

T_m = maintenance interval
q_o = performance unavailability
$q_f + q_m$ = functional unavailability

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-6002
BNL-NUREG-52332

2. TITLE AND SUBTITLE

Risk-Based Maintenance Modeling: Prioritization of Maintenance Importances and Quantification of Maintenance Effectiveness

3. DATE REPORT PUBLISHED

MONTH	YEAR
September	1995

4. FIN OR GRANT NUMBER

A3230

5. AUTHOR(S)

W.E. Vesely and J.T. Rezos /SAIC

6. TYPE OF REPORT

Formal

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION – NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide*

Science Applications International Corp.
Dublin, Ohio 43017

Under Contract to:
Department of Advanced Technology
Brookhaven National Laboratory
Upton, New York 11973

9. SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Systems Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This report describes approaches for prioritizing the risk importances of maintenances using a Probabilistic Risk Assessment (PRA). Approaches are then described for quantifying the reliability and risk effects of maintenance actions. Two different PRA importance measures, minimal cutset importances and risk reduction importances, are used to prioritize maintenances and the report shows that similar results are obtained if appropriate criteria are used. The justifications for the particular importance measures are also developed. The approaches which are developed for quantifying the reliability and risk effects of maintenance actions are extensions of the usual reliability models now used in PRAs. These extended models consider degraded states of the component and quantify the benefits of maintenance in correcting degradations and preventing failures. The negative effects of maintenance, including maintenance downtimes, are also included. These models are specific types of Markov models. This report analyzes a range of postulated values of input data in order to explore the potential usefulness of these models. The effects of maintenance are quantified to be large in specific cases.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Nuclear Power Plants - Maintenance, Reactor Components - Risk Assessment, Reactor Maintenance - Risk Assessment, Reactor Maintenance - Reliability BNL, Failure Mode Analysis, Failures, Markov Process, Probabilistic Estimation, Reliability, Statistical Models

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)
Unclassified

(This Report)
Unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)