NUREG/CR-5587
SAIC-92/1137

Approaches for Age-Dependent Probabilistic Safety Assessments With Emphasis on Prioritization and Sensitivity Studies

Prepared by
W. E. Vesely

Science Applications International Corporation

Prepared for
U.S. Nuclear Regulatory Commission

AVAILABILITY NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 2120 L Street, NW., Lower Level, Washington, DC 20555
2. The Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC bulletins, circulars, information notices, inspection and investigation notices; licensee event reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, international agreement reports, grant publications, and NRC booklets and brochures. Also available are regulatory guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG-series reports and technical reports prepared by other Federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions. *Federal Register* notices, Federal and State legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Office of Administration, Distribution and Mail Services Section, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, for use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

NUREG/CR-5587
SAIC-92/1137
RG, R1, R9

Approaches for Age-Dependent Probabilistic Safety Assessments With Emphasis on Prioritization and Sensitivity Studies

Manuscript Completed: May 1992
Date Published: August 1992

Prepared by
W. E. Vesely

Science Applications International Corporation
655 Metro Place South, Suite 745
Dublin, OH 43017

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN L1072

ABSTRACT

Approaches are described for incorporating component aging reliability models into a probabilistic safety assessment (PSA), or probabilistic risk assessment (PRA), of a nuclear power plant. These approaches and procedures are described from a technical standpoint and are not to be interpreted as having any regulatory implications. Component aging failure rate models and test and maintenance aging control models are presented for utilization. Different approaches for carrying out the aging evaluations are given. Demonstrations are given involving prioritizing aging contributors, evaluating maintenance effectiveness, carrying out time dependent evaluations, and carrying out uncertainty and sensitivity analyses of aging effects.

TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

TABLE OF CONTENTS CONTINUED

TABLE OF CONTENTS CONTINUED

LIST OF FIGURES

LIST OF FIGURES CONTINUED

LIST OF TABLES

LIST OF TABLES CONTINUED

PAGE: 1 U.S. NUCLEAR REGULATORY COMMISSION DATE: 08/25/93

PACKING SLIP

USNRC
J. VORA
217B N/LS

ORDER NUMB: A65617-00006
ORDER TYPE: 2

DOCUMENT NO.	QTY	@ COST	TOTAL COST	COMMENTS
NUREGCR5587	5			

TOTAL DOCUMENTS ORDERED : 5
TOTAL DOCUMENTS ENCLOSED: 5

LIST OF TABLES CONTINUED

EXECUTIVE SUMMARY

Overview

Explicit consideration of the risk effects of aging has been an important feature of the Nuclear Plant Aging Research (NPAR) program being conducted by the Office of Research of the Nuclear Regulatory Commission. By explicitly considering the risk effects of aging, aging contributors can be prioritized according to their risk importance. The aging contributors include active and passive components which are susceptible to aging and include the aging mechanisms and stressors which can cause component aging. By prioritizing aging contributors according to their risk effects, aging research and aging activities can thereby be focused on the risk important areas.

In addition to risk prioritizing the aging contributors, explicit consideration of the risk effects of aging allows aging management schemes to be explicitly evaluated for their risk effectiveness in controlling aging. Scheduled maintenance, corrective maintenance, operational testing, and condition monitoring can all be evaluated for their risk effectiveness in specific situations. Risk effective combinations of activities and risk effective schedules can thereby be identified. Furthermore, by focusing on the risk importance contributors, the risk effective aging management strategies can be made cost effective.

Finally, explicit consideration of the risk effects of aging allows component failure data to be evaluated for aging effects and associated risk implications. Aging of single components and simultaneous aging of multiple components exhibited in data can be evaluated for their risk effects. Because the risk effects of aging are not necessarily additive, the risk effects of aging of a single component can be insignificant but the same aging exhibited by several components can be extremely risk significant. The risk significant aging effects exhibited in data are of high priority and their causes need to be evaluated to assure that research programs and aging management programs focus on these causes.

Age-Dependent Probabilistic Safety Assessments

Because of the usefulness and importance of explicitly considering risk effects of aging, the NPAR program supported the development of a methodology for age-dependent probabilistic risk assessments (PRAs) and age dependent probabilistic safety assessments (PSAs). This report describes the procedures which have been developed for transforming a PRA or a PSA to an age-dependent evaluation. A probabilistic risk assessment, or PRA for short, has become a standard approach for modeling and quantifying accidents and their consequences which can occur at a nuclear power plant. A probabilistic safety assessment, or PSA for short, is a PRA which focuses on accidents leading to core damage and which quantifies the core damage frequency, but does not extend the evaluations to quantify the associated consequences, such as the expected manrem released. The age-dependent approaches which have been developed to date in the NPAR program have focused on age-dependent PSAs, however the general approaches are also applicable to age-dependent PRAs.

There are three basic differences between a standard PSA and an age-dependent PSA, or an APSA as we will term the age-dependent PSA. These three differences, which also apply to a PRA, are listed below:

1. An APSA explicitly models aging effects in component failure rates, which generally cause the failure rates to increase with age, while a standard PSA assumes component failure rates are constant.

2. An APSA explicitly models the effects of test and maintenances in controlling the aging of components while a standard PSA does not.

3. An APSA explicitly calculates the aging effects and age dependence on the core damage frequency and system unavailabilities, while a standard PSA does not and instead calculates constant values for the core damage frequency and system unavailabilities.

The Uses of Age-Dependent PSAs

Because an age dependent PSA, or APSA, explicitly models and evaluates aging effects on the core damage frequency and system unavailabilities, an APSA can be used in various ways to evaluate the risk effects of aging.* Three of the principal uses are listed below:

1. Aging effects on passive and active components can be explicitly prioritized with regard to their resulting impacts on core damage frequency and risk. Aging control activities can thus focus on the risk important aging contributors.

2. The risk effectiveness of given aging management programs, including specific test and maintenance strategies, can be explicitly evaluated and risk effective strategies can be identified.

3. Failure data and other experience data at a plant can be input to an APSA to monitor aging effects on risk to provide feedback to the aging management program being conducted at the plant.

Issues Associated with Age-Dependent PSAs

The issues associated with an APSA generally involve a lack of data to accurately determine the aging component failure rates and a lack of test and maintenance aging control information. At the present time, age dependent component failure rates and test and maintenance aging control parameters are indeed very sparse. Because of the present lack of data , the work in the NPAR program has focused on developing approaches using APSAs which do not necessarily require accurate data. The emphasis of the work has consequently been on prioritization of aging contributors and sensitivity studies of aging effects and of aging management program effectiveness which do not necessarily require precise data or information. This report describes the specific procedures which have been developed for carrying out APSA evaluations with this emphasis.

Approaches for Age-Dependent PSAs

An earlier NUREG, NUREG/CR-5510 (1), was published in June 1990 and described the basic methodology that was developed in NPAR for age dependent PSAs or APSAs. However, detailed procedures for utilizing APSAs for specific evaluations were not

---

* "Risk" is used in a general context here and includes the core damage ferquency, as well as public health risks.

covered. This report describes these detailed approaches, and specific evaluations that can be carried out using presently available information. The chapters of the report are summarized below:

1. *The Age-Dependent PSA Versus the Standard PSA*

The differences between an APSA and a standard PSA, which were summarized in the previous discussions, are described in some detail in this first chapter. The table on the next page highlights these differences.

2. *Component Reliability Models Used in an Age-Dependent PSA*

This chapter describes specific aging component failure rate models and specific test and maintenance aging control models which can be used in an APSA. The aging failure rate models which are described cover the spectrum of aging behaviors which are likely to be exhibited by nuclear plant components and include the Weibull failure rate model, the linear failure rate model, and the exponential failure rate model. The test and maintenance models which are presented cover the spectrum of aging renewal activities which can occur at a plant and include corrective maintenance models, preventive maintenance models, and piecepart maintenance models.

3. *Approaches for Transforming a PSA into an Age-Dependent PSA*

This chapter describes three approaches that can be used to incorporate aging evaluations into a standard PSA to transform it to an APSA. Procedures for each approach are given along with the strengths and limitations of the approach. One of the approaches is the approach described in NUREG/CR-5510, which provides detailed aging contributor prioritizations, including multiple component aging effects. In this prioritization approach, appropriate risk importance coefficients are extracted from the standard PSA and are combined with component aging models. Hence, the approach is efficient since existing PSAs can be directly used with minimal requantification required.

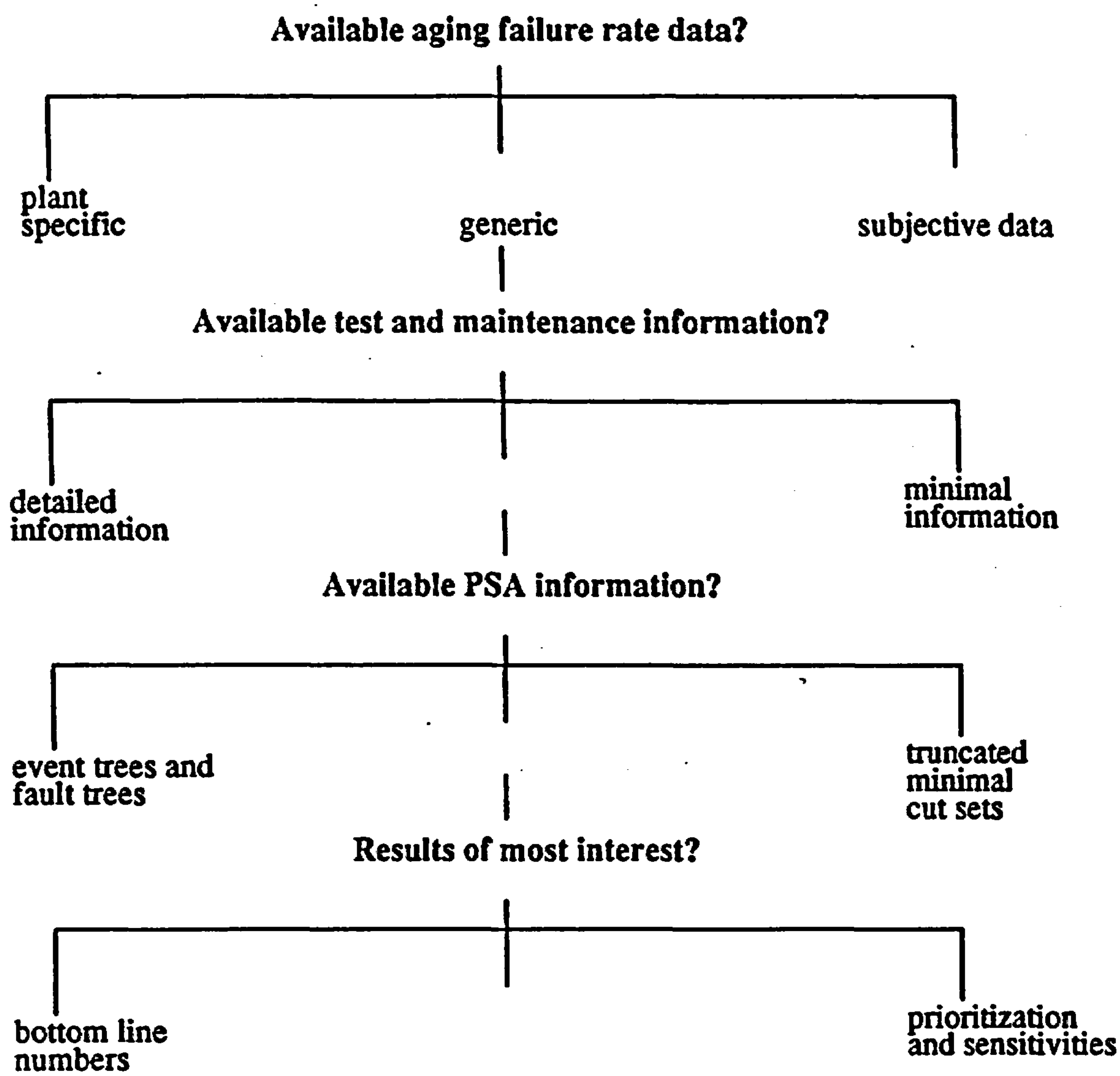
4. *Applications of an Age-Dependent PSA*

This chapter describes the different applications of an APSA and the questions that need to be addressed in setting up any application. The figure on page xvi presents the specific questions that need to be addressed to determine the specific aging models and

THE DIFFERENCES BETWEEN A STANDARD PSA AND AN AGE DEPENDENT PSA (AN APSA)

	PSA	APSA
Component Failure Rates	Constant Failure Rates	Age-Dependent Failure Rates
Surveillance Tests	Only Affects Component Up or Down Status	Effects on Component Age Also Modeled
Maintenances	Only Component Downtimes Considered	Effects on Component Age Also Modeled
Repairs	Does Not Affect Age	Effects on Component Age Also Modeled
Risks Results Calculated	Do Not Explicitly Account for Aging	Explicitly Accounts for Aging Effects
Prioritizations of Contributions	Based on Constant Risk Contributions	Aging Contributors Explicitly Identified
Maintenance Effectiveness Evaluations	Maintenance Downtimes Only Explicitly Evaluated for Risk Effects	Benefit of Maintenance in Controlling Aging Also Evaluated

QUESTIONS TO BE ANSWERED IN SETTING UP AN APSA EVALUATION



approaches that are most effectively used. As shown in the figure, the four questions that need to be asked involve the component aging failure rate data which is available, the test and maintenance information which is available, the standard PSA information which is available, and the aging results which are of most interest. The specific aging models and approaches which are most effective for each possible answer to the questions are defined. What is identified from these descriptions is the aging models which are available for a given application, and the applications which can be carried out, when there is little to detailed aging data and information.

5. *Prioritization of Aging Contributors*

This chapter demonstrates the use of an APSA to prioritize aging contributions with regard to their risk impacts. This application is important since it can provide a basis for focusing aging management activities. Those aging contributors which have significant risk impacts are most important and need priority attention. Prioritization procedures are described along with interpretation of the results. The tables on the next page illustrate a prioritization which is obtained as a part of a demonstration using a plant specific PSA. The components in the plant are prioritized in terms of the average increase in core damage frequency ΔC which is caused by component aging between replacements of the components. The average increase ΔC applies to each year, and the new core damage frequency for any year is $C_0 + \Delta C$ where C_0 is the baseline PSA core damage frequency. Every component in the PSA is prioritized for its aging contribution to core damage frequency and every interaction of aging components is also prioritized for the interaction contribution.

The two tables on the next page show the top 90% individual component aging contributors and the top 90% two-component aging interactions for given aging data. The tables rank the contributors, beginning with the highest aging contributor to the core damage frequency (cdf). In the top table, the component name as used in the standard PSA is given along with the importance of the component (I) as calculated from the standard PSA. The component unavailability q and the increase in component unavailability Δq due to aging are then given. The aging contribution to the core damage frequency ΔC is given in the last column and is the increase in core damage frequency (above the PSA value) caused by aging of the component. The aging contribution ΔC is simply the product of the importance I of the contributor and the aging effect on the contributor Δq which is extremely useful for applications. The table below is similar

TABLE 1. DOMINANT SINGLE COMPONENT AGING CONTRIBUTORS FOR A SPECIFIC BWR (ACTIVE COMPONENTS ONLY)

Rank	Component ID	Component Importance I	Component Unavailability q	Aging Factor Δq	ΔC (/yr)
1	ESW-AOV-CC-CCF	9.70E-05	1.0E-03	2.9E-01	2.8E-05
2	EHV-AOV-CC-CCF	6.34E-05	1.0E-03	2.9E-01	1.8E-05
3	ESW-AOV-CC-0241B	3.68E-05	1.0E-03	2.9E-01	1.1E-05
4	ESW-AOV-CC-0241C	3.68E-05	1.0E-03	2.9E-01	1.1E-05
5	EHV-SRV-CC-RV2	2.53E-05	3.0E-04	2.9E-01	7.0E-06
6	EHV-SRV-CC-RV3	2.53E-05	3.0E-04	2.9E-01	7.0E-06
7	DCP-BAT-LF-CCF	2.16E-04	1.08E-03	1.9E-02	4.1E-06
8	HCI-MOV-CC-MV14	5.42E-06	3.0E-03	2.6E-01	1.4E-06
9	HCI-MOV-CC-MV19	5.42E-06	3.0E-03	2.6E-01	1.4E-06
10	ACP-DGN-FR-EDGC	2.09E-05	1.6E-02	3.3E-02	7.0E-07

ΔC = Core damage frequency increase due to aging

TABLE 2. DOMINANT DOUBLE COMPONENT AGING INTERACTIONS FOR A SPECIFIC BWR (ACTIVE COMPONENTS ONLY)

Rank	Component ID	Component ID	Joint Importance I	Aging Factor Δq1	Aging Factor Δq2	ΔC (/yr)
1	ESW-AOV-CC-0241B	ESW-AOV-CC-0241C	1.34E-03	2.9E-01	2.9E-01	1.1E-04
2	ACP-DGN-LP-EDGB	ESW-AOV-CC-0241C	8.50E-04	3.3E-02	2.9E-01	8.1E-06
3	ACP-DGN-LP-EDGC	ESW-AOV-CC-0241B	8.50E-04	3.3E-02	2.9E-01	8.1E-06
4	ACP-DGN-LP-EDGC	EHV-SRV-CC-RV2	7.69E-04	3.3E-02	2.9E-01	7.1E-06
5	ACP-DGN-LP-EDGB	EHV-SRV-CC-RV3	7.69E-04	3.3E-02	2.9E-01	7.1E-06
6	ACP-DGN-FR-EDGC	ESW-AOV-CC-0241B	4.79E-04	3.3E-02	2.9E-01	4.6E-06
7	ACP-DGN-FR-EDGB	ESW-AOV-CC-0241C	4.79E-04	3.3E-02	2.9E-01	4.6E-06
8	ACP-DGN-FR-EDGC	EHV-SRV-CC-RV2	4.40E-04	3.3E-02	2.9E-01	4.1E-06
9	ACP-DGN-FR-EDGB	EHV-SRV-CC-RV3S	4.40E-04	3.3E-02	2.9E-01	4.1E-06
10	ACP-DGN-FR-EDGB	ACP-DGN-FR-EDGC	5.34E-04	3.3E-02	3.3E-02	5.9E-07

ΔC = Core damage frequency increase due to aging except the importance I is the joint importance of the two contributors from the PSA. The aging contribution ΔC represents the additional core damage frequency increase from the simultaneous aging of the components. ΔC is the product of the joint importance I and the two aging effects on the components (Δq_1 and Δq_2).

As demonstrated in the tables, it has generally been found that relatively few aging contributors dominate, even though many components may be aging. The importance of the contributor (I) as given by the PSA and the aging effect in the contributor (Δq) must both be properly taken into consideration to obtain the aging contribution to the core damage frequency. The procedures presented do this proper evaluation. Furthermore, the aging interactions from the simultaneous aging of multiple components must be considered since these interactions are nonlinear and are often the dominate aging contributions, being often larger than the single component aging contributions. Prioritization of aging contributors does not necessarily require precise data and can be a powerful tool to focus aging management activities.

6. *Identification of Risk-Directed Aging Management Strategies*

Once aging contributions are prioritized, aging management programs can be directed to the dominant risk contributors. This chapter illustrates how risk-directed aging management strategies can be defined and can be evaluated. The aging contributors prioritized in the previous chapter are used to define two alternative risk-directed maintenance and replacement programs. By carrying out more frequent maintenances and replacements on the 24 dominant components, it is shown that the aging effects on core damage frequency are basically controlled so as to be less than the baseline core damage frequency.

7. *Time dependent Aging Evaluations*

This chapter describes how detailed time dependent aging results can be obtained from the PSA using the models and approaches given in the previous chapters. Detailed time plots are obtained showing the progression of aging impacts on the core damage frequency and system unavailabilities. The time dependent results show when in a plant's lifetime aging effects will become significant from a risk standpoint and when actions need to be taken. Examples are given for a specific plant showing aging effects having significant impacts on the core damage frequency at a plant age of 15 years because of insufficient maintenances and replacements on the risk dominant components. Once the contributors are identified the aging impacts are controllable.

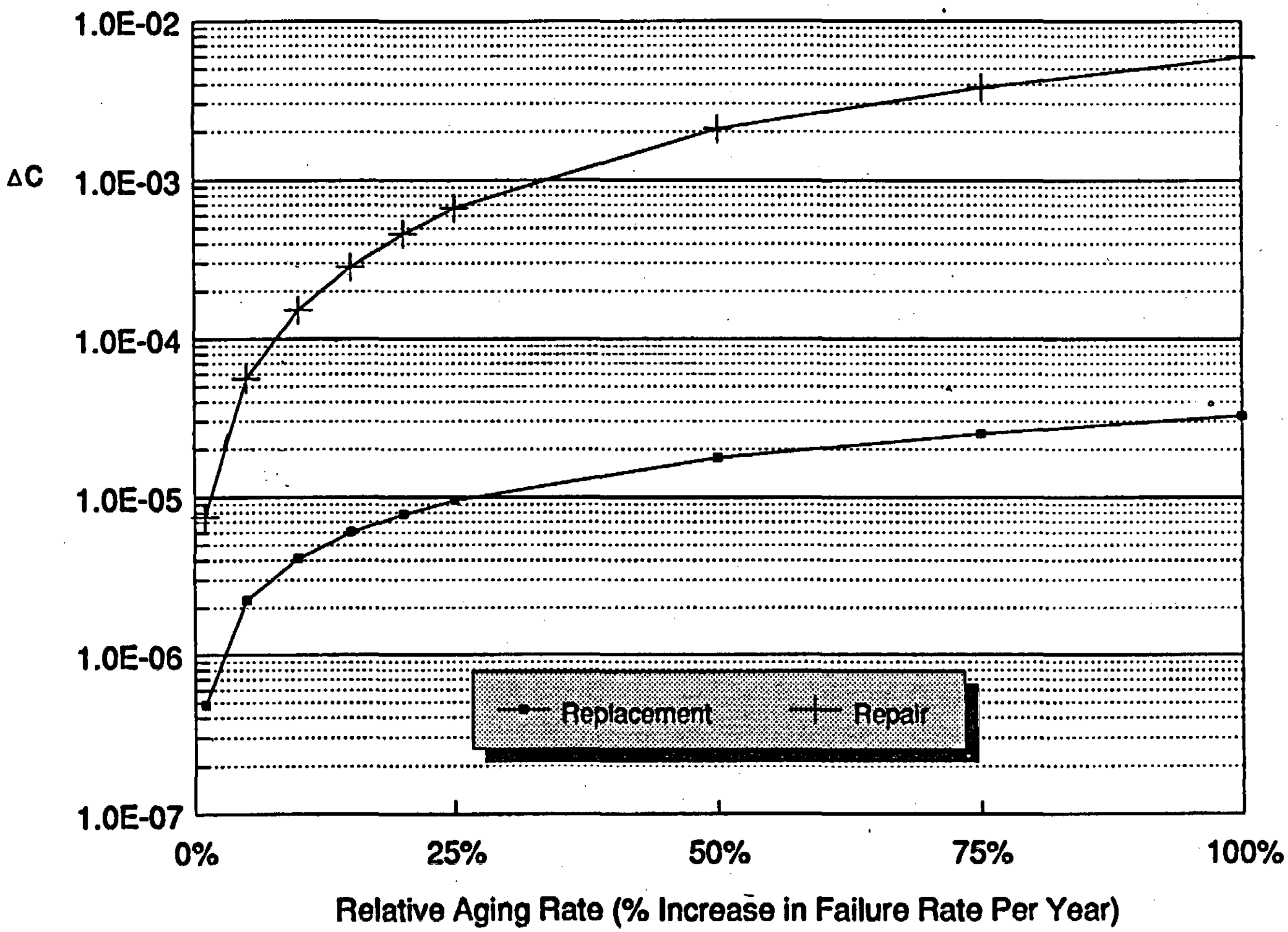
8. *Sensitivity and Uncertainty Evaluations*

Another important use of an APSA is for sensitivity and uncertainty evaluations of the risk effects of aging. Even where aging data are sparse, appropriate sensitivity and uncertainty evaluations can provide useful information on aging sensitivities and on the risk effectiveness of aging management programs. In this chapter, procedures are demonstrated for carrying out sensitivity and uncertainty analyses to evaluate plant sensitivities to aging, to evaluate capabilities of aging management programs, and to identify aging management strategies which effectively control risks from aging over a spectrum of plausible aging behaviors.

The figure on the next page illustrates a sensitivity study that is demonstrated to evaluate two policies: repair at failure versus replace at failure. Under a repair policy, when a component fails then minimal repairs are made; aged pieceparts are not replaced but are again made operational. For a replacement policy aged pieceparts are replaced with new parts at failure. The y-axis (ΔC) is the average increase in core damage frequency over 40 years due to aging, where ΔC is the increase above the standard PSA core damage frequency value. The average increase ΔC again applies to each year. The x-axis is the plausible range of aging exhibited by the components, expressed as a relative percentage increase per year in the component failure rate due to aging.

For the sensitivity study, all components were assumed to have the same relative aging. The same surveillance test intervals were assumed for both policies. The figure shows that the replacement policy controls the core damage frequency increase due to aging for a wide range of plausible aging behaviors. The repair policy does not control the risk effects due to aging, even for relatively small aging behaviors. From the prioritization of aging contributors, which can be carried out in parallel, the dominant aging contributors can be identified and replacements only carried out on the important contributors. Thus , an effective aging management policy can be identified which does not necessarily entail major costs. Similar sensitivity studies can be carried out for other proposed aging management programs or maintenance programs.

CORE DAMAGE FREQUENCY INCREASE: REPLACEMENT VERSUS REPAIR AT FAILURE



9. *Considerations in Using a PSA to Evaluate the Risk Effects from Aging of Passive Components*

Finally, this chapter discusses special considerations, beyond those already discussed, for evaluating the risk effects from aging of passive components. The discussions focus on more detailed analyses which can be done to estimate passive component aging failure rates from basic phenomenological models covering crack growth and corrosion. It is planned that this subject will be covered in greater depth in a subsequent report.

Conclusions

The report which has been developed presents detailed models and systematic procedures for incorporating aging evaluations into a probabilistic safety assessment (PSA) to explicitly evaluate the risk effects due to aging. The approaches can also be applied to a probabilistic risk assessment (PRA). The resulting age-dependent PSA (or age dependent PRA) will allow a spectrum of important applications to be carried out, including prioritization of aging contributors according to their risk importance, evaluation of the risk effectiveness of existing aging management programs, and identification of risk effective aging management policies. Even when aging data are sparse, applications can be carried out to identify the potentially dominant aging contributors, the risk sensitive maintenance practices, and the robust programs which can be carried out to control aging impacts over ranges of plausible aging behaviors that can exist.

ACKNOWLEDGEMENTS

Acknowledgement is given to G.H. Weidenhamer, the NRC project monitor, for providing competent and practical direction to the work and to J.P. Vora of the NRC for his ideas and inspirational guidance. Acknowledgement is given to P. Kafka, Gesellschaft fur Reactorsicherheit (GRS) mbh, for his discussions with the author on the reliability treatments of passive components. Finally, acknowledgement is given to S.M. Scalzo for her invaluable assistance in preparing this report.

1. THE AGE-DEPENDENT PSA VERSUS THE STANDARD PSA

1.0 Introduction

This report describes procedures for explicitly incorporating component aging evaluations into a probabilistic safety assessment of a nuclear power plant. A probabilistic safety assessment, or PSA as it is termed, is a probabilistic model of accidents which can occur at a nuclear plant which can lead to core damage. A PSA focuses on the evaluation of the core damage frequency as opposed to a probabilistic risk assessment (PRA) which also evaluates the resulting consequences and health risks from a core damage event.

Figure 1 is an overview of the basic steps in a PSA. A set of initiating events is first identified which require safety system responses. For each initiating event, an event tree is constructed to define the sequences of system responses (success or failure) which can occur for the given initiating event. The consequence of each sequence in the event tree, in terms of whether a core damage occurs or not, is determined from plant response considerations.

For each defined system failure in the event tree, a fault tree is constructed to identify the basic component failures which can cause the system failure. The fault tree is used to quantify the system failure probability using component reliability models and component data. Human errors, test contributions, and maintenance contributions are included as causes of components being down, in addition to failure causes. The system fault trees are incorporated into the event trees to identify the component contributors to the accidents and to quantify the accident sequence frequencies using component data. The frequencies of the individual accident sequences leading to core damage are finally summed to provided the core damage frequency. Additional details for carrying out a PSA or PRA are given in References 1-3, including specific models and formulas which are used, along with associated computer programs.

In standard PSA evaluations, aging of components is not explicitly included in the component failure models which are used to quantify the system failure probabilities and the core damage frequency. When the effect of component aging is to be specifically evaluated then the standard PSA component failure models need to be modified. Aging of components can significantly increase the component failure probabilities and can

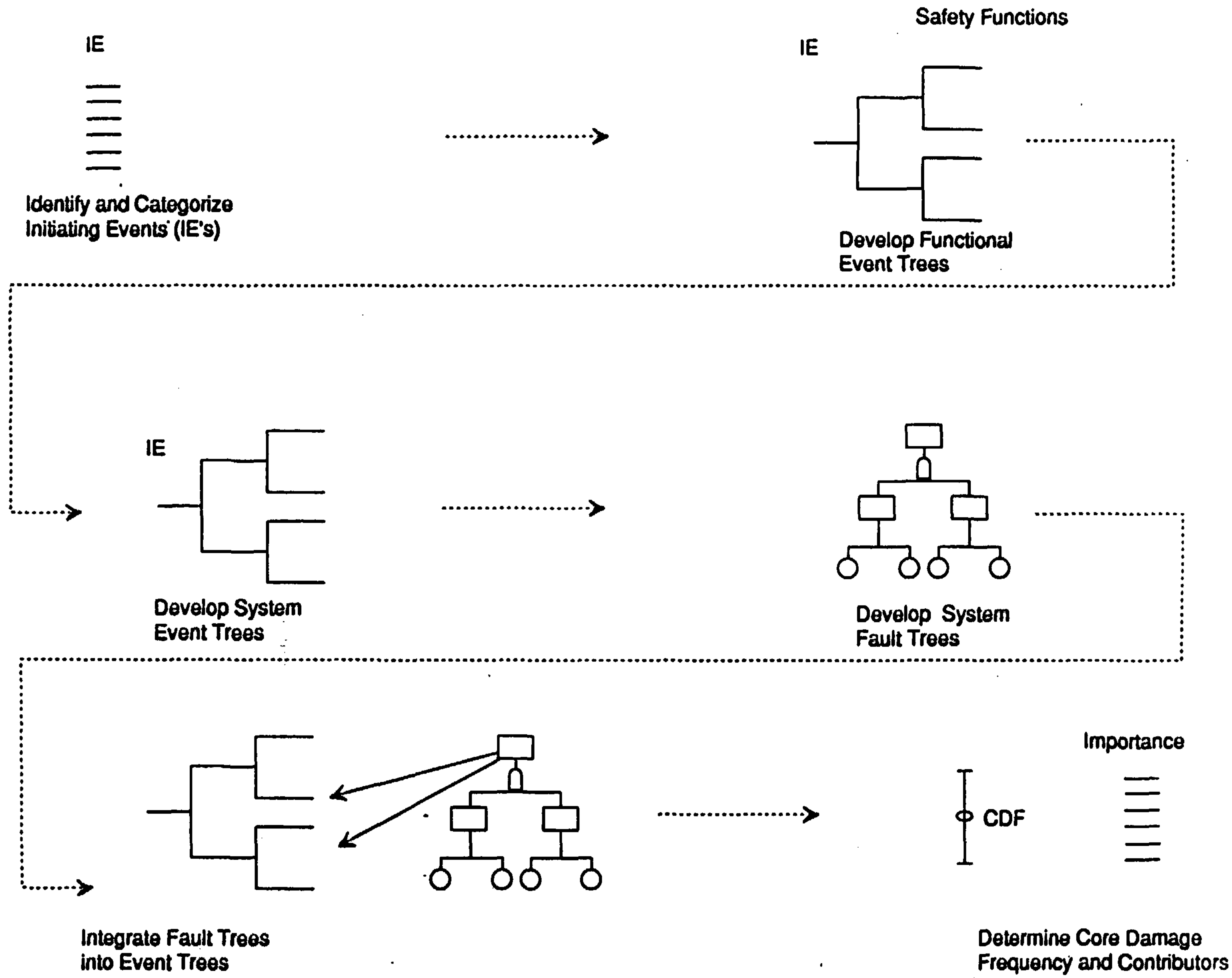


FIGURE 1. BASIC STEPS IN A PSA

significantly increase the core damage frequency, if the aging is not effectively controlled by tests and maintenances. The next section, Section 1.1, briefly describes the differences in component failure treatments which are needed when aging is to be explicitly evaluated using the PSA. This area is described in further detail in Chapter 2.

Standard PSAs also do not explicitly model the effectiveness of tests and maintenances in controlling aging effects. When the effect of aging is to be explicitly evaluated by the PSA then the standard PSA models for test and maintenance need to be modified to explicitly consider their effectiveness in controlling and mitigating aging effects. Section 1.2 briefly describes the differences in test and maintenance treatments that are needed to evaluate the aging control of test and maintenance activities. Detailed treatments are again provided in Chapter 2.

When aging effects are explicitly included in the PSA by using component aging failure models and test and maintenance aging control models then the PSA is transformed to an age-dependent PSA. As an abbreviation for an age-dependent PSA we shall use the term "APSA" where the first "A" denotes "Age-Dependent". The results which are obtainable from an APSA and the applications of an APSA are highlighted in Section 1.3. Finally, as the last part of Chapter 1, special modeling and evaluation issues associated with an APSA are highlighted in Section 1.4. Chapter 1 thus provides an overview of the differences between a PSA and an APSA.

Chapter 2 describes the detailed component models and test and maintenance models which can be used in an APSA. The focus of Chapter 2 is on modeling the reliability effects of aging of active components, such as pumps, valves and circuit breakers. The aging failure rate models in Chapter 2 can also be applied to passive components, however the aging failure rates may need to be determined using techniques different from those used for active components. Chapter 3 describes procedures for actually transforming a PSA to an APSA. Chapter 4 describes different applications of an APSA and their requirements. Chapter 5 presents example applications of an APSA focused on prioritizations of aging contributors . Chapter 6 demonstrates how APSA evaluations can be used to identify risk-effective aging management strategies. Chapter 7 describes how time-dependent applications can be carried out using an APSA. Chapter 8 demonstrates how aging sensitivity and uncertainty evaluations can be carried out. Finally, because the previous chapters focus on active components, Chapter 9 discusses specific considerations for incorporating passive components and their aging impacts into a PSA. It is planned that a separate report will be issued on the treatment of passive components in risk evaluations of aging.

1.1 The Difference in the Treatment of Component Failures

The component failure rate is the basic data used in a PSA to determine the failure probability and the unavailability of a component. Basically, the component failure rate is the probability of a component failure per unit time given no previous failure. A standard PSA assumes the component failure rate is constant and is the same value for all component ages. When aging is explicitly considered then the change in component failure rate as a function of component age must be considered. An APSA allows the component failure rate to be a function of age and to change as the component age increases. The effect of allowing the component failure rate to be age-dependent can cause significant impacts on the calculated system unavailabilities and the core damage frequency.

From reliability theory (see References (4-6)) when age dependence is considered then the component failure rate generally follows a bathtub curve as shown in Figure 2. At an early component age the failure rate decreases with age as design, manufacturing, and installation failures are corrected when they are found. This decreasing failure rate behavior is termed the burn-in period of the failure rate curve. After burn-in, the failure rate remains constant reflecting steady state failure behavior. This flat portion of the bathtub is the constant failure rate period of the failure rate curve. Finally, after the steady state period, the failure rate increases with age, reflecting wear-out and aging behavior. This is the aging period of the failure rate. The lengths of the burn-in, steady state, and aging periods of the bath tub curve can vary for different components and for different operating environments.

A standard PSA assumes a constant failure rate and hence focuses on the steady state portion of the failure rate curve. An APSA, in addition to the steady state behavior, also includes the increasing failure rate portion of the failure rate curve and thus can account

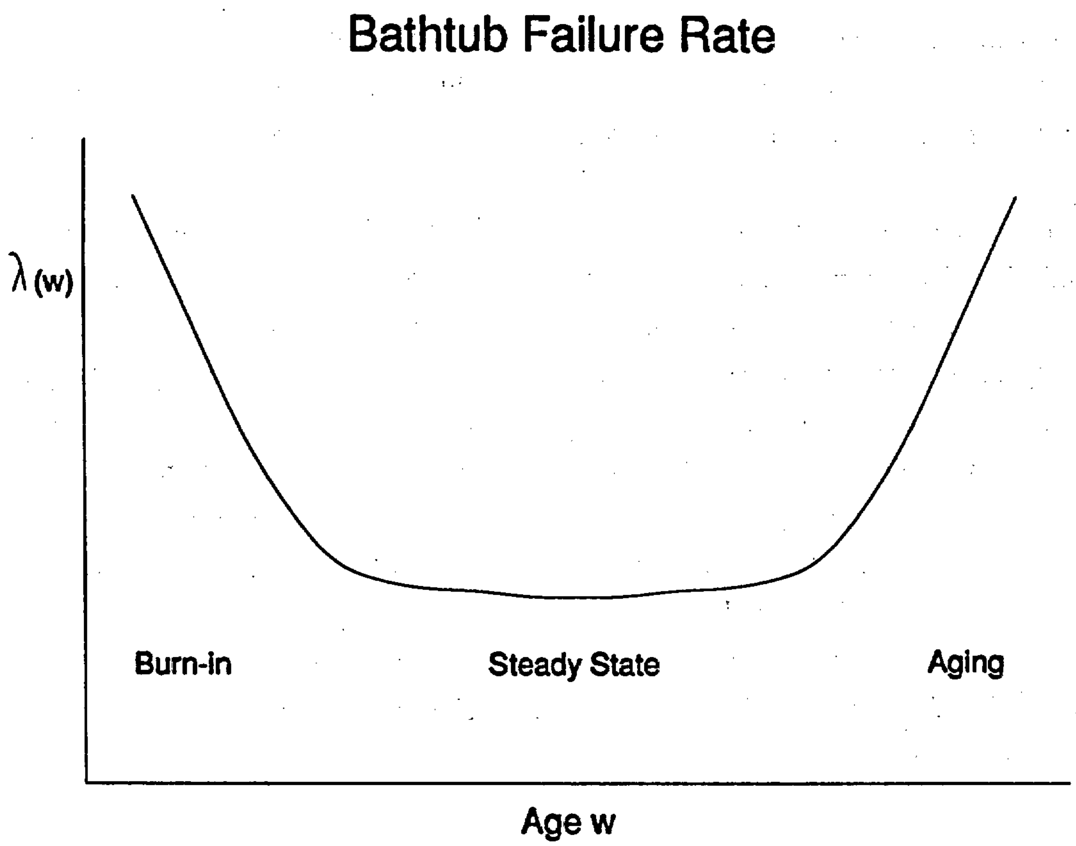


FIGURE 2. THE BATHTUB CURVE OF FAILURE RATE VERSUS AGE

for the transition from a constant failure rate to an increasing failure rate.* Chapter 2 presents specific models which can be used to explicitly include aging in the component failure rate. These models are standard models which are used in the reliability field.

When an APSA explicitly models the increasing component failure rate with age then as indicated, significant impacts can occur in the calculated risk results. If the test and maintenance practices do not control the component aging then the component failure probability and component unavailability can significantly increase with component age because of the increasing failure rate. This in turn can cause the system unavailability to increase with age. When the system unavailability increases with age then the core damage frequency can increase with age. Besides causing unavailabilities to increase, the increasing component failure rates can cause the accident initiating event frequency to increase with age, which can also cause the core damage frequency to increase with age. Whether the increases occur or not, and the sizes of the increases, depends on the aging control of the test and maintenance practices. The sizes of the unavailability effects and the size of the core damage frequency effect are explicitly calculated in an APSA.

1.2 The Difference in the Treatment of Test, Maintenance, and Repair

Since a standard PSA does not explicitly consider the age of the component, the effects of testing, maintenance, and repair in controlling aging are not evaluated in a PSA. Also, since a PSA assumes a constant component failure rate which never changes, the effect of a test, maintenance, or repair activity on the component failure rate is not considered. The effect of a test and maintenance in controlling the aging of a component is a special focus of an APSA. The control of aging is evaluated by determining the change in component age which results from a test or maintenance activity. The effect of a test or maintenance on the age of the component is important since the component failure rate depends on the component age. Hence as the component age is modified through testing and maintenance, the component failure rate is accordingly modified. The failure rate modifications which occur change the component unavailability and the component

*The burn-in period of the failure rate can also be included, and can be important when there can be initial design or manufacturing defects in a new component which is used to replace an aged component. When the component undergoes qualification testing or burn-in testing, as generally carried out for nuclear plant components, then the burn-in period is generally removed.

failure probability which in turn change the system unavailability and the core damage frequency.

Detailed models for the effects of testing, maintenance, or repair on the component age are used in an APSA. If the component is replaced with a new component then the age of the component is set back to the age of a new component. If aged pieceparts are not replaced then the age of the component is not affected and remains the same. Partial maintenances which only replace specific pieceparts, but not the entire component, will cause the age of the component to be set back to a partially restored value. A preventative maintenance, such as lubricating bearings, will not change the age of the component since piece parts are not replaced, but will slow the aging process of the component.

Because of the detailed testing and maintenance models which can be used, an APSA can comprehensively evaluate the effectiveness of a testing and maintenance program in controlling component aging and its resulting impacts on system unavailabilities and on the core damage frequency. Not only is the interval important at which the test or maintenance is performed, but the specific action which is performed is important. Chapter 2 describes models which are used in an APSA to model the aging control of different types of test, maintenance and repair activities. Even when minimal information exists, these models can be useful for evaluating maintenance sensitivities.

It is important to note that because a standard PSA does not model the removal of aging effects by maintenance, it can not explicitly model any benefits from maintenance. Only the negative downtime contribution while maintenance is being performed is explicitly modeled in a PSA. Thus, only the negative effect due to maintenance is explicitly modeled. An APSA models both the benefits and negative effects of maintenance. These effects determine the unavailabilities and core damage frequency which result. Specific formulas for calculating the unavailabilities, and specific approaches to determine the core damage frequency are given in the subsequent chapters. Table 1 summarizes the differences in test and maintenance treatments and in component failure treatments, which are together classified as differences in component reliability treatments, for a PSA and an APSA.

TABLE 1. THE DIFFERENCES IN COMPONENT RELIABILITY TREATMENTS FOR A PSA AND AN APSA

	PSA	APSA
Failure Rate Model	Constant failure rates are used.	Age dependent or time dependent failure rates are also used.
Test Model	A test only determines whether component is up or down.	A test can affect component age and failure rate as well as determining whether component is up or down.
Maintenance	Only downtime for maintenance is considered.	Effects of maintenance in correcting degradations and aging are modeled, as well as inefficiencies and downtime.
Repair Model	Repair does not affect the age or failure rate of component.	After repair, the age and failure rate of component are modified with appropriate models.

1.3 Results Obtainable from an APSA

As for a PSA, the core damage frequency, accident sequence frequencies, and safety system unavailabilities are obtainable from an APSA. For an APSA, however, these results now explicitly include the contributions from aging and explicitly quantify the effectiveness of given test and maintenance programs in controlling aging effects.

An APSA can produce detailed prioritizations of the aging contributors. This is perhaps one of the most important uses of an APSA since it allows one to focus on the dominant aging contributors for aging control, for data collection and monitoring, and for additional analyses. Table 2, for example, ranks the top 95% individual aging component contributors for a given APSA evaluation. Each line entry gives the rank (column 1), the specific component (column 2), the risk importance of the component (column 3), the component unavailbility (column 4), the increase in component unavailability due to aging (column 5), and the core damage frequency contribution from the component aging (column 6). As can be seen, for this application the top 95% contributors consists of only 10 components, and hence relatively few components contribute to the aging impacts on the core damage frequency, allowing one to effectively focus aging analyses and aging control. Details of prioritization evaluations of aging contributors are given in Chapter 5. Chapter 6 describes how the prioritized contributors can be used to identify risk-effective, and cost-effective, aging management programs.

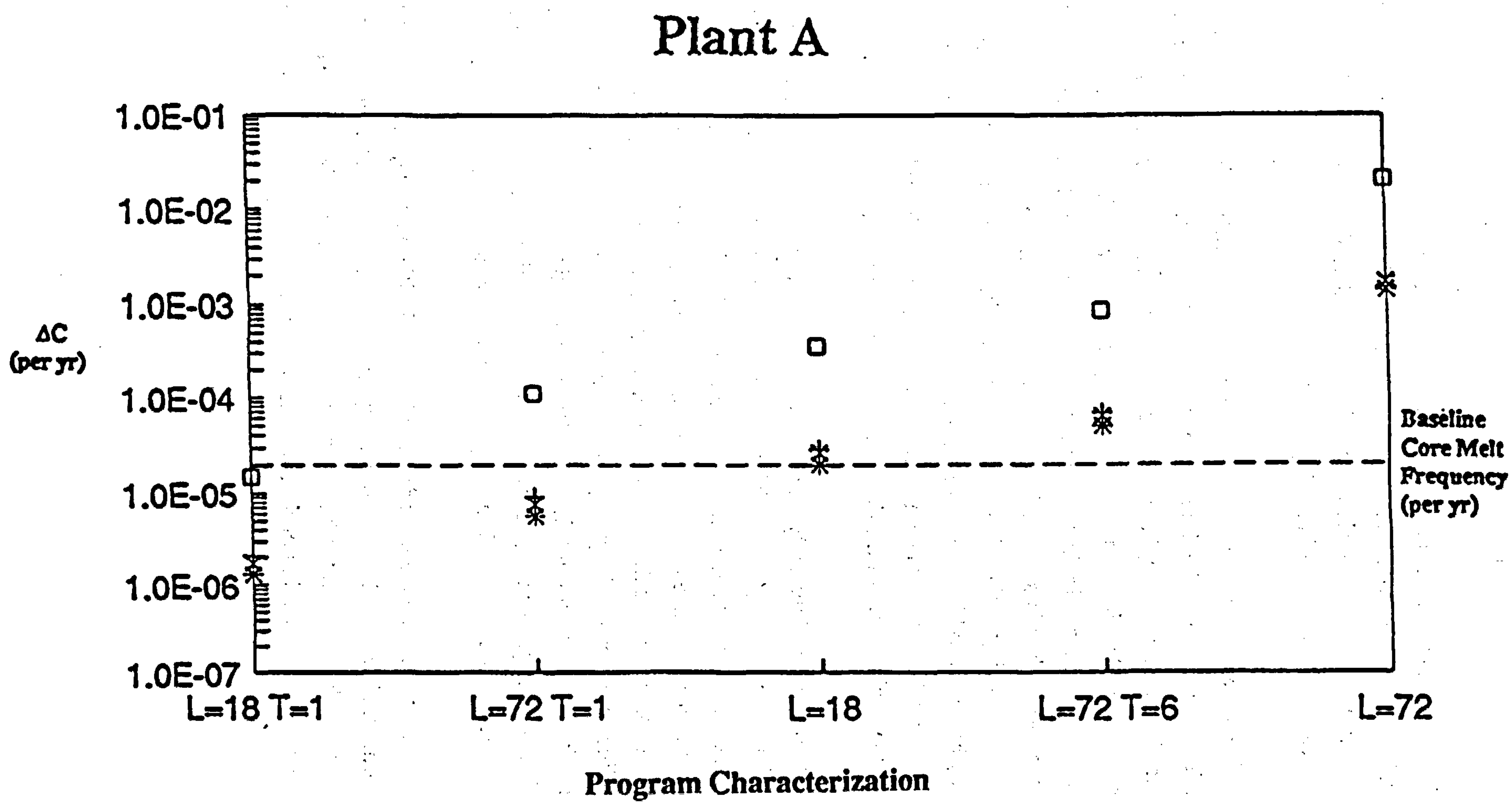
An APSA can calculate the core damage frequency and system unavailabilities as a function of plant age to explicitly show the dynamic, time dependent aging effects. The core damage frequency and system unavailabilities averaged over time periods or averaged over the plant age can also be obtained to show average aging effects. The increases in the core damage frequency or system unavailabilities due to aging as compared to the no aging case can furthermore be obtained to highlight aging increases. Figure 3, taken from NUREG/CR-5510 (7), shows the average increase in core damage frequency ΔC that results from aging at a plant when different test and maintenance programs are carried out. The average increase ΔC applies to each year and the overall core damage frequency for any year is $C_0 + \Delta C$, where C_0 is the baseline core damage frequency from the PSA. The specific test and maintenance programs are not of concern

TABLE 2. PRIORITIZED COMPONENT AGING CONTRIBUTORS

Rank	Component ID	Component Importance I	Component Unavailability q	Aging Factor Δq	ΔC (/yr)
1	ESW-AOV-CC-CCF	9.70E-05	1.0E-03	2.9E-01	2.8E-05
2	EHV-AOV-CC-CCF	6.34E-05	1.0E-03	2.9E-01	1.8E-05
3	ESW-AOV-CC-0241B	3.68E-05	1.0E-03	2.9E-01	1.1E-05
4	ESW-AOV-CC-0241C	3.68E-05	1.0E-03	2.9E-01	1.1E-05
5	EHV-SRV-CC-RV2	2.53E-05	3.0E-04	2.9E-01	7.0E-06
6	EHV-SRV-CC-RV3	2.53E-05	3.0E-04	2.9E-01	7.0E-06
7	DCP-BAT-LF-CCF	2.16E-04	1.08E-03	1.9E-02	4.1E-06
8	HCI-MOV-CC-MV14	5.42E-06	3.0E-03	2.6E-01	1.4E-06
9	HCI-MOV-CC-MV19	5.42E-06	3.0E-03	2.6E-01	1.4E-06
10	ACP-DGN-FR-EDGC	2.09E-05	1.6E-02	3.3E-02	7.0E-07

ΔC = Core damage frequency increase due to aging

FIGURE 3. INCREASE IN CORE DAMAGE FREQUENCY FROM AGING FOR DIFFERENT TEST AND MAINTENANCE PROGRAMS



L = Overhaul interval (in months) for all components

T = Surveillance interval (in months) for all components (if intermediate surveillance is performed) here. Test and maintenance modeling is discussed in Chapter 2. The different points for a test and maintenance program represent different possible component aging failure rates. The results indicate the significant differences that different test and maintenance programs can have in controlling aging effects.

Figure 4 illustrates the type of time dependent results which are also obtainable from an APSA. The figure shows the time dependent core damage frequency increase due to aging for given component aging failure rates and for a given test and maintenance program. The sudden drops in the core damage frequency in Figure 4 occur when major components are replaced in the test and maintenance program. Such time dependent results can show when in a plant's life, aging effects become significant and whether components are being replaced or being overhauled frequently enough. The core damage frequency becomes so high in Figure 4 because key components are not replaced frequently enough, allowing aging effects to build up to relatively high levels. Chapter 7 describes the application of time dependent aging evaluations.

Sensitivity and uncertainty analyses can also be carried out using an APSA to evaluate the core damage frequency sensitivities and uncertainties associated with aging effects. Figure 5 shows the results of a sensitivity analysis which evaluates the aging control of a given test and maintenance program. For the sensitivity analysis, the component aging failure rates are systematically increased to account for plausible aging which can occur. The baseline core damage frequency for the plant is 3×10^{-5} per year. As can be observed, the aging control of this particular test and maintenance program is effective over a plausible range of aging behaviors, limiting the aging increases to be no larger than the baseline core damage frequency. Chapter 8 provides further details.

In this report we focus on the use of an APSA for prioritizing aging contributors and for carrying out sensitivity and uncertainty analyses of aging effects. The models and approaches which are presented however, can also be used to obtain average core damage frequency results due to aging or time dependent core damage frequency results due to aging.

FIGURE 4. TIME DEPENDENT CORE DAMAGE FREQUENCY INCREASE DUE TO AGING

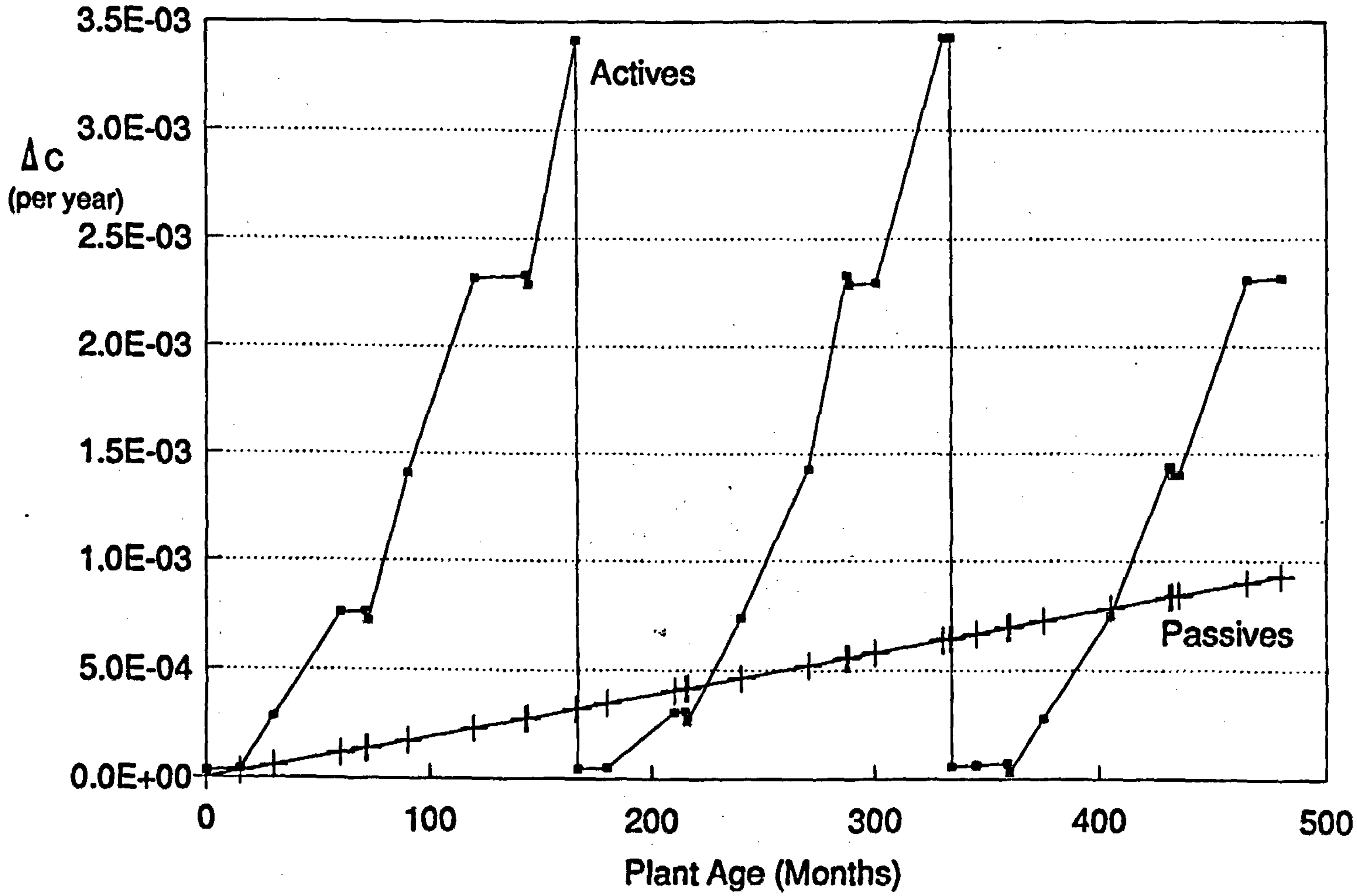
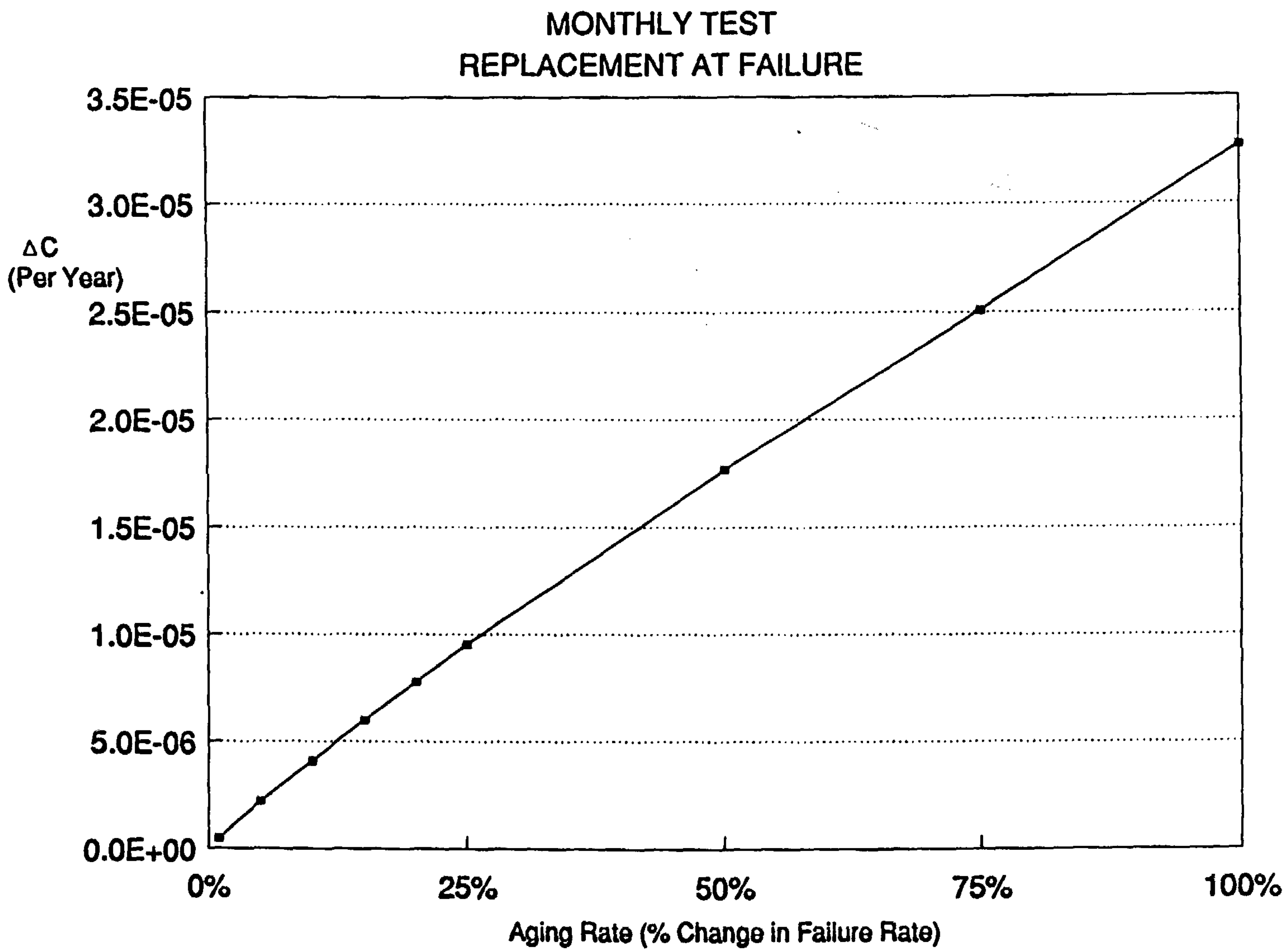


FIGURE 5. SENSITIVITY ANALYSIS EVALUATING THE AGING CONTROL OF A GIVEN TEST AND MAINTENANCE PROGRAM



1.4 Issues Associated with an APSA

An APSA requires more data and more extended models than a PSA and hence there are special issues associated with using an APSA. With regard to data, the basic issue is the present, general sparseness of failure histories for components and for structures. Because of this sparseness of failure data, aging failure rates which are estimated from the raw data will generally have large associated uncertainties. In addition to the imprecision in failure rate values, the shape of the aging failure rate curve will often not be known. When there is no plant specific data available, generic data or expert opinions will need to be used, which will also generally have large uncertainties. These uncertainties need to be taken into account in using an APSA for a given application. The most thorough way of treating these uncertainties is to carry out sensitivity studies or uncertainty analyses using different aging failure rates. Chapter 8 will illustrate how such studies can be carried out. Even with little precise aging failure rate data, useful information can be obtained from an APSA regarding important aging contributors and sensitivities to aging effects, as will be discussed in the subsequent chapters.

At present, there can also be a lack of information on detailed characteristics of specific tests and maintenances in controlling aging to allow their precise modeling in an APSA. Where information is lacking, approximate models may be used to approximate or bound the effects of the test or maintenance in controlling aging. Examples of approximate or bounding models are the "good as old" and "good as new" models as termed in reliability literature. These models are presented in subsequent chapters. More precise test and maintenance models are also presented, which allow more detailed analyses to be carried out if data is available, or which allow sensitivity analyses to be carried out. By using these models, the aging control of given test and maintenance practices can also be bounded or can be accurately evaluated where information is available. Perhaps as importantly, the sensitivity of risks to aging effects under given test and maintenance practices can be evaluated. The risk important tests and maintenances can thereby be determined to focus further evaluations and program improvements. The subsequent chapters describe the bases for these applications, as well as for other applications. Table 3 summarizes the issues which are associated with an APSA.

TABLE 3. ISSUES ASSOCIATED WITH AN APSA

Data Bases	Little time-history information exists to estimate age dependent or time dependent failure rates. Uncertainty and sensitivity studies need to account for this lack of data.
Failure Rate Models	Different failure rate models can cause significant differences in the calculated results in an APSA. Sensitivity studies can investigate these effects.
Test and Maintenance Models	Differences in the test and maintenance models can cause significant differences in APSA results. Bounding models and sensitivity studies can help address this issue.
Results	Results from an APSA can be uncertain. Relative results and more qualitative results can be focused on to address this issue. Sensitivity and uncertainty analyses can also identify the meaningful conclusions and interpretations.

2. COMPONENT RELIABILITY MODELS USED IN AN AGE-DEPENDENT PSA

2.0 Introduction

As described in the previous chapter, what makes an age-dependent PSA, or APSA, different from a standard PSA is the component failure models and the test and maintenance models, which together comprise the component reliability models which are used.

This section describes the component failure models and test and maintenance models which can be used for an APSA. These models are necessary to explicitly evaluate aging effects and their impacts on system unavailabilities and the core damage frequency. To begin the chapter, the definition of aging for reliability and risk applications is presented. The difference between the component age and running time is then discussed. With these basic concepts defined, the modeling of the aging component failure rate is described, and specific aging failure rate models which can be used in an APSA are given. Features of these models and ways these models can be applied are described.

Models are then presented for quantifying the effects of testing and maintenance with regard to controlling aging. Specific models are presented which can be applied to surveillance tests, corrective maintenances, preventative maintenances, and repairs. These models quantify the different effects a specific activity has on the component age and its associated aging failure rate. Models for maintenance and repair of component pieceparts are also included. Complete aging control, partial aging control, and inefficiencies in aging control are included in these models.

2.1 Definition of Aging for Reliability and Risk Applications

The definition of aging for reliability and risk applications is directly tied to the behavior of the component failure rate. From basic reliability theory (References 4-6) the definition of the component failure rate at a given time is:

The component failure rate at a given time t	=	The probability of component failure per unit time at time t given no previous failure of the component	(1)

The failure rate of a component at time t is thus basically the rate of failure at time t when the component has not previously failed. The failure rate always applies to a given failure mode (e.g., fail to open, fail to close, etc.) and different failure modes will have different failure rates.

The standard symbol used for the component failure rate is $\lambda(t)$. Thus,

$$\lambda(t) \quad = \quad \text{The component failure rate at a given time } t, \tag{2}$$

For aging evaluations, it is also necessary to express the component failure rate as a function of the component age. Let w denote the component age. Then,

$$\lambda(w) \quad = \quad \text{The component failure rate at a given component age } w. \tag{3}$$

The definition of $\lambda(w)$ now is in terms of the component age:

$$\lambda(w) \quad = \quad \text{The probability per unit age that the component fails at age } w \text{ given no previous failure of the component.} \tag{4}$$

The failure rate at age w is thus the rate of failure at the given age when the component has not previously failed. The failure rate as a function of age can be a different shape and form than the failure rate expressed as a function of time if time and age are not the same.

The component failure rate at a given time can be related to the component failure rate at a given age. To relate time t and age w, the age of a component at a given time needs to be known. This relationship can be expressed as $w = w(t)$. Then the failure rate as a function of the age can be translated to a failure rate expressed as a function of time. This failure rate relationship can be expressed as $\lambda(t)dt = \lambda(w(t))dw(t)$, where $\lambda(t)$ is the failure rate function versus time and $\lambda(w)$ is the failure rate function versus age, i.e., $\lambda(t)$

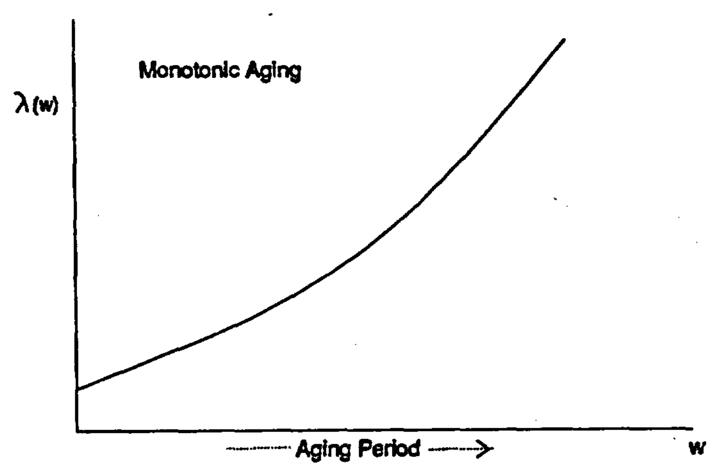
is given by Equation (2) and $\lambda(w)$ by Equation (3), which are generally different functions.*

For usual applications, a point in given time t is simply the component age w plus some constant c (which is the component installation time). For this usual case, $t = w + c$ and $\lambda(t) = \lambda(w(t))$ which is what we will assume for our applications.

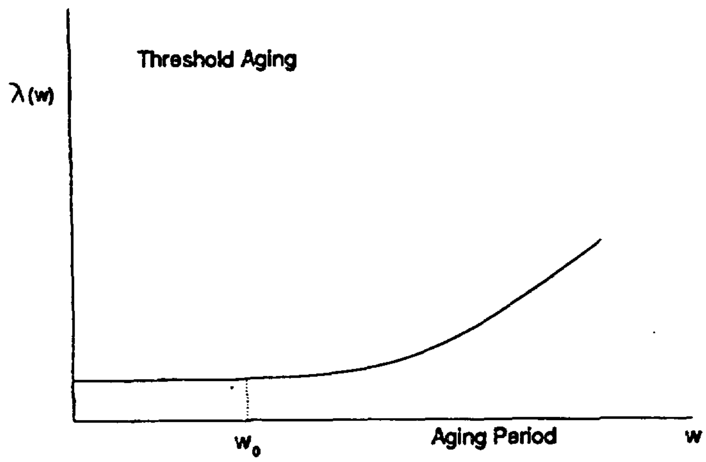
For reliability and risk applications the definition of aging is directly related to the failure rate as a function of age $\lambda(w)$. For reliability and risk applications, a component (or structure) is defined to be aging if the failure rate as a function of component age is increasing:

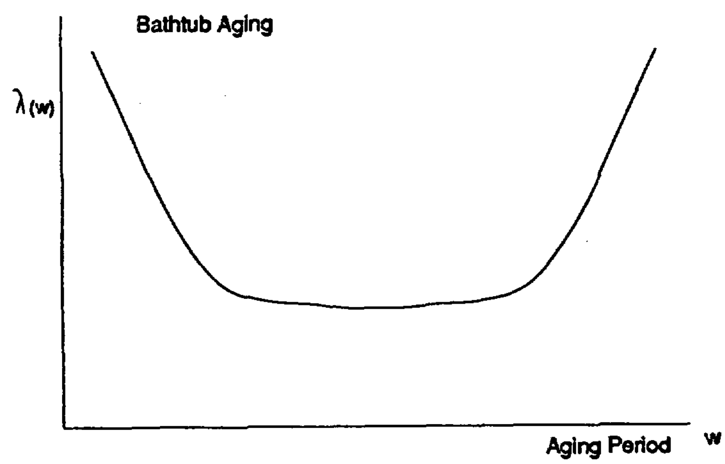
Aging occurs in the component if the failure rate $\lambda(w)$ as a function of component age is increasing.

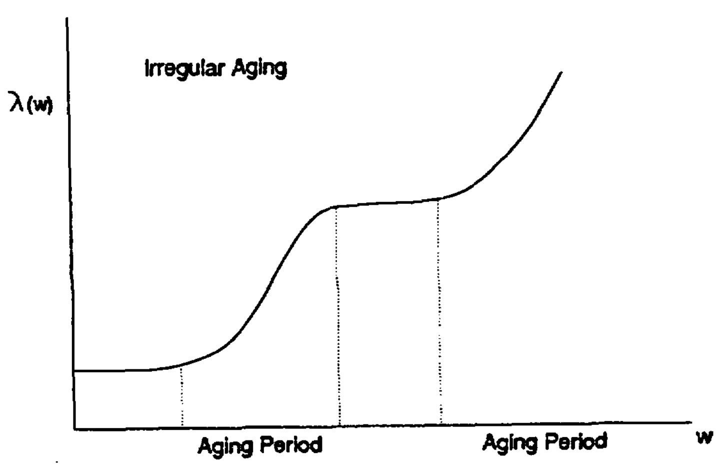
It is important to note that the definition of aging is related to the failure rate as a function of age and not as a function of time. The failure rate as a function of age may be increasing, i.e. may be aging, while the failure rate as a function of time may not. For aging to occur, the failure rate $\lambda(w)$ does not need to continuously increase with age. There can be periods in which there is no aging, i.e., in which $\lambda(w)$ does not increase with age w. Periods in which the failure rate $\lambda(w)$ is increasing, are aging periods. The figures below indicate different types of aging which can occur with different types of age dependent failure rates $\lambda(w)$.



*For simpler notation, the two different functions, $\lambda(w)$ and $\lambda(t)$, are not shown with different symbols. Which failure rate is being referenced, i.e., versus time or age, will be clear from the discussions.


Threshold Aging
λ(w)
w_0
Aging Period
w


Bathtub Aging
λ(w)
Aging Period
w


Irregular Aging
λ(w)
Aging Period
Aging Period
w

All the above failure rates exhibit some period or periods of aging. In general, aging periods at the end of the component age are of most interest and concern because of the large reliability and risk effects which can result if the aging continues unchecked. However, aging in any period can cause significant reliability and risk problems.

2.2 Aging Failure Rate Models

Various parametric models exist which can be used to model component failure rate aging behavior for reliability and risk applications. The models most often used for aging are the linear aging failure rate model, the Weibull aging failure rate model, and the exponential aging failure rate model. These models can represent increasingly more severe failure rate increases with age. Thresholds can be incorporated in any of these models to represent aging beginning at some nonzero age w_o. In general all the standard parametric models apply to aging periods occurring at the end of the component age with a possible initial threshold. To model aging periods occurring at earlier ages followed by some periods of nonaging, the models can be extended by reinitializing the age variable w or by defining a variable which is a nonlinear function of the age. Equations and representative graphs for the linear model, Weibull model, and exponential model are given below for aging occurring after some arbitrary threshold age w_o. Subsequent chapters will discuss how these failure rate models are applied in an APSA.

Linear Aging Failure Rate Model

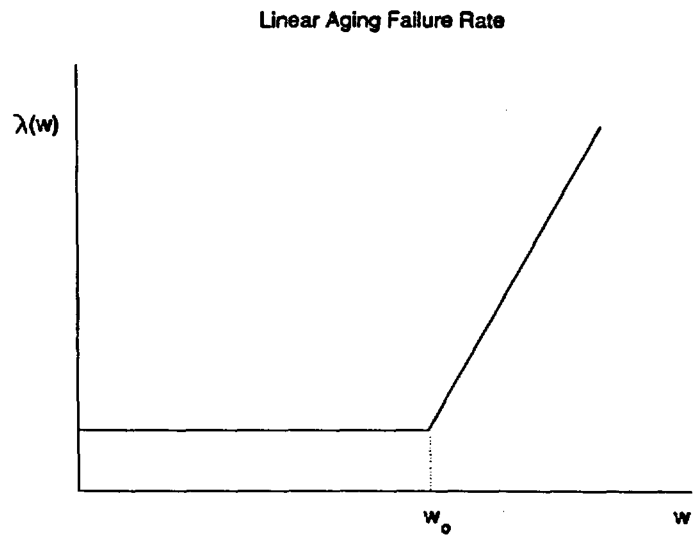
$$\lambda(w) = \lambda_o; \quad w \leq w_o \tag{5}$$

$$\lambda(w) = \lambda_o + \alpha(w - w_o); \quad w > w_o \tag{6}$$

$$\lambda_o = \text{initial constant failure rate} \tag{7}$$

$$\alpha = \text{constant aging rate} \tag{8}$$

$$w_o = \text{threshold age after which the failure rate increases} \tag{9}$$



Weibull Aging Failure Rate Model

$$\lambda(w) = \lambda_o \quad ; w \leq w_o \tag{10}$$

$$\lambda(w) = \lambda_o \left[\frac{w}{w_o}\right]^b ; w > w_o \tag{11}$$

where

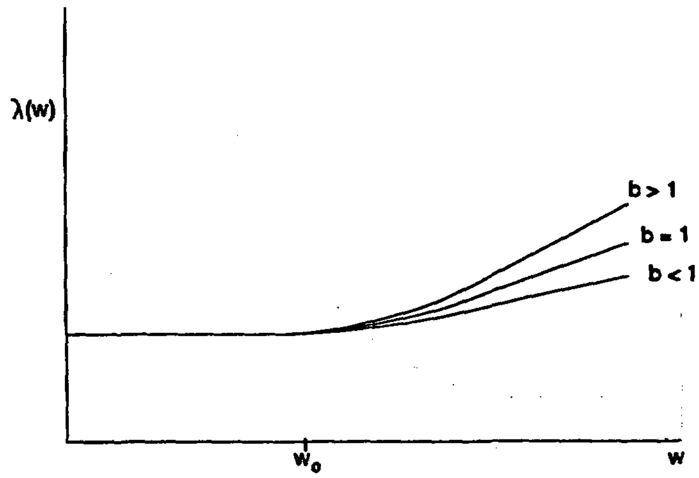
$\lambda_o =$ initial constant failure rate (12)

$b =$ Weibull shape parameter (13)

$w_o =$ threshold age after which the failure rate increases (14)

Other equivalent forms also exist for the Weibull model but the general property is that the failure rate increases as some power b of the age.

Weibull Aging Failure Rate



Exponential Aging Failure Rate Model

$$\lambda(w) = \lambda_o \quad : w \leq w_o \tag{15}$$

$$\lambda(w) = \lambda_o \exp\left(c(w-w_o)\right) : w > w_o \tag{16}$$

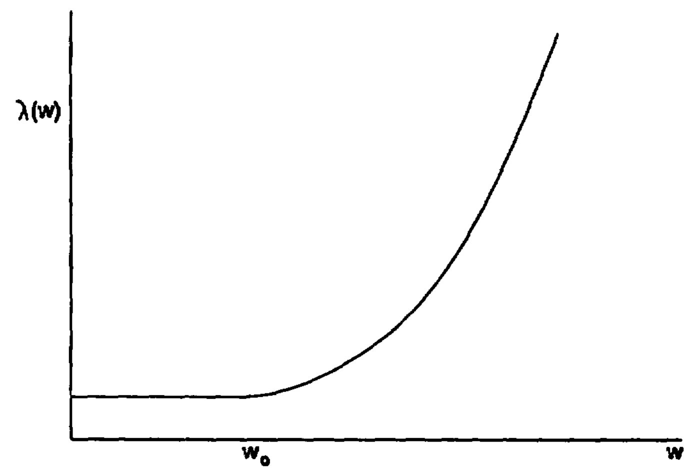
λ_o = initial constant failure rate (17)

c = exponential scale parameter (18)

and

w_o = threshold age after which the failure rate increases (19)

Exponential Aging Failure Rate



2.3 Failure Rate Aging Effects Versus Overall Time Trends

There is sometimes a confusion between failure rate aging effects and an overall time trend in the component failure behavior. One may, for example, observe no time trends in the failure behavior as recorded in data and erroneously conclude that there is no component failure rate aging effects. It is important to understand the difference between failure rate aging effects and overall time trends in the failure behavior to properly model aging effects in an APSA.

The overall component failure behavior as a function of time is generally described by the failure frequency and to understand the difference between failure rate aging effects and an overall time trend in the failure behavior one must first understand the definition of the failure frequency:

The component failure frequency at time t	=	The expected number of component failures at time t per unit time	(20)

Note that the failure frequency is the rate of failure at a given time regardless of whether the component previously failed or not. The component failure rate as previously defined by Equations (1) and (4) is the rate of failure from only first failures. The failure frequency as defined by Equation (20) is the rate of failure from first, second, third, etc. failures.

The failure frequency is sometimes given the symbol f(t):

$$f(t) = \text{the failure frequency at time t.} \tag{21}$$

The failure frequency can be estimated from failure histories by counting the number of failures which occur in given intervals of time and dividing by the time intervals.

The component failure rate versus age $\lambda(w)$ can show aging effects while the failure frequency f(t) versus time may show no overall trends or aging effects. This is because the failure frequency generally incorporates the effects of test and maintenance and does not account for any change in component age if the component is replaced or renewed. The component failure rate versus age on the other hand gives the failure rate behavior between maintenances and replacements. When a new component is installed the age starts over but the time doesn't. These differences are important to understand since confusion on age versus time can result in statements being made that components are not aging when indeed they are. This confusion can furthermore result in incorrect data analysis and incorrect aging modeling being carried out.

To more fully understand the difference between failure rate aging effects and overall time trends in the failure frequency one also needs to consider the impacts of component renewals. In reliability terms,

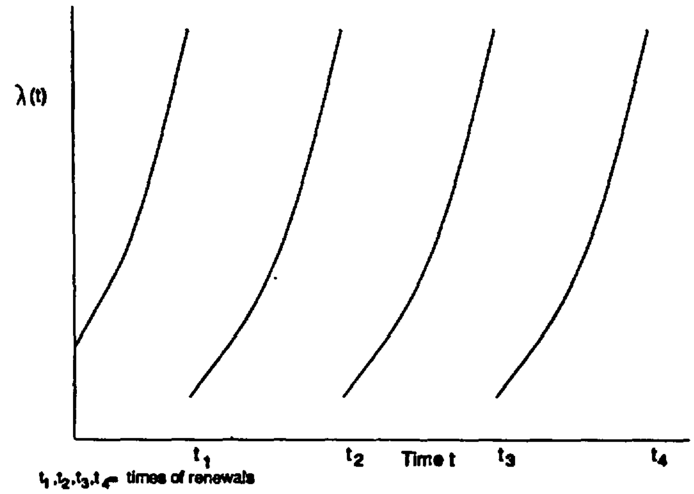
A renewal is a restoration of the component age back to zero, i.e., w = 0. (22)

Also,

At a renewal the failure rate is set back to its original value at age w = 0 and the aging behavior is restarted. (23)

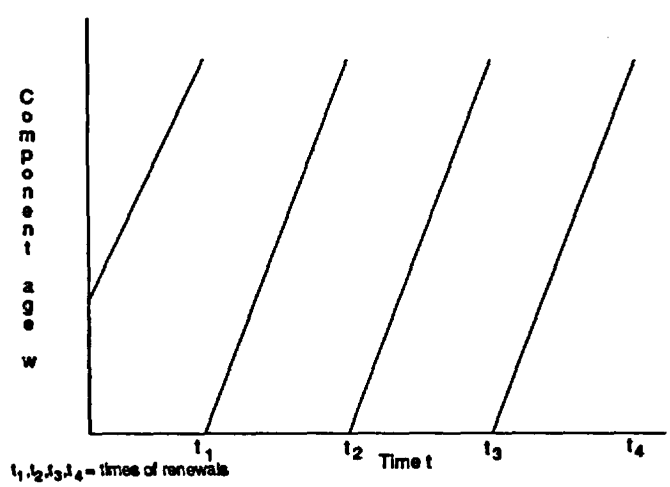
For reliability applications a renewal is defined in terms of its effect on the failure mode associated with the component failure rate. If a given piecepart of the component (e.g., a valve actuator) is the principal contributor to the failure mode and the part is replaced with a new part, then the component age for that failure mode is effectively reset to zero. If several parts of the component contribute to the failure rate for a given failure mode then all the parts will need to be replaced with new parts to reset the failure rate age back to zero. The figure below illustrates the failure rate behavior between renewals.

Failure Rate Behavior Versus Time



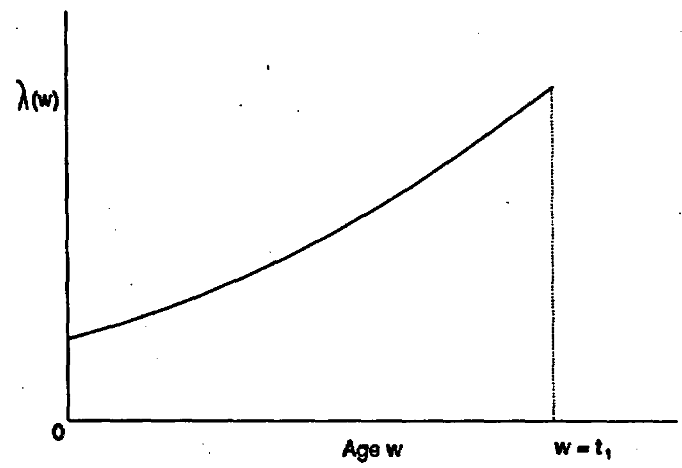
Note that what is plotted is the failure rate versus time. The failure frequency f(t) versus time follows the same behavior and incorporates the effects of the renewals. As a function of time there is no overall trend since the failure behavior is cyclic. The component age repeats at each renewal cycle. The relationship of the component age w with time t is shown below.

Component Age Versus Time



The failure rate versus age behavior is the behavior in the first renewal cycle which is then repeated for each renewal cycle. The failure rate versus age behavior for each renewal cycle is illustrated below.

Failure Rate Behavior Versus Age

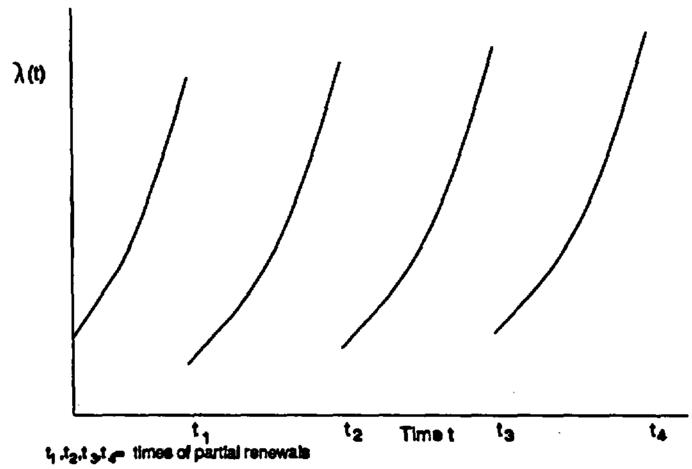


This difference between the failure rate behavior versus age and the failure frequency behavior versus time, or failure rate behavior versus time, is quite important. The failure frequency behavior *versus time* and the failure rate *versus time* show no overall time trend since the behavior is cyclic. The failure rate *versus age* increases with age and shows strong aging behavior.

Sometimes, failure data is analyzed and the failure frequency versus time or failure rate versus time is obtained. This is then mistakenly interpreted as being the failure rate behavior versus age. The failure frequency or failure rate versus time may show no overall trend with time. This is then mistakenly interpreted as the failure rate versus age showing no aging effects. However, when the failure rate is correctly determined versus age, then aging effects may be observed. Various data analysis techniques which are used to analyze data for aging effects actually analyze for overall time trends in the failure frequency. It is extremely important that the proper data analysis be carried out to differentiate aging behaviors versus age and overall trend behaviors versus time. Failure rates versus age are required for an APSA when test and maintenance effects on the age are explicitly modeled. This will be further amplified in subsequent sections.

Instead of complete component replacements or renewals, partial renewals can also take place at a maintenance or repair where the failure rate age is not reset to zero but to some lower but nonzero value. This can correspond to replacement of only specific pieceparts or replacement of a part, not with a new part but with a rebuilt part. The figure below illustrates the effects of partial renewal on the component. As can be seen, an overall time trend in the failure frequency now can be seen.

Failure Rate Behavior Versus Time:
Between Partial Renewals



2.4 Age Dependent and Time Dependent Component Reliability Results

Age dependent component failure rates are used in an APSA to calculate component reliability results. The component reliability results are then used to calculate the time dependent system unavailabilities and the time dependent core damage frequency. The time dependent system unavailabilities and core damage frequency are calculated with regard to the plant age which serves as the reference time. Because they are used to calculate the system unavailabilities and core damage frequency it is important to understand the component reliability results which are calculated in an APSA.

The component reliability results calculated in an APSA can include the age dependent component unreliability, the time dependent component unreliability, the age dependent component unavailability, and the time dependent component unavailability. These basic quantities define the age-dependent and time-dependent reliability and availability behavior of the component. Which characteristics are calculated for a particular APSA depends upon the calculational approach used in the APSA as will be discussed in Chapters 3.

The *age dependent component unreliability* is the probability of component failure by a given age:

The age dependent component unreliability at age w = The probability that the component will fail before age w (24)

The *age dependent reliability* is one minus the age dependent unreliability and is the probability that the component will not fail before age w. The symbol sometimes used for the age dependent unreliability is U(w). Thus,

U(w) = The age dependent component unreliability. (25)

From standard reliability theory (References 4-6),

$$U(w) = 1 - \exp\left(-\int_0^w \lambda(w')dw'\right) \tag{26}$$

where $\lambda(w')$ is the age dependent failure rate.

The *time dependent unreliability* is similar to the age dependent unreliability but is defined as a function of time:

U(t) = The time dependent unreliability (27)

= The probability that the component will fail before time t (28)

$$= 1 - \exp\left(-\int_0^t \lambda(t')dt'\right) \tag{29}$$

where now $\lambda(t')$ is the time dependent failure rate at time t'. As was indicated, the function $\lambda(t')$ is generally different than the function $\lambda(w')$. These failure rate functions will only be the same if the time origin (t=0) is the same as the age origin (w=0) and there is no test, maintenance or replacement activity which acts to set back the component age.

In addition to the component unreliability (or component reliability) the other basic component characteristic is the component unavailability. The *age dependent unavailability* is the probability that the component is down at a given age:

The age dependent component unavailability at age w	=	The probability that the component is down at age w.	(30)

The symbol sometimes used for the age dependent component unavailability is Q(w). Thus,

$$Q(w) \quad = \quad \text{The component unavailability at age w.} \qquad (31)$$

The *age dependent availability* is one minus the unavailability and is the probability that the component is up at a given age. The *time dependent unavailability* is the probability that the component is down at a given time:

The time dependent component unavailability at time t	=	The probability that the component is down at time t.	(32)

The symbol often used for the time dependent component unavailability is Q(t):

$$Q(t) \quad = \quad \text{The time dependent component unavailability.} \qquad (33)$$

The *time dependent availability* is one minus the time dependent unavailability and is the probability that the component is up at a given time.

For an APSA the time dependent component unreliability and time dependent component unavailability need to be calculated to obtain the time dependent system unavailabilities and time dependent core damage frequency where the reference time is again the plant age. The plant age is not generally the same as the component age since maintenances on the component and component replacements can reset the component age. The time dependent component unreliabilities and unavailabilities are determined from the age dependent component unreliabilities and unavailabilities by tracking the component age with time in the APSA.

The specific formulas for the above component reliability characteristics depend upon the specific aging failure rate model and the specific models used for testing, inspection, maintenance, and repair. Specific testing, inspection, maintenance, and repair models, and formula implications, are given in the next section. A summary of the formulas for the component unreliabilities and unavailabilities is also given in the appendix. These specific formulas can be used to transform the PSA into an APSA. The next chapter, Chapter 3, describes the approaches which can be used to actually transform the PSA to an APSA.

2.5 Modeling the Aging Control of a Test, Maintenance, or Repair Activity

When modeling the aging control of a specific test, maintenance, or repair activity for an APSA the following three questions need to be asked for the given activity:

1. What is the effect of the activity on the operational state of the component?

2. What is the effect of the activity on the age of component?

3. What is the effect of the activity on the aging of the component?

The answers to these questions determine the appropriate aging control model to be used for the test, maintenance, or repair activity. For many applications, the activity is performed on a component piecepart instead of the whole component, and the above questions then apply to the specific piecepart. We consider each of these questions in further detail.

1. What is the effect of the activity on the operational state of the component?

For the usual modeling in a PSA which also applies to an APSA, the component can either be up or down, i.e. can be available or unavailable. Hence for an APSA there is one of two possible answers:

a. The activity changes the state of the component,

or

b. The activity does not change the state of the component.

Testing and maintenance activities which bring the component down for the test or maintenance must have an associated downtime for the activity. The component is usually assumed to be in an up state after the activity. If inefficiencies are considered then there is a probability that the activity will leave the component in a down state due to testing or maintenance equipment failures, procedure problems, or human errors. The probability then needs to be assigned for each of these possibilities. If the component is modeled to have more than two states, as for Markov models, then the state or possible states after the activity needs to be defined with their associated probabilities. For the applications discussed here, it will generally be assumed that the component is modeled as having two states, an up state or down state.

2. *What is the effect of the activity on the age of the component?*

This is a question regarding the renewal effect of the activity with regard to the age of the component. The renewal effect is with regard to the failure mode of the component identified in the PSA (and APSA). There is one of three possible answers to this question:

a. The activity does not renew the component and hence does not change the age of the component with regard to the failure mode being considered,

b. The activity completely renews the component and sets the age back to zero for the failure mode being considered,

or

c. The activity partially renews the component and sets the age to some intermediate value for the failure mode being considered.

These three answers can be shortened to:

a. No renewal,

b. Complete renewal,

or

c. Partial renewal.

For a partial renewal answer, the degree of renewal and the new age after the activity need to be modeled. For a partial renewal, if possible inefficiencies are also modeled, then the age after the activity can be larger than the age before the activity. The proceeding sections describe specific maintenance models which can be used to determine the effect of an activity on the age of the component.

3. *What is the effect of the activity on the aging of the component?*

This is different than the previous question and addresses the effect of the activity on the aging rate of the component after the activity. For example, a preventative maintenance consisting of lubricating a pump does not generally renew the pump but slows down the wearing processes on the pump and hence slows down the aging rate of the pump.

There are two possible answers to this question:

a. There is no change in the aging, i.e., no change in the form of the aging failure rate,

or

b. There is a change in the aging failure rate and the change needs to be defined.

Specific models for determining the effect of an activity on the aging are also described in the following sections.

Table 4 summarizes the above questions and alternative answers which determine the appropriate aging control model to be used for the test, maintenance, or repair activity. In fact, it can be argued that the questions in Table 4 need to be answered to assess the aging control of any test, maintenance, or repair activity, regardless of whether an ASPA is done or not. The models which are presented in the following sections progress from simpler models to more complex models in addressing each of these questions.

2.6 The Good as New Restoration Model and The Good as Old Restoration Model

The two most straightforward models which can be used to quantify the aging control of a test, maintenance, or repair activity are the good as new restoration model and the good as old restoration model. These models are described below in terms of the answers they

TABLE 4. QUESTIONS AND ALTERNATIVE ANSWERS TO EVALUATE THE AGING RELIABILITY EFFECTS OF AN ACTIVITY

QUESTIONS	ALTERNATIVE ANSWERS
What is the effect of the activity on the operational state?	Changes the state of the component. Does not change the state of the component.
What is the effect of the activity on the component age?	No effect on the age(age remains the same). Completely renews the component (age set back to zero). Partially renews the component (age determined by a model).
What is the effect of the activity on the component aging?	No change in aging rate (same aging failure rate used). Aging rate modified (new aging failure rate determined by a model).

give to the questions regarding the effect of the activity on the operational state of the component, the age of the component, and the aging of the component.

The Good as New Restoration Model

The good as new restoration model provides the following answers with regard to 1) the operational state of the component after the activity, 2) the effect on the age of the component, and 3) the effect of the activity on the aging of the component:

1. The component is in an up state after the activity,

2. The activity renews the age back to zero (to "as good as new"),

and

3. There is no change in the aging behavior after the activity (the same aging failure rate applies with the age reset to zero).

The good as new restoration model is used to model an activity which replaces or completely renews the component (or component piecepart if pieceparts are being modeled). If a component piecepart is the dominant contributor to the component failure mode being considered then renewal of the piecepart will basically result in renewal of the component. The good as new restoration model or good as new model for short, is thus used to model a maintenance or repair activity which replaces or effectively overhauls the component or the dominant contributing component piecepart. Relatively simple equations for the component unreliability and unavailability result when the good as new model is used.

The Good as Old Restoration Model

The good as old restoration model is the other straightforward model which can be used to model a testing, inspection, maintenance, or repair activity. The good as old restoration model is the model opposite to the good as new restoration model with regard to renewal. The good as old model provides the following answers to the three questions regarding 1) the component state 2) the age effect, and 3) the aging effect:

1. The component is in an up state after the activity,

2. The age remains the same after the activity (no renewal) and there is no age setback,

and

3. There is no change in the aging behavior after the activity; the same aging failure rate applies with the same age after the activity as before the activity.

The good as old restoration model, or good as old model for short, is used to model an activity which assures that the component is in an operational state (up state) but does minimal repairs on the component if the component is not functionally failed. Thus, there is no removal of degradations or no major renewal of the component and the age of the component basically remains the same. When applied to a component piecepart, then the piecepart is not renewed or significantly refurbished. The good as old model is used to model a surveillance test or inspection activity which does not involve major maintenance or repair actions. If a failure or severe degraded state is detected which requires correction then the repair activity can be separately modeled as a good as new activity using the good as new model. Thus, routine surveillance testing and inspection can be modeled as being as good as old activities and when failure or severe degradation occurs then the repair or corrective activity can be modeled as being a good as new activity. The good as old model again produces relatively simple equations for the component unreliability and unavailability.

To utilize the formulas for the good as new restoration model or the good as old restoration model one must determine whether the aging control of a given test, maintenance, or replacement is best described as being good as new or as being good as old. The good as old model can be used to provide an upper bound and the good as new model a lower bound for the effect of the activity. Combinations of the good as old and good as new models can be used for different activities carried out at a plant. For example, as was indicated, a surveillance test carried out to assure a component is operational can be modeled as having minimal aging control unless the component is found failed. The surveillance test can thus be modeled as being as good as old with the repair of a failure being modeled as good as new. The surveillance test interval can be used as the good as old restoration interval and the good as new restoration interval can be taken to be the mean time to failure. If scheduled replacements or overhauls are in addition carried out then these activities can separately be modeled. Thus, the good as new and good as old models can provide flexibility in modeling the aging control of testing and maintenance activities.

2.7 More Complex Maintenance and Restoration Models

The good as new and good as old models are useful for providing a first order evaluation of the aging control of a test or maintenance activity. They can also provide bounds on the aging control effects. More complex maintenance and restoration models involve modeling the testing or maintenance activity to not be good as old or as good as new, but somewhere between. More complex models can also involve modeling inefficiencies associated with a test or maintenance. These more complex models can be applied when detailed test and maintenance data is available. These more complex models can also be useful for sensitivity studies to determine the sensitivity to the details of the test or maintenance activity. For example, a useful analysis is to use the good as old and good as new models to identify the risk important test and maintenances and then to carry out more detailed sensitivity analyses on the risk important tests and maintenances. The more complex models which will be covered are:

1) Modeling the effect of tests or maintenances on individual pieceparts of the component,

2) Modeling the effect of tests or maintenances which only cover specific failure causes or mechanisms,

3) Modeling explicitly the age setback which results from a maintenance or repair activity,

4) Modeling the aging control of preventative maintenances in reducing the aging rate,

and

5) Modeling inefficiencies associated with a test or maintenance activity.

These more detailed models are discussed in the subsequent sections.

Modeling Tests or Maintenances on Individual Pieceparts

When modeling tests or maintenances on individual pieceparts, the component is subdivided into its pieceparts and each piecepart is treated as a separate component. Each piecepart can then be evaluated using the good as old or good as new model or more complex models. For example, a valve can be divided into the valve driver (the actuator, motor etc.), the valve interior (valve disk, etc.), and the valve exterior body. A surveillance test which only tests a given piecepart can be modeled as being good as old and an overhaul or repair of the piecepart can be modeled as being good as new, the models now being applied to the specific piecepart.

The actual modeling involves replacing the component failure rate by the sum of its piecepart failure rate contributions (e.g., in fault tree terminology replacing the component by an "or gate" of its piecepart contributions).* The failure rate for each piecepart then needs to be determined and the appropriate test and maintenance model for each piecepart needs to be determined. When the good as old model is used for a surveillance test and the good as new model is used for repairs the information required is the appropriate test interval on the piecepart and the mean time to failure for the piecepart. The test and maintenance procedures and historical data are used to identify the specific pieceparts which are tested or maintained and the test and maintenance frequency and characteristics. To prevent the models from becoming overly large, only the major components can be expanded into their pieceparts. For components which have one piecepart as the major contributor to the failure mode, the component may be treated as being equivalent to the piecepart.

Modeling Tests or Maintenances on Specific Failure Causes

If a test or maintenance only covers specific failure causes or failure mechanisms then the activity can be modeled as only controlling a portion of the component failure rate. The portion or fraction of the failure rate which is controlled is determined based on the fraction of total failure contributions which is covered by the test or maintenance. This fractional restoration modeling is similar to the previous piecepart modeling except instead of pieceparts being identified, the fraction of failure causes or mechanisms which is controlled is modeled.

To apply the fractional restoration approach, the total component aging failure rate is multiplied by the fraction of failure contributions which is controlled by a given test or maintenance. This fractional failure rate contribution (the total failure rate times the

*The piecepart contributions can more accurately be modeled as being competing cause contributions, however the difference from the summation of the contributions, which ignores the interactions, is generally insignificant.

fraction) can then be assigned to be good as new after the given failure causes or mechanisms are corrected. Surveillance tests which only detect this fraction of failure contributions can be assigned to be as good as old for the fractional contribution. The failure rate can be divided into different fractional contributions and each separately tracked. Failure causes or mechanisms not detectable are treated as not being testable or maintainable.

Explicitly Modeling Age Setback

A partial restoration of a component can be explicitly modeled as a partial age setback, where the component age is setback to a given value. In modeling age setback, the age reduction after a given repair or maintenance activity is explicitly determined. For the good as old model, there is no age setback i.e., the age reduction is zero after the activity, but the component is assured to be an up state. For the good as new model, there is a complete age setback, i.e., the age reduction is equal to the age of the equipment before the activity, resulting in as good as new equipment. For a repair or maintenance activity modeled as having an intermediate age setback, the value of age setback needs to be estimated. For a given age setback of Δw after an activity the age of the component is reduced from w to w_1 where

$$w_1 = w - \Delta w \tag{34}$$

where w is the component age before the activity. The aging component failure rate then begins at w_1 after the activity for the calculation of the component unreliability and component unavailability.

To calculate the component unreliability or component unavailability versus time, the component age versus time needs to be tracked, accounting for age setbacks by repairs and maintenances. The formulas in the appendix can be used to calculate the unreliability and unavailability with appropriate setback of the age using Equation (34). With regard to applications, the more difficult question is the appropriate age setback value to assign to a given repair or maintenance activity. Little work has been done in this area. Sensitivity studies can be performed by varying Δw to determine the sensitivity to the degree of restoration. Data analyses can also be carried out to estimate the age setbacks associated with different types of maintenances by constructing appropriate likelihood functions with the age setback the parameter to be estimated.

Modeling the Effects of Preventative Maintenances in Reducing the Aging Rate

Preventative maintenances may not restore an aged part, but instead may slow the aging process of the component. Preventative maintenances which involve lubrication or cleaning are of this type and can be modeled as reducing the aging rate of the equipment. Before the preventative maintenance the aging rate has a value say of α and after the maintenance, the aging rate is reduced to α_1 where

$$\alpha_1 = \alpha - \Delta\alpha \tag{35}$$

and where $\Delta\alpha$ is the aging rate reduction due to the preventative maintenance.

To determine the aging control of a preventative maintenance the aging rate reduction needs to be related to the component failure rate change. If the linear aging failure rate model is used (Equations (5)-(9)) then the aging rate reduction $\Delta\alpha$ can be directly interpreted as the change in the linear aging rate α. The new linear aging rate after the preventative maintenance is then α_1. Preventative maintenances may be more generally carried out to control continually increasing rates of aging. To determine the aging control on aging rates which increase with time, nonlinear failure rate models are required.

For a nonlinear aging failure rate model, the aging rate α is more generally defined to be the rate of increase in the failure rate with age:

$$\alpha = \frac{d\lambda}{dw} \tag{36}$$

where the right hand side of Equation (36) is the derivative of the failure rate with age. The aging rate α is thus generally a function of the age w, i.e., $\alpha = \alpha(w)$ and can increase with age.

From the above relationships, a change in the aging rate can be related to the change in the failure rate, which is what is required for application in an APSA. If $\Delta\alpha$ is modeled for a preventative maintenance activity, then the new aging rate can be determined from Equation (35), and Equation (36) can be used to determine the failure rate after the preventative maintenance. With the failure rate after the activity determined, the component unreliability and unavailability can then be calculated using the equations in the appendix.

For example, for the Weibull failure rate model (Equations (10)-(14)) the failure rate derivative is

$$\frac{d\lambda}{dw} = \frac{\lambda_o b}{w_o^b} w^{b-1} \tag{37}$$

Equating the derivative to the new aging rate α_1 after the preventative maintenance gives the component age w_1 after the preventative maintenance,

$$\frac{\lambda_o b}{w_o^b} w_1^{b-1} = \alpha_1 \tag{38}$$

or

$$w_1 = \left[\frac{\alpha_1 w_o^b}{\lambda_o b}\right]^{\frac{1}{b-1}} \tag{39}$$

The new age w_1 can then be used for the Weibull failure rate to calculate the unreliability and unavailability of the component. The more difficult task is to estimate the aging rate change $\Delta\alpha$ for a given preventative maintenance activity. Perhaps the best use of the model is to carry out sensitivity analysis to determine the importance of preventative maintenance actions. This preventative maintenance model can also be used to analyze maintenance data to estimate the aging rate reductions for given preventative maintenances using appropriate likelihood functions with $\Delta\alpha$ as the unknown parameter to be estimated.

Modeling Test and Maintenance Inefficiencies

Finally, sometimes a test or maintenance may be inefficient in detecting or correcting a degradation or failure. One of the most straightforward ways to model a test or maintenance inefficiency is to increase the test interval or replacement interval to be an "effective" interval. The use of an effective interval models the inefficiency as being associated with a constant probability per activity of not detecting or correcting the degradation or failure. Let e_T be the test efficiency which is defined to be the probability of detecting a failure at a test. Let T be the actual test interval and T_e be the effective test interval which is the expected test interval at which the failure is detected. Then using standard probability relationships*,

$$T_e = \frac{T}{e_T}. \tag{40}$$

Similarly if e_L is the probability of a restoration activity effectively restoring the component, L the actual restoration interval, and L_e the effective restoration interval, then

$$L_e = \frac{L}{e_L}. \tag{41}$$

The effective intervals can then be used in the formulas for the component unavailability in place of the actual intervals. Sensitivity studies can be performed by varying e_T or e_L to determine the risk impact of inefficiencies. Those tests or maintenances which are most sensitive are those where the efficiencies need to be the highest.

Maintenance and repair inefficiencies can also be modeled using the partial restoration model or age setback model previously given. Instead of assuming good as new restorations these partial restoration models can be used to model partial restorations associated with the maintenance or repair. Sensitivity studies can be performed to evaluate the impacts of partial restorations instead of complete restorations.

2.8 Summary of Models and Data Needed to Quantify Component Reliability and Unavailability Effects of Aging

The previous sections described the failure models and test and maintenance models which can be used to quantify the reliability and unavailability of a given aging component. The data required for these models were also discussed. It is useful to

*For a detection probability of e_T per test the average number of tests before detection is $1/e_T$ based on the standard geometric probability distribution. For an interval of T between tests, the average interval to detection is then T/e_T.

summarize these modeling and data needs since this encompasses what is needed to transform a PSA into an APSA.

In summary, for each component for which aging effects are to be explicitly quantified an aging reliability model is needed. This consists of:

1. A model of the age-dependent failure rate for the component. Commonly used age-dependent failure rate models are:

   The linear failure rate model,
   The Weibull failure rate model,

or

   The exponential failure rate model.

The formulas for the above failure rate models were given in Section 2.2. For a given age-dependent failure rate model the parameters of the model must be estimated from failure rate data or from engineering information. Instead of the age dependent failure rate, a model of the overall time trend in the failure rate or in the failure frequency can be used to show overall trends due to aging. However, an overall time trend model cannot be used with different test and maintenance models since the overall time trend has the test and maintenance effects already incorporated and the aging failure rate is not separated out as a function of age.

In addition to the age-dependent failure rate model when the aging control effects of test and maintenance practices are also to be explicitly evaluated then appropriate test and maintenance models are required. Specifically,

2. A model of the age control of each test, maintenance, or repair performed on the component or component piecepart is required. The most straightforward models are

   The good as old restoration model,

and

   The good as new restoration model.

More complex models can also be used, including piecepart models, fractional restoration models, age setback models, and preventative maintenance models. Inefficiencies in an activity can also be modeled. For a given test or maintenance model, the parameters in the model need to be determined from the procedures and from historical data if available. For the good as old or good as new model the only required input data is the interval at which the activity is performed. Sections 2.6 and 2.7 described the different test and maintenance models. The appendix gives formulas for calculating the component reliability characteristics using the aging failure rate model and the appropriate test and maintenance models. These reliability characteristics are then used to transform the PSA to an APSA. The next chapter, Chapter 3, describes the approaches which can be used for this transformation process.

3. APPROACHES FOR TRANSFORMING A PSA INTO AN AGE-DEPENDENT PSA

3.0 Introduction

There are different approaches that can be used for transforming a PSA to an age-dependent PSA, or an APSA. We describe three basic approaches. The first approach involves carrying out a standard PSA evaluation a number of times with different component failure rates used in each evaluation. The different component failure rates which are used are stepwise approximations to time dependent component failure rates. This approach is straightforward, but the age of each component cannot be separately tracked. Hence, the effect of testing, maintenance, or repair on the age of the component or on the aging rate cannot be explicitly modeled.

The second approach for transforming a PSA into an APSA is to substitute age dependent component models into the PSA quantification formulas. The fundamental PSA formulas for the core damage frequency in terms of the component failure probabilities and component unavailabilities are still used. However, the quantification formulas for the component failure probabilities and component unavailabilities are changed from the usual, steady state formulas to those which explicitly incorporate aging. This approach efficiently calculates the core damage frequency and system unavailabilities as a function of plant age. However, the aging contributors are not resolved in detail and the calculations can be time consuming if sensitivity studies are performed.

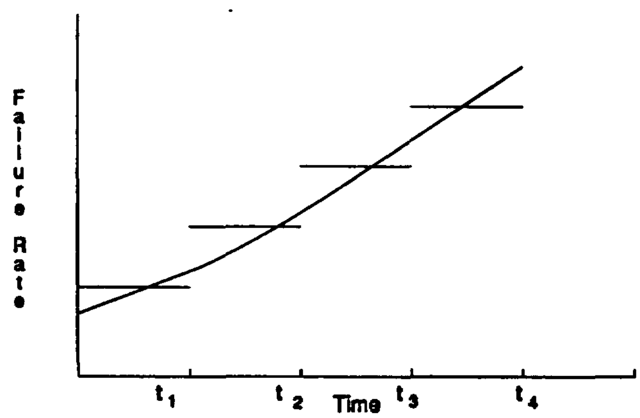
The third approach for transforming a PSA to an APSA is to calculate appropriate risk importance coefficients from the standard PSA and to combine these with calculated component aging effects using separate component aging models. This approach is effective for resolving in detail aging contributors, including all the aging interactions. The approach also allows sensitivity studies to be efficiently carried out. However, the approach can be time-consuming calculationwise. Formal uncertainty analyses can also be time consuming.

The following sections describe each of the above approaches. The features of each approach are further described. Each approach is described in sufficient detail to allow implementation of the approach for specific applications.

3.1 Successive Stepwise Evaluations Using a Standard PSA

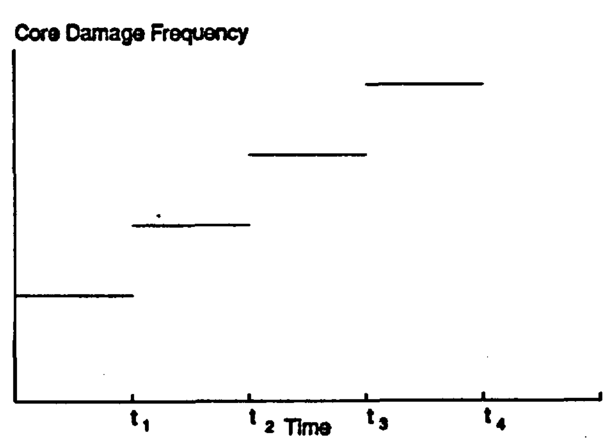
The approach of successively quantifying a standard PSA to approximate aging effects is straightforward. The time dependent failure rate of a component is approximated by a series of stepwise constant failure rates as shown below.

Approximation of a Time Dependent Failure Rate by a Stepwise Constant Failure Rate



For a time interval with a given approximate constant failure rate, the component can thus be treated as in a standard PSA which assumes the component has a constant failure rate. For multiple components which have time dependent failure rates, the time dependent failure rate of each component is approximated by a series of constant failure rates using the same set of time intervals for each component. A standard PSA evaluation (computer run) is then made for each time interval using the associated constant failure rate for each component. The results from the quantifications for different intervals then serve as a stepwise approximation of the time dependent core damage frequency as illustrated below.

Core Damage Frequency at Different Time Points



The advantage of the successive stepwise approach is that standard PSA models and standard PSA computer codes can be used. Care must be taken in selecting the width of the time intervals, though this is a numerical accuracy problem which can be addressed by using finer time intervals.

The basic disadvantage of using the stepwise, approximate approach is that individual component ages cannot be explicitly tracked since a common time must be used for all components. Thus, the effects of test, maintenance, or repair on the age of the component and on the aging rate cannot be explicitly modeled. When a component is replaced, repaired or maintained, the failure rate value after the activity is the same as the failure rate value before the activity. This is because of the constant failure rate assumption used in the PSA run.

The implications of using the same failure rate before and after an activity depend upon the type of component failure rate function which is used as the basis for the histogram approximations. When overall time trend failure rates (or failure frequencies) are used as the basis for the histogram approximations, then the effects of testing, maintenances, and repair are already factored into the failure rates. The effects of testing, maintenance, and repair thus cannot be separated out and be explicitly modeled. Different testing, maintenance, and repair programs consequently cannot be evaluated because of the built-in effects of the testing, maintenance, and repair program under which the time, dependent failure rates were collected. The PSA results then provide a best-estimate, stepwise approximation of the time dependent core damage frequency and system unavailabilities under the given testing, maintenance, and repair programs built into the failure rates.

If age dependent component failure rates are instead used as the basis for the histograms, where test, maintenance, and repair effects have been removed, then the PSA runs generally will provide a conservative, upper bound evaluation of the aging impacts. All the component ages are equated to a common running time in using the common set of time intervals for the histogram approximations. Thus, it is assumed that components are never overhauled or replaced with new components. Because of the constant failure rate assumption, surveillance tests, maintenances, repairs, and replacements are thus all effectively modeled as being good as old. No component is ever replaced with a new component and no degradation is ever removed from a component, causing a renewal of the component. Because of the good as old assumption for all activities, the stepwise approximation approach in this case generally provides a conservative, upper bound evaluation of the age-dependent core damage frequency and system unavailability.

Thus, it is important to know whether the basic component failure rate functions which are used are time trends and incorporate the effects of testing, maintenance, and repair or whether they are age dependent failure rates which separate out the effects of testing, maintenance, and repair. This was the basic aging failure rate issue that was discussed in Section 2.3 and is important for the proper understanding and application, not only for the approximate stepwise PSA approach, but for the other approaches for carrying out an APSA as well. It is an issue since as was indicated in Section 2.3, failure rate data bases may not clearly differentiate as to whether the failure rates are overall trends or are age dependent with the test and maintenance effects removed. Compounding the problem, data analyses may calculate overall time dependent failure rates and erroneously call them age dependent.

One final point involves the PSA minimal cut sets.* A truncated list of minimal cut sets which have been evaluated as being the most important is among the standard results provided by the PSA. A list of minimal cut sets is used not only in the successive stepwise approach, but in all approaches to quantify the aging effects. Truncation of the minimal cut sets by the PSA can lead to underestimating of the aging effects because minimal cut sets which were unimportant in the original PSA can become important when aging is considered. This can particularly be the case for minimal cut sets which contain components which are simultaneously aging. The simultaneous aging will cause a multiplicative increase in the minimal cut set contribution to the core damage frequency. To check on the effect of additional minimal cut sets being considered, the minimal cut sets can be expanded to include the multiple components which are aging and the evaluations carried out again using the expanded set. If this checking is not done then it should be made clear as to what contributions are included and which are not. This applies to all the approaches. A summary of the basic features of the stepwise approach is given in Table 5.

---

*A minimal cut set is a standard PSA term and is a smallest combination of component failures with an initiating event that will cause a core damage event.

TABLE 5. THE SUCCESSIVE STEPWISE APPROACH FOR PSA AGING EVALUATIONS

Basic Procedure: Approximate the time-dependent component failure rate by a series of constant stepwise failure rates in given time intervals. Use the same time intervals for all components. For a given time interval select the appropriate constant failure rate for each component and quantify the PSA as usual. Repeat for each time interval of interest.

Advantages: Standard PSA models and software can be used with no modifications required.

Disadvantages: Because of the constant failure rate assumption in the PSA, the age of the component and the aging rate are never modified. Thus, different test, maintenance, and repair programs which affect the aging or aging rate cannot be evaluated.

Special Points: If overall, time dependent (time trend) failure rates or failure frequencies are used for the histogram fittings then the effects of tests, maintenances, and repairs are built into the failure rates. The PSA results then give a best estimate, stepwise approximation to the core damage frequency for the aging data and given test, maintenance, and repair programs built into the failure rates. If age-dependent failure rates are used with the test, maintenance, and repair effects removed then all tests, maintenances, and repairs are effectively treated as good as old because of the constant failure rate assumption. This will generally give conservative, upper bound core damage frequency results within the histogram approximations. Truncation of the minimal cut sets, can lead to underestimation of the aging effects if omitted minimal cut sets become significant because of aging effects.

3.2 Substitution of Aging Models Into a PSA

A second approach for transforming a PSA into an APSA is to substitute aging models into the PSA component quantification formulas. Instead of calculating component unavailabilities and component unreliabilities using standard PSA constant failure rate models, appropriate component aging reliability equations are substituted to calculate age-dependent component unavailabilities and unreliabilities. The same fault tree and event tree models in the PSA are used. However, different values are calculated for the component unavailabilities and unreliabilities using appropriate component quantification formulas as given in the appendix. The component unavailabilities and unreliabilities need to be calculated for each of the times of interest to obtain the time dependent core damage frequency. If average aging effects are of interest, then averages are calculated over appropriate time intervals.

To understand the substitution of the component aging models into the PSA, consider the standard PSA formula for the core damage frequency C in terms of the component contributors:

$$C = \sum_{i=1}^{N} I_i \, q_{i1} \, q_{i2} \ldots q_{im_i} \tag{42}$$

where

I_i = the initiating event frequency for a given accident (43)

and

$q_{i1} \, q_{i2} \ldots q_{im_i}$ = the product of component unavailabilities * in the ith minimal cut set (a combination of component failures causing a core damage event if the initiating event occurs) (44)

* A component unreliability is used instead of a component unavailability when the failure mode is failure to run, instead of failure to start.

The minimal cut sets can vary in size, and to be general there are assumed to be m_i components in the ith minimal cut set. Also, to be general it is assumed that N minimal cut sets are obtainable from the original PSA. The unavailabilities can also include human error contributions. The same general formula as Equation (42) also applies for system unavailabilities, expected health consequences, and other results calculated by the PSA.

Equation (42) is dependent only upon the basic logic structure of the PSA and doesn't depend on any specific quantitative models used for the initiating event frequencies and component unavailabilities. In standard PSA evaluations, constant failure rate models are used to calculate values for I_i and $q_{i1}\ q_{i2} \ldots q_{im_i}$. For age-dependent evaluations, age-dependent models are instead used to calculate these values at different time points or plant ages. The calculations need to be repeated for each time point of interest, however the same basic PSA formula, Equation (42), is used with only different numbers substituted for I_i and $q_{i1}\ q_{i2} \ldots q_{im_i}$.

In substituting age-dependent models for the component unavailabilities and unreliabilities (or initiating event frequencies) the following points need to be considered for implementations:

1. Truncation of minimal cut sets can again cause certain aging contributors to be omitted. A truncated minimal cut set contribution can become particularly important if multiple components in the minimal cut set are aging, multiplying the contribution of the minimal cut set. The truncation effect can be investigated by expanding the minimal cut sets to include those omitted minimal cut sets containing aging components.

2. If different test and maintenance policies are to be evaluated, then age-dependent component failure rates need to be used which separate out the effects of tests, maintenances, and repairs. Appropriate test, maintenance, and repair models of age control, such as those given in Chapter 2, should be used to calculate the component unavailabilities.

3. If time dependent (time trend) failure rates or failure frequencies with built in test, maintenance, and repair effects are used then different test, maintenance, and repair practices cannot be evaluated. Good as old restoration models should then be used in the component quantifications to maintain the time dependent behaviors in the failure rates.

The advantage of the substitution technique is its straightforwardness. Standard PSA models and minimal cut sets are used with the quantification formulas modified for the component unavailabilities and unreliabilities (or initiating event frequencies). Separate computer subroutines or modules can be developed to calculate the age dependent component unavailabilities and unreliabilities which can then be used in the standard minimal cut set expressions for the core damage frequency and system unavailabilities. Sensitivity and uncertainty analyses can also be incorporated into the quantifications.

The disadvantage of the substitution technique is its limited resolution of aging contributors. The final core damage frequency and system unavailabilities are determined but the aging contributors are not delineated. The minimal cut set contributions give the total contributions from component combinations, but the aging effects are not separated out. How much a component's aging contributes to the core damage frequency and how much component aging interactions contribute are not identified. Also, the calculations at different time points can be tedious if many sensitivity calculations are carried out, although efficient calculational algorithms can be constructed to help address this problem. Table 6 summarizes the features of the approach for substituting aging models into a PSA.

3.3 The Risk Importance Approach for Evaluating Aging Effects

The third approach for transforming a PSA into an APSA is the risk importance approach whose methodology is described in NUREG/CR-5510(7). Appropriate risk importances are calculated from the standard PSA and are then combined with component aging models to give the core damage frequency increase due to aging. Other risk importances can also be calculated from the PSA to give the increase in any risk result due to aging, such as increases in system unavailability due to aging. Even though the approach is described in NUREG/CR-5510, it is summarized here in context of its use for transforming a PSA into an APSA.

TABLE 6. THE SUBSTITUTION APPROACH FOR PSA AGING EVALUATIONS

Basic Procedure: Use aging models to calculate the component unavailabilities (or unreliabilities) at a given time point (or given plant age) for the aging components. Alternatively, use the aging models to calculate average increases in unavailability due to aging. Substitute the component unavailability values into the PSA minimal cut set equations to obtain the age-dependent core damage frequency. Repeat at different time points for time dependent evaluations.

Advantages: The standard PSA logic models and minimal cut sets can be used with only the quantification formulas modified for the component unavailabilities, unreliabilities and initiating event frequencies. Separate subroutines can be set up to calculate the age-dependent unavailabilities, unreliabilities, and initiating event frequencies to replace the standard PSA quantifications. Different test and maintenance programs can be evaluated for their risk effectiveness if appropriate age dependent failure rates are used.

Disadvantages: The aging effects are not delineated and hence prioritization of the aging effects can not be readily carried out. The calculations can be tedious and time consuming if different aging calculations are performed such as for sensitivity evaluations

Special Points: Age-dependent component failure rates should be used which separate out the test and maintenance effects if different test and maintenance programs are to be evaluated. If time dependent failure rates or failure frequencies are used which incorporate test and maintenance effects then good as old restoration models should be used to maintain the time dependent failure rates or failure frequencies. Truncation of the minimal cut sets can lead to underestimation of the aging effects and can be expanded to determine the impacts. The contributors included and those omitted should be described.

Let ΔC be the increase in the core damage frequency due to aging, i.e. the difference between the core damage frequency with aging and without aging. Then ΔC can be expressed as a sum of contributions,

$$\Delta C = \sum_{i} S_i \Delta q_i + \sum_{j>i} S_{ij} \Delta q_i \Delta q_j \tag{45}$$

$$+ \sum_{k>j>i} S_{ijk} \Delta q_i \Delta q_j \Delta q_k \ldots$$

$$+ \sum_{n} S_{12..n} \Delta q_1 \Delta q_2 \ldots \Delta q_n$$

where

Δq_i	=	the increase in the unavailability of component i due to aging (the difference between the unavailability with and without aging)	(46)

and where S_i, S_{ij}, . . . $S_{12...n}$ are appropriate risk importance coefficients determined from the standard PSA. NUREG/CR-5510 describes how to calculate the risk importance coefficients and provides algorithms which can be used for implementations. The last term on the right hand side is the contribution from the largest size minimal cut sets obtainable from the PSA (without truncation). The total core damage frequency C with aging can be obtained by adding ΔC to the core damage frequency without aging calculated in the PSA C_o, i.e., $C = C_o + \Delta C$. Similar expressions can be written for the aging increase in any other risk result.

Equation (45) is an exact expression and gives a detailed breakdown of all the aging contributions to the core damage frequency increase due to aging. Each Δq_i is the difference between the unavailability q calculated with aging and the unavailability q_o calculated without aging in the PSA, $\Delta q = q - q_o$. The unavailability increase Δq_i can be time dependent (or age dependent) or can be an average aging effect over given time periods or replacement intervals.

With regard to the detailed breakdown of contributions, the first term on the right hand side of Equation (45) gives the sum of the contributions from individual component aging effects:

$S_i \Delta q_i$ = the core damage frequency contribution from the aging of component i. (47)

The second term gives the sum of the two component interaction contributions from two components simultaneously aging:

$S_{ij} \Delta q_i \Delta q_j$ = the core damage frequency contribution from the simultaneous aging of components i and j. (48)

The higher order interaction contributions for three components simultaneously aging, etc. are given by the succeeding terms on the right hand side of Equation (45) up to the maximum interaction contribution, which is the size of the largest minimal cut set modeled in the PSA.

Besides breaking down the core damage frequency impact due to aging into the detailed individual and interaction aging contributions, each contribution in Equation (45) shows the risk importance factor and the aging effect. For an individual component contribution $S_i \Delta q_i$, S_i is the standard PSA core damage frequency importance of the component and Δq_i is the aging effect. Similarly, for an interaction contribution, the first factor is the core damage frequency importance of the interaction and the second factor, the product of Δq_i's, is the aging effect. For example, for the two component interaction contribution $S_{ij}\Delta q_i\Delta q_j$, S_{ij} is the risk importance of the contribution and $\Delta q_i\Delta q_j$ is the aging interaction effect. Thus, one can determine how much of each core damage frequency contribution is due to the core damage frequency importance of the components and how much is due to the aging of the components. The core damage frequency importances of the components are determined from the basic PSA and reflects the basic design and operation of the plant. The aging effects Δq_i depend upon the component aging failure rates and the aging control of the test and maintenance programs.

In applications, the contributions to ΔC are often truncated to only consider second or third order interactions, i.e. the terms on the right hand side of Equation (45) are truncated at the second or third summation. As indicated, NUREG/CR-5510 gives algorithms for calculating the risk importance coefficients S_i,S_{ij}, etc. The aging effects Δq_i are calculated using appropriate aging reliability models as has been previously described. If the aging control of test and maintenance programs are to be explicitly evaluated for their risk effectiveness, then again age-dependent component failure rates which separate out the effects of testing, maintenance, and repair should be used. Appropriate formulas for Δq_i are given in the appendix.

The disadvantage of the above aging-risk importance approach is that the risk importance coefficients S_i, S_{ij}, etc. can be tedious to calculate, particularly if many terms are determined for the contributions to ΔC. Efficient algorithms for determining the risk importance coefficients focused on those components which are aging can help address this problem. Uncertainty and sensitivity evaluations can also be tedious if uncertainties and sensitivities in the risk importance coefficients are included. Equations and algorithms for the risk importance coefficients given in NUREG/CR-5510 can be used to obtain the uncertainties and sensitivities in terms of basic component data uncertainties.

The advantage of the aging risk importance approach is that it provides a detailed breakdown of all the aging contributions to the core damage frequency increase due to aging. How much of the contribution is due to the risk importance of the contributor and how much is due to the aging effect is also given. Prioritization of the aging contributors and of test and maintenance activities thus can be effectively carried out using the approach. From an implementation standpoint, because the aging evaluations Δq_i are separated from the PSA risk importances S_i, S_{ij}, etc., the PSA needs to be solved only once to determine the risk importances, regardless of the number of aging evaluations carried out using different aging rates, test and maintenance models, etc. Because the focus of this report is on aging prioritizations and sensitivity studies, the risk importance aging approach will be principally used in the applications to be discussed. Table 7 summarizes the features of the risk importance aging approach.

TABLE 7. THE RISK IMPORTANCE APPROACH FOR PSA AGING EVALUATIONS

Basic Procedure: Use the standard PSA to calculate the risk importance coefficients (S_i, S_{ij}, etc.) for each component and combination of components which are aging. Multiply the coefficients by the increases in unavailability (Δq_i, Δq_j, etc.) due to aging and add to obtain the total core damage frequency change (ΔC). Recalculate the unavailability increases for the time points or ages of interest for time dependent evaluations.

Advantages: The detailed aging contributions are identified and prioritized. The risk importance factor and the aging effect factor for each contribution is identified. The risk importance coefficients need only be calculated once for different aging evaluations which are carried out.

Disadvantages: Calculation of the risk importance coefficients can be time consuming if many higher order coefficients are calculated. Including uncertainties and sensitivities in the risk importance coefficients can be tedious.

Special Points: Age-dependent component failure rates which separate out test, maintenance, and repair effects should again be used if the aging control of test and maintenance programs are to be explicitly evaluated. If the summation of terms for ΔC is truncated at some term then the effects of the truncation can be examined by calculating additional terms. The truncation limit should be documented as part of the results.

4. APPLICATIONS OF AN AGE-DEPENDENT PSA

4.0 Introduction

An age-dependent PSA, which we have called an APSA, can be used for various applications. A particular application of an APSA can be classified according to the principal focus of the analysis, which can be:

Evaluation of the core damage frequency with aging effects incorporated,

Evaluation of test and maintenance effectiveness in controlling aging impacts,

Prioritization of aging contributors to the core damage frequency,

or

Evaluation of the sensitivities and uncertainties in risks due to aging effects.

When the focus is on evaluation of the core damage frequency with aging effects incorporated then the emphasis is on determining the bottom line number for the core damage frequency and system unavailabilities with aging effects explicitly modeled. When the focus is on evaluation of test and maintenance effectiveness in controlling aging effects then the emphasis is on evaluating the effectiveness of test and maintenance programs in controlling the risk impacts of aging under specified aging behaviors. Different test and maintenance strategies may be investigated and different plausible aging failure rates may be used. When the focus is on prioritization of aging contributions then the evaluations are geared toward the ranking and screening of aging contributors. Finally, when sensitivity and uncertainty analyses are the principal focus then variations and distributions in the risk are determined for variations and distributions in aging behaviors.

The next section identifies the basic questions that need to be answered in setting up an APSA calculation for any of the above applications. These questions and their answers provide a framework for carrying out one or more of the above applications. These questions address the aging data, the test and maintenance models, the PSA information and the results from the APSA.

4.1 Questions To Be Addressed in Setting Up an APSA Application

There are four basic questions that need to be answered in setting up an APSA for any specific evaluation. These questions are:

1. What is the available component aging failure rate data?

2. What is the available test and maintenance information?

3. What is the available type of PSA information?

and

4. What are the aging results of most interest?

The answers to the questions will determine the type of APSA application which can be best carried out and the type of APSA approach which is most suitable. Figure 6 presents these questions in terms of a decision tree with the possible answers. The following sections discuss in more detail the alternative answers to each of these questions and the implications of these answers.

4.2 Impact of Available Component Aging Failure Rate Data

The component aging failure rates which are available can be of three types:

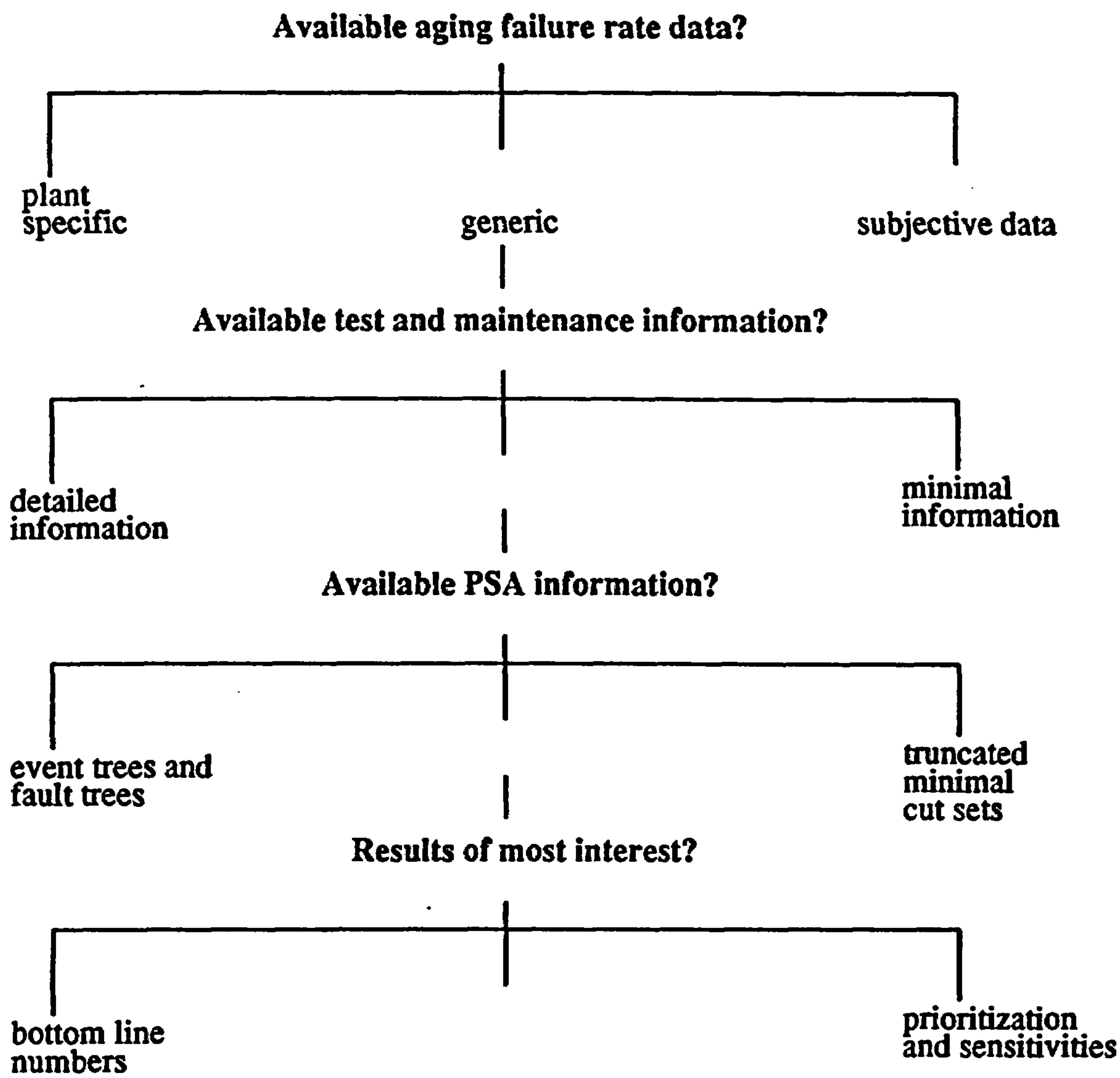
Plant specific aging failure rates,

Generic aging failure rates,

or

Subjective estimates of aging failure rates.

FIGURE 6. QUESTIONS TO BE ANSWERED IN SETTING UP AN APSA EVALUATION



Plant specific aging failure rates are the most precise data and are based on failure histories of components at the plant being analyzed. The component failure rate model (e.g. linear, Weibull, or exponential) can be selected which is most consistent with the data, and the parameters of the model can be estimated using statistical data analysis approaches. Plant specific aging failure rates are, however, generally not available, or are available for only selected components.

Generic aging failure rates are aging failure rates which have been obtained from a population of plants. The generic aging failure rates represent average aging failure rates over the components which are combined in the data base. In performing uncertainty analyses or carrying out sensitivity studies, it is therefore important to include possible plant specific variations. Generic aging failure rates are potentially obtainable from existing generic data bases such as the Nuclear Plant Reliability Data System (NPRDS), if times of failures are recorded. Incomplete records and possible errors in failure classification in these data bases need to be considered as part of any uncertainty or sensitivity analyses which are performed.

The last type of data consists of subjective estimates of aging component failure rates. Because of the lack of plant specific aging data and even generic aging data, subjective estimates of aging failure rates will often be the data which is most available. An example of this type of data is the data base which is utilized in NUREG/CR-5510 (7). Subjective estimates of aging failure rates involve translating engineering information and experience about a component into an equivalent aging failure rate estimate. If subjective aging failure rate estimates are used then it is important that sensitivity or uncertainty analyses be also carried out to evaluate uncertainties and variabilities associated with the subjective data.

The type of aging data which is principally available is an important factor in determining the most meaningful focus of application for an APSA. The type of aging data which is principally available also is an important factor in determining the meaningful interpretations which should be placed on the results from the APSA. If plant specific data is principally available then all the different focuses of applications of an APSA discussed in the previous section are equally meaningful because accurate aging data relevant to the plant is available. The APSA results furthermore can be interpreted as being directly applicable to the plant within the associated data uncertainties. All the different approaches for transforming a PSA to an APSA can be effective with the substitution approach most efficiently providing the bottom line core damage frequency value and system unavailability values. The risk importance aging approach is most effective if detailed aging contributors are of prime interest, broken down into the individual component contributors and the contributions from aging interactions. Finally, the successive approximation approach can provide quick bounds or approximations to the aging impacts.

If generic data is principally available then all applications can be carried out but the results must be interpreted as under the limitation of generic data being used. The most meaningful applications are those which account for possible plant specific variations by varying the aging rate data to account for plant specific effects. Results which are not sensitive to these aging rate variations are the most meaningful. Prioritizations of aging contributors and sensitivity studies, along with uncertainty analyses, are thus among the more meaningful applications. With regard to APSA approaches, the successive stepwise approach is effective for efficiently bounding or approximating the aging effects. The risk importance aging approach is effective if aging contributor prioritizations are the focus. The substitution approach is useful if the focus is on final core damage frequency values. For all these approaches, the effects of plant specific data variations about the generic data values must again be included.

If subjective aging failure rate estimates are principally available then the aging failure rate data can have especially large uncertainties. For subjective aging failure data, the most meaningful applications involve prioritizations of aging contributors and sensitivity analyses of aging impacts. The meaningful results are those which are account for the large uncertainties in the subjective aging failure rate data. Extracting meaningful results thus includes focusing on the order of magnitude of the value and focusing on relationships between values. The relationships which can be focused on include relationships between sizes of core damage frequency impacts and sizes of aging rates, relationships between types of maintenance and resulting aging impacts, and relationships between types of aging contributors and their aging rates. The risk importance approach can be useful for identifying these relationships as well as for prioritizing aging contributors in terms of order of magnitude impacts. The other APSA approaches can also be useful for these types of results.

4.3 Impacts of Available Test and Maintenance Information

There are two levels of test and maintenance information which can be available:

> Minimal information, basically providing only the type of activity performed and its frequency,

or

> Detailed historical information providing the times the activity was performed, the type of activity, degradations monitored and corrected, and pieceparts replaced.

When minimal information is only available then one basically only knows the type of activity, i.e. whether a surveillance test, maintenance, or replacement was performed, and the average frequency of the activity. Preventative maintenances may be differentiated from corrective maintenances. The frequency of the activity may also only be known approximately. When only minimal information is available then the basic, good as new and good as old restoration models described in Chapter 2 are the most meaningful models which are consistent with the minimal test and maintenance information. These models are first order models and can be used to obtain a first order evaluation of the aging impacts.

As described in Chapter 2, the good as new model treats the test or maintenance activity as basically removing all significant aging effects and restoring the component to as good as new. The good as old model treats the test or maintenance activity as assuring the component is operational but as carrying out no major renovations of the component so as not to affect the age of the component or its failure rate. As was indicated, surveillance tests which principally check the operational status of the component can be modeled to be as good as old restoration activities. Maintenances which correct degradations and repairs can be modeled to be as good as new restoration activities. The good as old and good as new restoration models require only the frequency of the activity and hence data requirements are minimal. Sensitivity studies can be carried out by changing various good as new models to good as old and vice versa. Also, the partial restoration models previously described in Chapter 2 can be used for sensitivity studies to study the effects of partial restorations between good as old and good as new.

When detailed historical information on tests and maintenances is available then such information as the time of each test or maintenance, the specific actions that were carried out, the degradations and component conditions that were observed, and the pieceparts that were replaced are obtainable. This means that, first of all, information is available to determine the applicability of the good as old or good as new model for a particular activity. Information is also available to determine whether preventative maintenances need to be separated from corrective maintenances as discussed in Chapter 2. Information may also be available to determine the applicability of the partial restoration models or piecepart maintenance models described in Chapter 2.

For the more complex test and maintenance models, the parameters of the model can be determined from the information which is available on the activity. The parameters may be estimated from engineering information and data analyses. The maintenance data can be analyzed to not only estimate the parameters, but also to determine the most applicable model.

When more detailed information is available on the test and maintenance activities, any of the approaches for transforming a PSA to an APSA can be effective depending upon the focus of the evaluation. The successive stepwise approach will be useful when only a bound or first approximation for the resulting core damage frequency is desired. The substitution approach will be effective when the traditional PSA results are desired but now with aging effects incorporated. The risk importance approach is most useful for prioritization and sensitivity studies.

4.4 Impact of PSA Information Which is Available

The type of PSA information which is available affects the completeness and detail to which aging contributors can be evaluated. The PSA information which is available can be:

The complete PSA event tree and fault tree models

or can be:

A restricted PSA set of minimal cut sets.

For each of these cases, it is assumed that the PSA has been developed to a basic component level i.e. to an individual valve, pump, and relay level. If the PSA has only been developed to a grouped component level or to a train level in which individual components are not identified then component aging effects cannot be evaluated by transforming the PSA. For each of the above cases of information, it is also assumed that the data used for the PSA quantification is also available, which includes the initiating event frequencies, component failure rate data, the test and maintenance data, and the human error data.

All the approaches for transforming a PSA to an APSA generally use as basic input the PSA minimal cut sets which are generated from the event trees and fault trees. In the first case above, when the complete event tree and fault tree models are available then the minimal cut sets can potentially be generated to the level needed to include all the aging component contributors. In particular, the minimal cut sets can be generated to include all significant aging contributors including minimal cut sets containing multiple aging contributors.

In the second case, when only a restricted PSA set of minimal cut sets is available then only those components in the restricted minimal cut sets can be evaluated for their aging contributions. As was indicated previously, a set of minimal cut sets is usually generated by the PSA as the contributors which are most important. The set of minimal cut sets is truncated to contain those minimal cut sets whose probability is above some cutoff value such as 1×10^{-8}. If this truncated set of minimal cut sets is only available then certain aging contributions may be neglected, especially multiple aging components in the same minimal cut set which can significantly increase the cut set probability when aging is considered.

Consequently, when a restricted set of minimal cut sets is only available then particular individual component aging contributions and particular multiple component aging contributions (aging interactions) may be neglected which can change the results. For any application it is thus important to specifically define the contributions which are included for the aging evaluations. This applies to the case where any truncated set of minimal cut sets is used, even when the event trees and fault trees are used to generate an expanded, but still truncated set of minimal cut sets. The criteria used for selecting the minimal cut sets and the contributors included and excluded should be carefully documented.

Finally, in addition to the level of PSA information, the scope of contributors included in the PSA is important since it determines the scope of aging contributors which are included in the APSA. A standard PSA generally does not consider individual balance of plant (BOP) contributors, lumping all pertinent contributors into a transient initiating frequency value. Thus, the effects of aging of BOP contributors cannot be evaluated using this PSA. PSAs also do not generally include many passive component contributors such as piping and cables. The PSA should be expanded to include these other contributors, when impacts from these contributors are desired. In all cases, the scope of the PSA should be documented.

4.5 Impact of Results Which Are of Most Interest

Finally, for a particular application, there can be specific results which are of most interest, with other results being of lesser importance. All the APSA approaches can provide a complete set of risk results. However, as was previously noted, a given approach is most efficient in providing certain types of results. The successive stepwise approach is best at providing relatively quick approximations or bounds on the aging impacts. The substitution approach is best at providing bottom line values for the core damage frequency and system unavailabilities. The risk importance approach is best at providing prioritizations of aging contributors and sensitivity results.

As was also previously indicated, the desire for specific results must be tempered with the availability of aging failure rate data, test and maintenance data, and PSA information. When minimal data exists then the selected models and the APSA approach used need to account for the lack of data. Bottom line core damage frequencies and system unavailabilities can be obtained but uncertainty analyses and sensitivity analyses need to accompany the results. With little data, the most meaningful results are sensitivity analyses, prioritizations of aging contributors, and relationships determined which are not sensitive to specific data values. This applies for any APSA approach used.

5. PRIORITIZATIONS OF AGING CONTRIBUTORS

5.0 Introduction

This chapter illustrates the applications of an APSA for the objective of prioritizing aging contributors. The prioritization of the contributions to the core damage frequency from aging active components will be specifically evaluated. The same methodology could be applied in prioritizing passive component contributions, provided the PSA contains the passive components and aging failure rates can be obtained for the passive components. For the prioritization of active components demonstrated here, a PSA will be used which has already been developed for a plant. The particular PSA which is used is not of concern since the focus here is on the basic approaches for using an APSA to prioritize aging contributors.

For the prioritization of aging contributors, the approach which will be used for transforming a PSA into an APSA will be the risk importance approach for evaluating aging effects previously described in Section 3.3. As was described in Section 3.3, the risk importance approach provides a detailed accounting of the aging contributors including all the aging interactions. The substitution approach for evaluation aging effects described in Section 3.2 could also be used, however the prioritization of the contributors would be in terms of the minimal cut sets instead of the detailed individual and interaction contributors. The successive stepwise approach could also be used to produce first approximations of the contributors but again they would be in terms of the minimal cut sets which contribute to the core damage frequency.

The following sections describe specific steps that need to be carried out in applying an APSA for prioritization evaluations. Considerations involved in selecting aging failure rate models and aging failure rate data are described. Selection of test and maintenance models is also discussed. Finally, organization and grouping of the results for prioritization applications is discussed. Even though the specific focus is on using the risk importance approach for prioritizing aging contributors, the considerations apply to any APSA approach used for prioritizing contributors.

5.1. Application of the Risk Importance Aging Approach

As was discussed in Section 3.3, in the risk importance aging approach, the core damage frequency increase ΔC due to aging is expressed as a sum of contribution terms from successively higher order aging interactions;

$$\Delta C = \Delta C_1 + \Delta C_2 + \ldots + \Delta C_n \tag{49}$$

Where ΔC_1 is the contribution from individual component aging effects, ΔC_2 the contribution from two component aging interaction effects, etc. The maximum size n of the interactions is the largest core damage minimal cut sets obtainable from the PSA.

For prioritization applications, we must first decide upon the maximum size of interactions to consider. Considering all interactions will be exact but can be time consuming in calculating all the contributions. The higher order interaction terms can also be repetitive in that the same components will appear in the contributions. Considering only single component aging effects ΔC_1 will include the dominant individual components which individually contribute most to the core damage frequency effects from aging. We shall consider interactions up to second order to include in the prioritization those additional components which individually may not be important but which jointly can be important aging contributors. Even though we consider only second order interactions, the approaches and guidelines we describe are applicable for any size interactions considered.

When interactions up to second order are considered then Equation (49) for ΔC approximates to

$$\Delta C = \Delta C_1 + \Delta C_2 \ . \tag{50}$$

The first order contribution ΔC_1 is the sum of the individual component aging contributors;

$$\Delta C_1 = \sum_i \Delta c_i \tag{51}$$

where Δc_i is the core damage frequency contribution from the aging of component i. As indicated in Section 3.3, Δc_i can be expressed as a product of the risk importance S_i of the component and the aging effect aging Δq_i on the unavailability of the component,

$$\Delta c_i = S_i \Delta q_i \tag{52}$$

Similarly, the second order contribution ΔC_2 is the sum of the joint component aging contributors,

$$\Delta C_2 = \sum_{j>i} \Delta c_{ij} \tag{53}$$

where Δc_{ij} is the interaction contribution from the simultaneous aging of components i and j. As was indicated in Section 3.3, the contribution Δc_{ij} can be expressed as a product of the joint risk importance S_{ij} of the component combination and the effect of simultaneous aging $\Delta q_i \, \Delta q_j$ on the component unavailabilities,

$$\Delta c_{ij} = S_{ij} \Delta q_i \Delta q_j \; . \tag{54}$$

All the individual aging contributors and second order contributors are thus identified in this joint prioritization evaluation. Additional, higher order terms ΔC_3, etc. can be generated to check whether any new contributors appear.

A personal computer program was constructed to calculate the risk importance coefficients S_i and S_{ij} from the core damage frequency minimal cut sets supplied by the PSA using the algorithm given in the NUREG/CR-5510(7). All the data in the original PSA (failure rates, test intervals, initiating event frequencies, etc.) are used to calculate values for S_i and S_{ij}. The aging effects Δq_i are calculated with reference to the baseline values determined in the PSA. The core damage frequency effects ΔC_1 and ΔC_2 are thus calculated with reference to the baseline core damage frequency in the PSA. To obtain the total core damage frequency including aging, one can add the aging contribution ΔC to the baseline PSA value. As was indicated in Section 3.3, the advantage of the risk importance approach is that the original PSA may be used to calculate the risk importance coefficients, which need to be done only once for as many different aging analyses that may be carried out which only involve changing Δq_i or Δq_j.

The core damage frequency increase ΔC (including ΔC_1 and ΔC_2) which will be calculated will be the average increase due to aging between replacements (renewals) of the component. The average core damage frequency increase is calculated by using the average unavailability increase Δq between component replacements in Equations (52) and (54). If the component is not replaced during the plant lifetime then the average increase over the plant lifetime is used. The average increase applies to any year. The average increase ΔC added to the baseline core damage frequency from the PSA will give the new, average core damage frequency at any year. The appendix gives the time dependent unavailability formulas which can be averaged to obtain the average Δq.

5.2 Selection of Aging Failure Rate Models and Data

When plant specific failure data is available then the appropriate failure rate aging models and data would be selected based on this plant data. To determine the aging models and data for these models, the failure data would need to include at minimum for each component of interest, the times of failure and times of major overhauls or replacements. Using statistical approaches, the appropriate failure rate model, e.g. whether linear, Weibull, or exponential, would be determined by fitting the alternative models using likelihood or Bayesian approaches.

In lieu of having available plant specific data, generic aging failure rates or subjective estimates of aging failure rates need to be used. Generic or subjective estimates of aging failure rates can be useful in providing an initial prioritization of the aging contributors to help initially focus maintenance activities, monitoring activities, and data collection activities. When generic or subjective aging failure rates are used then sensitivity studies or uncertainty analyses can carried to investigate effects of data variations and uncertainties. The results from the sensitivity or uncertainty analyses can then be factored into the prioritization conclusions. For the application here, the subjective, aging failure rate data base in NUREG/CR-5248 (8) is used. This aging failure rate data base is often called the TIRGALEX data base referencing the committee which had oversight on the work.

The TIRGALEX aging rate data base assumes a linear aging failure rate model,

$$\lambda(w) = \lambda_0 + aw \qquad (55)$$

where $\lambda(w)$ is the age dependent failure rate as a function of the component age w, λ_0 is the underlying constant failure rate as used in the PSA and a is the component aging rate (the symbol "a" is used here instead of "α" in chapter 2). For the TIRGALEX data base, a panel of experts estimated the aging rates a for various classes of components. Though no systematic illicitation or estimation techniques were used, there was an attempt to be consistent and to effectively utilize available engineering knowledge.

The TIRGALEX aging rates a are given in Table 8 for the active components in the PSA. The TIRGALEX aging rates are intended to be subjective, generic aging rates. NUREG/CR-5248 warns about the uncertainties associated with the values. As a means of assessing the uncertainties in the TIRGALEX aging rates, NUREG/CR-5510 (7) compared the TIRGALEX aging rates with aging rates which were obtained from samples of Licensee Event Report (LER) data, data from the Nuclear Plant Reliability Data System (NPRDS), and plant specific data. For diesels, pumps, and motor operated valves, the median aging rate values from the samples of data agreed within approximately a factor of 10 with the associated TIRGALEX values. For check valves the TIRGALEX aging rate value was a factor of 10 to 100 lower than specific plant estimates, principally because of check valve backleakage problems at specific plants. Thus, the TIRGALEX aging rates generally agreed to within an order of magnitude with the aging rates estimated from plant data and were biased low when plants had specific problem components.

The TIRGALEX aging rates were generated in NUREG/CR-5248 for prioritizing research needs. Thus, the TIRGALEX aging rates are best suited for prioritization analysis as is carried out here. Because the aging rates are based on subjective judgments and have large uncertainties, sensitivity analyses are also carried out for the prioritization applications here. For the sensitivity analyses, two different aging rate data bases are constructed for the components which were dominant PSA contributors. One sensitivity aging rate data base represents low aging rates and one represents high aging rates. Further details of the steps involved in generating the aging rates are provided in NUREG/CR-5510.

Table 9 gives the low sensitivity aging rates for those components identified as being dominant contributors in the baseline PSA. The aging rates are low aging rates in that

TABLE 8. TIRGALEX AGING RATES USED FOR ACTIVE COMPONENTS	
COMPONENT	AGING RATE (per hour per year)
Ac Bus	1.0E-09
Air-Operated Valve	4.0E-07
Battery	3.0E-07
Check Valve	4.0E-09
Circuit Breaker	2.0E-08
DC Bus	1.0E-09
Diesel Generator	3.6E-06
Motor-Driven Pump	2.0E-07
Motor-Operated Valve	3.6E-06
Relay	3.0E-07
Safety/Relief Valve	7.0E-07
Transformer	2.0E-09
Turbine Driven Pump	3.0E-06
Solenoid-Operated Valve	6.7E-07

the aging rate only doubles the baseline PSA failure rate of the component after 40 years. All aging rates for other components not shown in the table are kept at their TIRGALEX values. Table 10 gives the high sensitivity aging rates that are defined for these same components. All other component aging rates are kept at their TIRGALEX values. These high sensitivity aging rates are the same as the upper threshold aging rates used in NUREG/CR-5510 and cause an unavailability of 0.1 after 18 months, which is a significantly high unavailability and which is characteristic of severe aging.

One final comment should be made regarding the use of the linear failure rate aging model given by Equation (55). Use of the linear aging model, instead of the Weibull model or exponential model, ignores nonlinear aging effects exhibited by the components. The linear aging model can thus be viewed as a first order linear approximation for the aging behavior of the component. Prioritizations using linear aging rates can consequently be viewed as first order prioritizations of the risk importances of component aging effects. Investigations of the impacts of nonlinear aging effects could then be carried out using appropriate nonlinear models.

5.3 Selection of Test and Models

If test and maintenance effects are to be explicitly incorporated when aging contributors are prioritized, then appropriate test and maintenance models must be selected. For the prioritization we shall assume technical specifications are followed at the plant with no additional scheduled maintenance being carried out. This can be termed the minimal maintenance situation. The prioritization of contributors which are obtained can then be used to help focus and structure a risk-based aging maintenance program. Prioritization of aging contributors under an existing scheduled maintenance program would require selection of the applicable maintenance models. The prioritization results would then identify what contributors would need further emphasis and what contributors could be relaxed in terms of their maintenance activities.

For the prioritization, we thus assume surveillance tests are good as old. That is, if degradations are detected at a test they are not removed as long as the component is still functional. We also assume that when a component is found to be functionally failed at a surveillance test that it is replaced or is repaired so that it is as good as new. This can be an optimistic assumption if minimal repairs are only carried out. The assumption

TABLE 9. LOW SENSITIVITY AGING RATES USED FOR DOMINANT CONTRIBUTORS	
COMPONENT	AGING RATE (per hour per year)
Air-Operated Valve	7.0E-08
Battery	2.0E-08
Check Valve	4.0E-09
Diesel Generator	2.0E-07
Motor-Driven Pump	2.0E-07
Motor-Operated Valve	2.0E-07
Safety/Relief Valve	7.0E-08
Turbine Driven Pump	2.0E-06

TABLE 10. HIGH SENSITIVITY AGING RATES USED FOR DOMINANT CONTRIBUTORS	
COMPONENT	AGING RATE (per hour per year)
Air-Operated Valve	1.0E-05
Battery	1.0E-05
Check Valve	1.0E-05
Diesel Generator	1.0E-05
Motor-Driven Pump	1.0E-05
Motor-Operated Valve	1.0E-05
Safety/Relief Valve	1.0E-05
Turbine Driven Pump	1.0E-05

can be checked by treating repairs to also be good as old.(See the next chapter.) We assume the same test intervals as used in the basic PSA. We do not assume that testing is carried out more frequently if aging occurs. The applicable test interval for each component will be shown in subsequent result printouts. In addition to the surveillance test interval, we also need to assume efficiencies for the surveillance tests. From Section 2.7 again, the efficiency of a surveillance test is the probability that a given failure is detected by the test.

Two sets of efficiencies are used for the prioritization evaluations. For one set of evaluations, the surveillance tests are assumed to have 100% efficiency (efficiency fraction $\varepsilon_T = 1$). For the second set of evaluations, the surveillance tests are assigned the efficiencies ε_T given in Table 2.6 of the TIRGALEX report NUREG/CR-5248. The efficiencies are reproduced in Table 11. The APSA results from both these efficiency data sets will be factored into the prioritizations.

5.4 Selection of the Formulas for the Component Aging Impacts

As additional input information required for the prioritization application, we need formulas for Δq, the aging effect on the component. More specifically, Δq is the increase in component unavailability over the base PSA value without aging effects;

$$\Delta q = q - q_o \tag{56}$$

where q is the component unavailability explicitly including aging and q_o is the value calculated in the base PSA assuming no aging (i.e. assuming a constant component failure rate).

The formula for Δq, or equivalently for q, for each aging component is required. These formulas are required, not only for the risk importance approach we are using here, but also for the substitution approach. For the successive stepwise approach, age-dependent formulas are not needed, but time steps would need to be selected which apply to all components and which are used to approximate the time dependent or age dependent component failure rates for each component.

TABLE 11. TIRGALEX SURVEILLANCE TEST EFFICIENCIES	
COMPONENT	**TEST EFFICIENCY**
Ac Bus	0.45
Air-Operated Valve	0.45
Battery	0.86
Check Valve	0.09
Circuit Breaker	0.45
DC Bus	0.45
Diesel Generator	0.27
Motor-Driven Pump	0.44
Motor-Operated Valve	0.60
Relay	0.18
Safety/Relief Valve	0.82
Transformer	0.62
Turbine Driven Pump	0.44
Solenoid-Operated Valve	0.82

If we were also including aging effects on initiating event frequencies (e.g. on the pipe rupture frequency) then we would also need formulas for the change in initiating event frequency $\Delta\lambda$ due to aging. However, we will not consider aging effects on initiating event frequencies since our focus is on prioritizing active safety components. It is useful to note however that the aging effect $\Delta\lambda$ is simply

$$\Delta\lambda = \lambda - \lambda_0 \;, \tag{57}$$

where λ is the age dependent failure rate (i.e. initiating event frequency) such as the Weibull failure rate and λ_0 is the constant value used in the PSA. For the core damage frequency contributions from aging, $\Delta\lambda$ would then simply replace Δq in Equation (45).

We will prioritize the aging contributors with regard to their average aging effects on the core damage frequency. The average aging effect for a component is the average increase Δq due to aging between replacements or renewals of the component.* From NUREG/CR-5510 (7), for a linear aging failure rate, the average unavailability increase Δq due to aging is

$$\Delta q = \frac{1}{4}a(L-T)T + \frac{1}{6}aT^2 \tag{58}$$

where a is the aging rate, L is the replacement interval (or overhaul interval), and T is the surveillance test interval for the component. The above formula models a surveillance test as being good as old. The above formula can also be obtained by substituting a linear aging failure rate into the general formula given in the appendix.

If components are replaced at failure, as we assume, then the replacement interval L for each component is the mean time to failure for the component plus the time until the failure is detected. The time until the failure is detected is, on the average, one half the interval between tests. Since the test interval is generally small compared to the mean time to failure we shall ignore the additional time until detection.

*If we were to prioritize the contributors for a given time, i.e. at a given plant age, then Δq would be the time dependent unavailability increase. We would need to know the times at which the tests or maintenances are performed in addition to the intervals.

Using the PSA constant failure rate value, the mean time to failure is simply one over the component failure rate. The value for the mean time to failure for each component is given as part of the results presented in the subsequent section. Calculation of the mean time to failure using the PSA failure rate ignores the effects that the additional aging rate has on the mean time to failure. For the baseline and low sensitivity aging rates, because the aging rates are relatively small compared to the constant failure rates, these effects are small, particularly when compared to the uncertainties in the failure rates. For the high aging rates, neglect of these effects will cause the mean time to failure to be larger than if these effects were considered. This will add an extra conservatism to these upper bound evaluations.

Consequently, we assume

$$L = \frac{1}{\lambda_o} \tag{59}$$

where λ_o is the PSA constant failure rate.

If there are no surveillance tests expected on the component between replacements, then T is set equal to L in Equation (58) for Δq, as discussed in the appendix. As previously discussed in Section 2.7, inefficiencies in surveillance tests can be modeled by interpreting T in Equation (58) to be the effective test interval:

$$T = \frac{T_0}{\varepsilon_T} \tag{60}$$

where ε_T is the test efficiency.

Finally, we need to consider the case where the mean time to failure of the component is larger than the plant lifetime. We will assume an extended plant lifetime of 50 years. Then from NUREG/CR-5510 or using the formulas in the appendix,

$$\Delta q = \frac{1}{2} a \left[t_o T + \frac{T^2}{3} \right] \tag{61}$$

where t_o is equal to 50 years. Whether t_o is set equal to 40, 50, or 60 years should have little effect on the prioritization results. If there is no surveillance test expected in 50 years then the formula for the unavailability increase with no testing is,

$$\Delta q = \frac{1}{2} a t_o^2 \ , \qquad (62)$$

where again t_o is 50 years. We thus have all the formulas required for the analysis.

5.5 Detailed Prioritizations of and Component Contributors

Tables 12A and B, 13A and B, and 14A and B present the prioritizations of component contributors for the three cases which were analyzed, which are termed the base case, the upper bound sensitivity case, and the lower bound sensitivity case. The base case utilizes the TIRGALEX aging rates and the TIRGALEX surveillance test efficiencies . The upper bound case utilizes the high sensitivity aging rates and the TIRGALEX test efficiencies. The lower bound case utilizes the low sensitivity aging rates and assumes surveillance test efficiencies of unity.

For each case analyzed, two tables are presented. The first table presents the core damage frequency increase ΔC_1 for individual component aging effects. This gives the prioritization of individual component aging effects. The second table presents the core damage frequency increases ΔC_2 for double component aging interactions. This gives the prioritization of two component aging interactions. For example, Table 12A presents the ranked individual component contributions for the base case and Table 12B presents the ranked two component contributions. The total core damage frequency increase from aging is the sum of the contributions from the two tables. The top 25 contributors are given in each table, representing approximately 99% of the total contribution to ΔC_1 and to ΔC_2. The results are straightforwardly obtained using the risk importance approach previously described and are organized in a tabular format to explicitly detail information on the aging contributors.

The first column in a given table is the rank of the contributor according to the impact of the aging effect on the core damage frequency contribution. The core damage frequency

TABLE 12A. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS
PLANT A: BASE CASE, SINGLE CONTRIBUTIONS

Plant A: Single Contributions
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 1.8E-04 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Δq1	Test Interval (months)	ΔC (/year)
1	LPR-MOV-FT-1862A	1.5E-04	3.6E-06	167	2.6E-01	30	3.9E-05
2	LPR-MOV-FT-1860A	1.5E-04	3.6E-06	167	2.6E-01	30	3.9E-05
3	LPR-MOV-FT-1890A	1.4E-04	3.6E-06	167	2.6E-01	30	3.5E-05
4	HPI-MOV-FT-1350	6.7E-05	3.6E-06	167	2.6E-01	30	1.7E-05
5	LPR-MOV-FT-1862B	2.1E-05	3.6E-06	167	2.6E-01	30	5.4E-06
6	OEP-DGN-FS-DG01	3.8E-04	3.6E-06	72	1.4E-02	4	5.3E-06
7	LPR-MOV-FT-1860B	2.0E-05	3.6E-06	167	2.6E-01	30	5.3E-06
8	OEP-DGN-FR-6HDG1	3.4E-04	3.6E-06	72	1.4E-02	4	4.8E-06
9	OEP-DGN-FS-DG03	2.0E-04	3.6E-06	72	1.4E-02	4	2.8E-06
10	OEP-DGN-FS-DG02	2.0E-04	3.6E-06	72	1.4E-02	4	2.8E-06
11	OEP-DGN-FR-6HDG3	1.9E-04	3.6E-06	72	1.4E-02	4	2.7E-06
12	OEP-DGN-FR-6HDG2	1.7E-04	3.6E-06	72	1.4E-02	4	2.5E-06
13	PPS-MOV-FT-1535	9.5E-06	3.6E-06	167	2.6E-01	30	2.4E-06
14	HPI-CKV-FT-CV225	2.1E-03	4.0E-09	0	4.8E-04	11	1.7E-06
15	HPI-CKV-FT-CV25	2.1E-03	4.0E-09	0	4.8E-04	11	1.7E-06
16	HPI-CKV-FT-CV410	2.1E-03	4.0E-09	0	4.8E-04	11	1.7E-06
17	HPI-MOV-FT-1115C	5.7E-06	3.6E-06	167	2.6E-01	30	1.5E-06
18	HPI-MOV-FT-1115D	5.7E-06	3.6E-06	167	2.6E-01	30	1.5E-06
19	HPI-MOV-FT-1115B	5.7E-06	3.6E-06	167	2.6E-01	30	1.5E-06
20	HPI-MOV-FT-1115E	5.7E-06	3.6E-06	167	2.6E-01	30	1.5E-06
21	LPR-MOV-FT-1890B	4.5E-06	3.6E-06	167	2.6E-01	30	1.2E-06
22	PPS-MOV-FT-1536	3.4E-06	3.6E-06	167	2.6E-01	30	8.8E-07
23	HPI-MOV-FT-1867D	2.9E-06	3.6E-06	167	2.6E-01	30	7.5E-07
24	OEP-DGN-FR-DG01	5.0E-05	3.6E-06	72	1.4E-02	4	7.2E-07
25	SIS-ACT-FA-SISA	1.8E-05	3.0E-07	0	1.8E-02	6	5.4E-07

TABLE 12B. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS
PLANT A: BASE CASE, DOUBLE CONTRIBUTIONS

Plant A: Double Contributions
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 7.6E-04 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Δq1	Test Interval (months)	Component Name	Aging Rate (/hr/yr)	MTBF (months)	Δq2	Test Interval (months)	ΔC (/year)
1	HPI-MOV-FT-1115B	1.9E-03	3.6E-06	167	2.6E-01	30	HPI-MOV-FT-1115D	3.6E-06	167	2.6E-01	30	1.3E-04
2	HPI-MOV-FT-1115C	1.9E-03	3.6E-06	167	2.6E-01	30	HPI-MOV-FT-1115E	3.6E-06	167	2.6E-01	30	1.3E-04
3	LPR-MOV-FT-1890A	1.5E-03	3.6E-06	167	2.6E-01	30	LPR-MOV-FT-1890B	3.6E-06	167	2.6E-01	30	1.0E-04
4	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	167	2.6E-01	30	LPR-MOV-FT-1860B	3.6E-06	167	2.6E-01	30	1.0E-04
5	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	167	2.6E-01	30	LPR-MOV-FT-1860B	3.6E-06	167	2.6E-01	30	1.0E-04
6	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	167	2.6E-01	30	LPR-MOV-FT-1862B	3.6E-06	167	2.6E-01	30	1.0E-04
7	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	167	2.6E-01	30	LPR-MOV-FT-1862B	3.6E-06	167	2.6E-01	30	1.0E-04
8	SIS-ACT-FA-SISB	6.5E-03	3.0E-07	0	1.8E-02	6	SIS-ACT-FA-SISA	3.0E-07	0	1.8E-02	6	5.9E-06
9	RMT-ACT-FA-RMTSA	1.5E-03	3.0E-07	0	1.8E-02	6	RMT-ACT-FA-RMTSB	3.0E-07	0	1.8E-02	6	1.4E-06
10	OEP-DGN-FR-6HDG3	5.6E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FR-6HDG1	3.6E-06	72	1.4E-02	4	1.1E-06
11	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FS-DG02	3.6E-06	72	1.4E-02	4	9.9E-07
12	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FS-DG03	3.6E-06	72	1.4E-02	4	9.9E-07
13	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FR-6HDG2	3.6E-06	72	1.4E-02	4	8.1E-07
14	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FR-6HDG3	3.6E-06	72	1.4E-02	4	8.1E-07
15	OEP-DGN-FS-DG02	4.0E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FR-6HDG1	3.6E-06	72	1.4E-02	4	8.1E-07
16	OEP-DGN-FR-6HDG1	4.0E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FR-6HDG2	3.6E-06	72	1.4E-02	4	8.1E-07
17	OEP-DGN-FS-DG03	3.9E-03	3.6E-06	72	1.4E-02	4	OEP-DGN-FR-6HDG1	3.6E-06	72	1.4E-02	4	7.8E-07
18	OEP-DGN-FS-DG01	5.0E-03	3.6E-06	72	1.4E-02	4	MSS-SRV-OO-SGSRV	7.0E-07	22	3.4E-03	22	2.4E-07
19	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	5.8E-04	2	LPR-MOV-FT-1862A	3.6E-06	167	2.6E-01	30	2.3E-07
20	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	5.8E-04	2	LPR-MOV-FT-1860B	3.6E-06	167	2.6E-01	30	2.3E-07
21	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	5.8E-04	2	LPR-MOV-FT-1860A	3.6E-06	167	2.6E-01	30	2.3E-07
22	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	5.8E-04	2	LPR-MOV-FT-1862B	3.6E-06	167	2.6E-01	30	2.3E-07
23	OEP-DGN-FR-6HDG1	4.6E-03	3.6E-06	72	1.4E-02	4	MSS-SRV-OO-SGSRV	7.0E-07	22	3.4E-03	22	2.2E-07
24	PPS-MOV-FC-1536	2.9E-06	3.6E-06	167	2.6E-01	30	PPS-MOV-FC-1535	3.6E-06	167	2.6E-01	30	1.9E-07
25	OEP-DGN-FS-DG03	9.1E-04	3.6E-06	72	1.4E-02	4	OEP-DGN-FR-DG01	3.6E-06	72	1.4E-02	4	1.8E-07

TABLE 13A. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: UPPER BOUND CASE, SINGLE CONTRIBUTIONS

Plant A: Single Contributions
High Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 1.0E-02 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Δq1	Test Interval (months)	ΔC (/year)
1	HPI-CKV-FT-CV225	2.1E-03	1.0E-05	0	7.0E-01	11	2.5E-03
2	HPI-CKV-FT-CV410	2.1E-03	1.0E-05	0	7.0E-01	11	2.4E-03
3	HPI-CKV-FT-CV25	2.1E-03	1.0E-05	0	7.0E-01	11	2.4E-03
4	ACC-CKV-FT-CV145	5.0E-04	1.0E-05	0	7.0E-01	11	5.8E-04
5	ACC-CKV-FT-CV147	5.0E-04	1.0E-05	0	7.0E-01	11	5.8E-04
6	ACC-CKV-FT-CV130	5.0E-04	1.0E-05	0	7.0E-01	11	5.8E-04
7	ACC-CKV-FT-CV128	5.0E-04	1.0E-05	0	7.0E-01	11	5.8E-04
8	LPR-MOV-FT-1862A	1.5E-04	1.0E-05	167	5.1E-01	30	7.8E-05
9	LPR-MOV-FT-1860A	1.5E-04	1.0E-05	167	5.1E-01	30	7.8E-05
10	LPR-MOV-FT-1890A	1.4E-04	1.0E-05	167	5.1E-01	30	7.0E-05
11	HPI-MOV-FT-1350	6.7E-05	1.0E-05	167	5.1E-01	30	3.4E-05
12	OEP-DGN-FS-DG01	3.8E-04	1.0E-05	72	3.9E-02	4	1.5E-05
13	OEP-DGN-FR-6HDG1	3.4E-04	1.0E-05	72	3.9E-02	4	1.3E-05
14	LPR-MOV-FT-1862B	2.1E-05	1.0E-05	167	5.1E-01	30	1.1E-05
15	LPR-MOV-FT-1860B	2.0E-05	1.0E-05	167	5.1E-01	30	1.0E-05
16	OEP-DGN-FS-DG02	2.0E-04	1.0E-05	72	3.9E-02	4	7.9E-06
17	OEP-DGN-FS-DG03	2.0E-04	1.0E-05	72	3.9E-02	4	7.9E-06
18	OEP-DGN-FR-6HDG3	1.9E-04	1.0E-05	72	3.9E-02	4	7.6E-06
19	OEP-DGN-FR-6HDG2	1.7E-04	1.0E-05	72	3.9E-02	4	6.8E-06
20	PPS-MOV-FT-1535	9.5E-06	1.0E-05	167	5.1E-01	30	4.8E-06
21	MSS-CKV-FT-SGDHR	4.1E-06	1.0E-05	0	7.0E-01	11	4.7E-06
22	HPI-MOV-FT-1115C	5.7E-06	1.0E-05	167	5.1E-01	30	2.9E-06
23	HPI-MOV-FT-1115D	5.7E-06	1.0E-05	167	5.1E-01	30	2.9E-06
24	HPI-MOV-FT-1115E	5.7E-06	1.0E-05	167	5.1E-01	30	2.9E-06
25	HPI-MOV-FT-1115B	5.7E-06	1.0E-05	167	5.1E-01	30	2.9E-06

TABLE 13B. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS
PLANT A: UPPER BOUND CASE, DOUBLE CONTRIBUTIONS

Plant A: Double Contributions
High Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 4.5E-03 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Δq1	Test Interval (months)	Component Name	Aging Rate (/hr/yr)	MTBF (months)	Δq2	Test Interval (months)	ΔC (/year)
1	HPI-MOV-FT-1115B	1.9E-03	1.0E-05	167	5.1E-01	30	HPI-MOV-FT-1115D	1.0E-05	167	5.1E-01	30	4.9E-04
2	HPI-MOV-FT-1115C	1.9E-03	1.0E-05	167	5.1E-01	30	HPI-MOV-FT-1115E	1.0E-05	167	5.1E-01	30	4.9E-04
3	HPI-CKV-OO-CV258	1.3E-02	1.0E-05	0	7.0E-01	11	HPI-MDP-FR-1A24H	1.0E-05	86	2.9E-02	2	4.4E-04
4	LPR-MOV-FT-1860A	1.5E-03	1.0E-05	167	5.1E-01	30	LPR-MOV-FT-1862B	1.0E-05	167	5.1E-01	30	3.9E-04
5	LPR-MOV-FT-1890A	1.5E-03	1.0E-05	167	5.1E-01	30	LPR-MOV-FT-1890B	1.0E-05	167	5.1E-01	30	3.9E-04
6	LPR-MOV-FT-1860A	1.5E-03	1.0E-05	167	5.1E-01	30	LPR-MOV-FT-1860B	1.0E-05	167	5.1E-01	30	3.9E-04
7	LPR-MOV-FT-1862A	1.5E-03	1.0E-05	167	5.1E-01	30	LPR-MOV-FT-1862B	1.0E-05	167	5.1E-01	30	3.9E-04
8	LPR-MOV-FT-1862A	1.5E-03	1.0E-05	167	5.1E-01	30	LPR-MOV-FT-1860B	1.0E-05	167	5.1E-01	30	3.9E-04
9	AFW-TDP-FS-FW2	5.4E-03	1.0E-05	72	2.4E-02	2	AFW-CKV-OO-CV142	1.0E-05	0	7.0E-01	11	1.5E-04
10	HPI-CKV-OO-CV258	4.0E-03	1.0E-05	0	7.0E-01	11	HPI-MDP-FR-1A6HR	1.0E-05	86	2.9E-02	2	1.4E-04
11	AFW-MDP-FS-FW3A	3.6E-03	1.0E-05	86	2.9E-02	2	AFW-CKV-OO-CV157	1.0E-05	0	7.0E-01	11	1.2E-04
12	AFW-CKV-OO-CV172	3.6E-03	1.0E-05	0	7.0E-01	11	AFW-MDP-FS-FW3B	1.0E-05	86	2.9E-02	2	1.2E-04
13	PPS-MOV-FT-1535	1.1E-04	1.0E-05	167	5.1E-01	30	AFW-CKV-OO-CV142	1.0E-05	0	7.0E-01	11	6.7E-05
14	AFW-CKV-OO-CV142	1.1E-04	1.0E-05	0	7.0E-01	11	PPS-MOV-FT-1536	1.0E-05	167	5.1E-01	30	6.7E-05
15	LPI-MDP-FS-SI1A	1.5E-03	1.0E-05	86	2.9E-02	2	LPI-CKV-OO-CV58	1.0E-05	0	7.0E-01	11	5.1E-05
16	LPI-MDP-FS-SI1B	1.5E-03	1.0E-05	86	2.9E-02	2	LPI-CKV-OO-CV50	1.0E-05	0	7.0E-01	11	5.1E-05
17	MSS-SRV-OO-SGSRV	7.9E-04	1.0E-05	22	4.9E-02	22	AFW-CKV-OO-CV172	1.0E-05	0	7.0E-01	11	4.5E-05
18	AFW-CKV-OO-CV157	6.4E-05	1.0E-05	0	7.0E-01	11	PPS-MOV-FT-1536	1.0E-05	167	5.1E-01	30	3.8E-05
19	AFW-CKV-OO-CV172	6.4E-05	1.0E-05	0	7.0E-01	11	PPS-MOV-FT-1536	1.0E-05	167	5.1E-01	30	3.8E-05
20	PPS-MOV-FT-1535	6.4E-05	1.0E-05	167	5.1E-01	30	AFW-CKV-OO-CV157	1.0E-05	0	7.0E-01	11	3.8E-05
21	PPS-MOV-FT-1535	6.4E-05	1.0E-05	167	5.1E-01	30	AFW-CKV-OO-CV172	1.0E-05	0	7.0E-01	11	3.8E-05
22	OEP-DGN-FS-DG01	6.6E-04	1.0E-05	72	3.9E-02	4	AFW-CKV-OO-CV172	1.0E-05	0	7.0E-01	11	3.0E-05
23	LPI-MDP-FS-SI1B	1.5E-03	1.0E-05	86	2.9E-02	2	LPR-MOV-FT-1860A	1.0E-05	167	5.1E-01	30	2.2E-05
24	LPI-MDP-FS-SI1A	1.5E-03	1.0E-05	86	2.9E-02	2	LPR-MOV-FT-1862B	1.0E-05	167	5.1E-01	30	2.2E-05
25	LPI-MDP-FS-SI1A	1.5E-03	1.0E-05	86	2.9E-02	2	LPR-MOV-FT-1860B	1.0E-05	167	5.1E-01	30	2.2E-05

TABLE 14A. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: LOWER BOUND CASE, SINGLE CONTRIBUTIONS

Plant A: Single Contributions
Low Aging Rates
Efficiency = 1

Total ΔC: 6.4E-06 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Δq1	Test Interval (months)	ΔC (/year)
1	LPR-MOV-FT-1862A	1.5E-04	2.0E-07	167	8.8E-03	18	1.3E-06
2	LPR-MOV-FT-1860A	1.5E-04	2.0E-07	167	8.8E-03	18	1.3E-06
3	LPR-MOV-FT-1890A	1.4E-04	2.0E-07	167	8.8E-03	18	1.2E-06
4	HPI-MOV-FT-1350	6.7E-05	2.0E-07	167	8.8E-03	18	5.9E-07
5	HPI-CKV-FT-CV225	2.1E-03	5.0E-09	0	5.5E-05	1	1.9E-07
6	HPI-CKV-FT-CV410	2.1E-03	5.0E-09	0	5.5E-05	1	1.9E-07
7	HPI-CKV-FT-CV25	2.1E-03	5.0E-09	0	5.5E-05	1	1.9E-07
8	LPR-MOV-FT-1862B	2.1E-05	2.0E-07	167	8.8E-03	18	1.8E-07
9	LPR-MOV-FT-1860B	2.0E-05	2.0E-07	167	8.8E-03	18	1.8E-07
10	AFW-TDP-FS-FW2	6.8E-05	2.0E-06	72	2.2E-03	1	1.5E-07
11	SIS-ACT-FA-SISA	1.8E-05	3.0E-07	0	3.3E-03	1	9.8E-08
12	SIS-ACT-FA-SISB	1.8E-05	3.0E-07	0	3.3E-03	1	9.8E-08
13	PPS-MOV-FT-1535	9.5E-06	2.0E-07	167	8.8E-03	18	8.4E-08
14	OEP-DGN-FS-DG01	3.8E-04	2.0E-07	72	2.2E-04	1	8.2E-08
15	OEP-DGN-FR-6HDG1	3.4E-04	2.0E-07	72	2.2E-04	1	7.4E-08
16	AFW-TDP-FR-2P6HR	2.6E-05	2.0E-06	72	2.2E-03	1	5.6E-08
17	HPI-MOV-FT-1115B	5.7E-06	2.0E-07	167	8.8E-03	18	5.0E-08
18	HPI-MOV-FT-1115D	5.7E-06	2.0E-07	167	8.8E-03	18	5.0E-08
19	HPI-MOV-FT-1115C	5.7E-06	2.0E-07	167	8.8E-03	18	5.0E-08
20	HPI-MOV-FT-1115E	5.7E-06	2.0E-07	167	8.8E-03	18	5.0E-08
21	ACC-CKV-FT-CV130	5.0E-04	5.0E-09	0	5.5E-05	1	4.6E-08
22	ACC-CKV-FT-CV145	5.0E-04	5.0E-09	0	5.5E-05	1	4.6E-08
23	ACC-CKV-FT-CV128	5.0E-04	5.0E-09	0	5.5E-05	1	4.6E-08
24	ACC-CKV-FT-CV147	5.0E-04	5.0E-09	0	5.5E-05	1	4.6E-08
25	OEP-DGN-FS-DG02	2.0E-04	2.0E-07	72	2.2E-04	1	4.3E-08

TABLE 14B. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: LOWER BOUND CASE, DOUBLE CONTRIBUTIONS

Plant A: Double Contributions
Low Aging Rates
Efficiency = 1

Total ΔC: 1.1E-06 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Δq1	Test Interval (months)	Component Name	Aging Rate (/hr/yr)	MTBF (months)	Δq2	Test Interval (months)	ΔC (/year)
1	SIS-ACT-FA-SISB	6.5E-03	3.0E-07	0	3.3E-03	1	SIS-ACT-FA-SISA	3.0E-07	0	3.3E-03	1	1.9E-07
2	HPI-MOV-FT-1115C	1.9E-03	2.0E-07	167	8.8E-03	18	HPI-MOV-FT-1115E	2.0E-07	167	8.8E-03	18	1.5E-07
3	HPI-MOV-FT-1115B	1.9E-03	2.0E-07	167	8.8E-03	18	HPI-MOV-FT-1115D	2.0E-07	167	8.8E-03	18	1.5E-07
4	LPR-MOV-FT-1862A	1.5E-03	2.0E-07	167	8.8E-03	18	LPR-MOV-FT-1860B	2.0E-07	167	8.8E-03	18	1.2E-07
5	LPR-MOV-FT-1862A	1.5E-03	2.0E-07	167	8.8E-03	18	LPR-MOV-FT-1862B	2.0E-07	167	8.8E-03	18	1.2E-07
6	LPR-MOV-FT-1860A	1.5E-03	2.0E-07	167	8.8E-03	18	LPR-MOV-FT-1862B	2.0E-07	167	8.8E-03	18	1.2E-07
7	LPR-MOV-FT-1860A	1.5E-03	2.0E-07	167	8.8E-03	18	LPR-MOV-FT-1860B	2.0E-07	167	8.8E-03	18	1.2E-07
8	LPR-MOV-FT-1890A	1.5E-03	2.0E-07	167	8.8E-03	18	LPR-MOV-FT-1890B	2.0E-07	167	8.8E-03	18	1.2E-07
9	RMT-ACT-FA-RMTSA	1.5E-03	3.0E-07	0	3.3E-03	1	RMT-ACT-FA-RMTSB	3.0E-07	0	3.3E-03	1	4.5E-08
10	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2.6E-04	1	LPR-MOV-FT-1860A	2.0E-07	167	8.8E-03	18	3.4E-09
11	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2.6E-04	1	LPR-MOV-FT-1860B	2.0E-07	167	8.8E-03	18	3.4E-09
12	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2.6E-04	1	LPR-MOV-FT-1862A	2.0E-07	167	8.8E-03	18	3.4E-09
13	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2.6E-04	1	LPR-MOV-FT-1862B	2.0E-07	167	8.8E-03	18	3.4E-09
14	LPR-MOV-FT-1862A	1.0E-03	2.0E-07	167	8.8E-03	18	LPI-MDP-FR-B21HR	2.0E-07	86	2.6E-04	1	2.3E-09
15	LPR-MOV-FT-1862B	1.0E-03	2.0E-07	167	8.8E-03	18	LPI-MDP-FR-A21HR	2.0E-07	86	2.6E-04	1	2.3E-09
16	LPR-MOV-FT-1860B	1.0E-03	2.0E-07	167	8.8E-03	18	LPI-MDP-FR-A21HR	2.0E-07	86	2.6E-04	1	2.3E-09
17	LPR-MOV-FT-1860A	1.0E-03	2.0E-07	167	8.8E-03	18	LPI-MDP-FR-B21HR	2.0E-07	86	2.6E-04	1	2.3E-09
18	AFW-TDP-FR-2P6HR	1.8E-04	2.0E-06	72	2.2E-03	1	AFW-ACT-FA-PMP3B	3.0E-07	0	3.3E-03	1	2.1E-09
19	AFW-TDP-FR-2P6HR	1.8E-04	2.0E-06	72	2.2E-03	1	AFW-ACT-FA-PMP3A	3.0E-07	0	3.3E-03	1	2.1E-09
20	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2.6E-04	1	SIS-ACT-FA-SISB	3.0E-07	0	3.3E-03	1	2.1E-09
21	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2.6E-04	1	SIS-ACT-FA-SISA	3.0E-07	0	3.3E-03	1	2.1E-09
22	LPR-MOV-FT-1862B	5.0E-04	2.0E-07	167	8.8E-03	18	LPI-MDP-FR-A24HR	2.0E-07	86	2.6E-04	1	1.1E-09
23	LPR-MOV-FT-1862A	5.0E-04	2.0E-07	167	8.8E-03	18	LPI-MDP-FR-B24HR	2.0E-07	86	2.6E-04	1	1.1E-09
24	AFW-TDP-FS-FW2	5.4E-03	2.0E-06	72	2.2E-03	1	AFW-CKV-OO-CV142	5.0E-09	0	5.5E-05	1	1.1E-09
25	AFW-TDP-FS-FW2	1.3E-03	2.0E-06	72	2.2E-03	1	MSS-SRV-OO-SGSRV	7.0E-08	22	3.1E-04	18	9.0E-10

contribution from every aging component and every combination of aging components in the PSA is determined allowing the contributions to be ranked in detail. The second column in the table is the name of the component as defined in the PSA. The component name identifies the system, component type, failure mode, and specific component identifier. The codes for the identifiers used in the PSA are given in Table 15.

The third column in a given table is the risk sensitivity coefficient, or risk importance coefficient, S_i or S_{ij} for the contributor. The coefficient gives the core damage frequency importance of the contributor as determined by the original PSA. Basically, S_i or S_{ij} is the change in core damage frequency per unit change in the unavailability of the contributor. The value of the risk sensitivity coefficient, or risk importance coefficient, is determined by the basic design and operational procedures of the plant.

The next three columns give the component aging rate, component replacement interval, and component test interval which determine the component unavailability increase Δq caused by aging. The aging effect Δq is determined using the equations previously given. Because we are assuming the component is replaced at failure, the replacement time is the mean time to failure (denoted as MTBF in the tables)*. Where there is no MTBF given, the mean time to failure is larger than 50 years and the formula for a nonreplaceable component (Equation (61) or (62)) is used. The test interval given is the effective test interval for the base case and upper bound case. For the lower bound case, test efficiencies of 1 were assumed as was indicated.

It is useful to print out the aging rate, replacement interval, and test interval as shown to identify the factors which determine the aging effect Δq. The core damage frequency increase ΔC due to aging is the aging effect on the contributor multiplied by the risk importance of the contributor. For the single component contributor, the aging effect is simply Δq_1 and ΔC is the product of the sensitivity coefficient S_i and Δq_i. For the double component contributors, the aging effect is $\Delta q_i \Delta q_j$ and ΔC is the product of the sensitivity coefficient S_{ij} and $\Delta q_i \Delta q_j$.

The tables thus provide all the ranked contributors to the core damage frequency increase ΔC due to aging. The risk importance factor (sensitivity coefficient) and the aging effect factor which combine to give ΔC are explicitly given and the aging rate, replacement

* The mean time between failure (MTBF) includes the component repair time, which is assumed to be small compared to the mean time to failure (MTTF). Hence MTBF $\cong$ MTTF.

TABLE 15. COMPONENT IDENTIFIERS

SYSTEM CODE

ACC - Accumulators
AFW - Auxliary Feedwater
HPI - High Pressure Injection
LPI - Low Pressure Injection
SIS - Safety Injection System
LPR - Low Pressure Recirculation
PPS - Primary Pressure Relief
OEP - Onsite Emergency Power
MSS - Main Steam System

COMPONENT CODE

ACT - Actuator
CKV - Check Valve
DGN - Diesel Generator
MDP - Motor Driven Pump
MOV - Motor Operated Valve
SRV - Safety Relief Valve
TDP - Turbine Driven Pump

FAILURE MODE CODE

FA - Fail to Actuate
FR - Fail to Run
FS - Fail to Start
FT - Fail to Transfer
OO - Fail to Open

interval, and test interval which determine the aging effect Δq are explicitly identified. The tables can now be used to help focus aging control and aging management activities.

5.6 Grouped Component Prioritizations

The detailed prioritizations in Tables 12, 13, and 14 can also be used to obtain grouped prioritizations of the component contributors in which the components are grouped according to various criteria. We will demonstrate the grouping approach by grouping contributors which have the same order of magnitude contribution. Tables 16, 17 and 18 provide the grouped prioritizations of the contributors by order of magnitude of their core damage frequency (ΔC) contribution. The groupings of the contributors in the tables thus focus on the general sizes of core damage frequency contributions. The groupings also serve to account for uncertainties in the calculated contributions.

Table 16 groups the component contributors in Tables 12A and 12B for the base case by order of magnitude contribution. Each component in a double contributor set in Table 12B is assigned to a group in Table 16 based on the size of the double component contribution ΔC. Thus, the grouping combines the single and double contributors into one overall prioritization. Tables 17 and 18 provide similar grouped prioritizations for the upper bound case and lower bound case, respectively. From Tables 16, 17, and 18 it is observed that the same contributors often appear even when different aging rate data are used, although in some cases new contributors appear.

Table 19 combines Tables 16, 17, and 18 and gives the top order of magnitude contributors from each of the three tables, then the second highest order of magnitude contributors etc. Table 19 is thus a relative way of incorporating sensitivity results into one prioritization. Table 20 is another way of combining the sensitivity study results into one grouped prioritization by identifying all contributors above a given value of ΔC. Table 20 is thus a threshold approach for combining the results from the sensitivity studies. Other groupings of the contributors can also be carried out depending on the specific objectives of the analysis.

TABLE 16. COMPONENTS PRIORITIZED BY ORDER OF MAGNITUDE CONTRIBUTION: BASE CASE

Contributor	Range of ΔC
	1E-5 to 1E-4
HPI-MOV-FT-1115B	•
HPI-MOV-FT-1115C	•
HPI-MOV-FT-1115D	•
HPI-MOV-FT-1115E	•
LPR-MOV-FT-1860A	•
LPR-MOV-FT-1860B	•
LPR-MOV-FT-1862A	•
LPR-MOV-FT-1862B	•
LPR-MOV-FT-1890A	•
LPR-MOV-FT-1890B	•
	1E-6 to 1E-5
HPI-MOV-FT-1350	•
	1E-7 to 1E-6
SIS-ACT-FA-SISA	•
SIS-ACT-FA-SISB	•
OEP-DGN-FS-DG01	•
OEP-DGN-FR-6HDG1	•
OEP-DGN-FS-DG02	•
OEP-DGN-FS-DG03	•
OEP-DGN-FR-6HDG3	•
OEP-DGN-FR-6HDG2	•
PPS-MOV-FT-1535	•
HPI-CKV-FT-CV225	•
HPI-CKV-FT-CV25	•
HPI-CKV-FT-CV410	•
RMT-ACT-FA-RMTSA	•
RMT-ACT-FA-RMTSB	•
	•

TABLE 17. COMPONENTS PRIORITIZED BY ORDER OF MAGNITUDE CONTRIBUTION: UPPER BOUND CASE

Contributor	Range of ΔC	Contributor	Range of ΔC
	1E-3 to 1E-2		1E-5 to 1E-4
HPI-CKV-FT-CV225	•	LPR-MOV-FT-1862A	•
HPI-CKV-FT-CV410	•	PPS-MOV-FT-1536	•
HPI-CKV-FT-CV25	•	PPS-MOV-FT-1535	•
		LPI-MDP-FS-SI1B	•
	1E-4 to 1E-3	LPI-MDP-FS-SI1A	•
ACC-CKV-FT-CV147	•	LPI-CKV-OO-CV58	•
ACC-CKV-FT-CV145	•	LPI-CKV-OO-CV50	•
ACC-CKV-FT-CV130	•	MSS-SRV-OO-SGSRV	•
ACC-CKV-FT-CV128	•	HPI-MOV-FT-1350	•
HPI-MOV-FT-1115E	•	OEP-DGN-FS-DG01	•
HPI-MOV-FT-1115D	•	CPC-MDP-FR-SWA24	•
HPI-MOV-FT-1115C	•	CPC-CKV-OO-CV113	•
HPI-MOV-FT-1115B	•	LPI-MDP-FR-B21HR	•
HPI-MDP-FR-1A24H	•	LPI-MDP-FR-A21HR	•
HPI-CKV-OO-CV258	•	OEP-DGN-FR-6HDG1	•
LPR-MOV-FT-1890B	•	OEP-DGN-FS-DG03	•
LPR-MOV-FT-1890A	•	OEP-DGN-FS-DG02	•
LPR-MOV-FT-1862B	•	OEP-DGN-FR-6HDG2	•
LPR-MOV-FT-1862A	•		1E-6 to 1E-5
LPR-MOV-FT-1860B	•	PPS-MOV-FC-1536	•
LPR-MOV-FT-1860A	•	PPS-MOV-FC-1535	•
AFW-TDP-FS-FW2	•	OEP-DGN-FR-6HDG3	•
AFW-CKV-OO-CV142	•	LPI-MDP-FR-B24HR	•
HPI-MDP-FR-1A6HR	•	LPI-MDP-FR-A24HR	•
AFW-MDP-FS-FW3B	•	SIS-ACT-FA-SISB	•
AFW-MDP-FS-FW3A	•	SIS-ACT-FA-SISA	•
AFW-CKV-OO-CV172	•	MSS-CKV-FT-SGDHR	•
AFW-CKV-OO-CV157	•	OEP-DGN-FR-DG01	•
		CVC-MDP-FR-2A1HR	•
		HPI-MOV-FT-1867D	•
		RMT-ACT-FA-RMTSB	•
		RMT-ACT-FA-RMTSA	•
		OEP-DGN-FR-DG03	•
		OEP-DGN-FR-DG02	•
		AFW-MDP-FS	•

TABLE 18. COMPONENTS PRIORITIZED BY ORDER OF MAGNITUDE CONTRIBUTION: LOWER BOUND CASE

Contributor	Range of ΔC
	1E-7 to 1E-6
LPR-MOV-FT-1862A	•
LPR-MOV-FT-1860A	•
LPR-MOV-FT-1890A	•
	1E-8 to 1E-7
HPI-MOV-FT-1350	•
SIS-ACT-FA-SISA	•
SIS-ACT-FA-SISB	•
HPI-CKV-FT-CV225	•
HPI-CKV-FT-CV25	•
HPI-CKV-FT-CV410	•
LPR-MOV-FT-1862B	•
LPR-MOV-FT-1860B	•
AFW-TDP-FS-FW2	•
HPI-MOV-FT-1115B	•
HPI-MOV-FT-1115C	•
HPI-MOV-FT-1115D	•
HPI-MOV-FT-1115E	•
LPR-MOV-FT-1890B	•
	1E-8 to 1E-9
PPS-MOV-FT-1535	•
OEP-DGN-FS-DG01	•
OEP-DGN-FR-6HDG1	•
AFW-TDP-FR-2P6HR	•
ACC-CKV-FT-CV128	•
ACC-CKV-FT-CV130	•
ACC-CKV-FT-CV145	•
ACC-CKV-FT-CV147	•
RMT-ACT-FA-RMTSA	•
RMT-ACT-FA-RMTSB	•
OEP-DGN-FS-DG02	•
OEP-DGN-FS-DG03	•
OEP-DGN-FR-6HDG3	•
OEP-DGN-FR-6HDG2	•
PPS-MOV-FT-1536	•
AFW-ACT-FA-PMP3A	•
AFW-ACT-FA-PMP3B	•
HPI-MOV-FT-1867D	•
	•

TABLE 19. RELATIVE ORDERING OF THE COMPONENT CONTRIBUTORS: COMBINATIONS OF THE THREE CASES

Contributor	Relative Contribution	Contributor	Relative Contribution
HPI-CKV-FT-CV225	1st order of magnitude	LPR-MOV-FT-1862A	3rd order of magnitude
HPI-CKV-FT-CV25	•	PPS-MOV-FT-1536	•
HPI-CKV-FT-CV410	•	PPS-MOV-FT-1535	•
HPI-MOV-FT-1115B	•	LPI-MDP-FS-SI1B	•
HPI-MOV-FT-1115C	•	LPI-MDP-FS-SI1A	•
HPI-MOV-FT-1115D	•	LPI-CKV-OO-CV58	•
HPI-MOV-FT-1115E	•	LPI-CKV-OO-CV50	•
LPR-MOV-FT-1860A	•	MSS-SRV-OO-SGSRV	•
LPR-MOV-FT-1860B	•	HPI-MOV-FT-1350	•
LPR-MOV-FT-1862A	•	OEP-DGN-FS-DG01	•
LPR-MOV-FT-1862B	•	CPC-MDP-FR-SWA24	•
LPR-MOV-FT-1890B	•	CPC-CKV-OO-CV113	•
LPR-MOV-FT-1890A	•	LPI-MDP-FR-B21HR	•
		LPI-MDP-FR-A21HR	•
ACC-CKV-FT-CV128	2nd order of magnitude	OEP-DGN-FR-6HDG1	•
ACC-CKV-FT-CV130	•	OEP-DGN-FS-DG03	•
ACC-CKV-FT-CV145	•	OEP-DGN-FS-DG02	•
ACC-CKV-FT-CV147	•	OEP-DGN-FR-6HDG2	•
HPI-MOV-FT-1115B	•	SIS-ACT-FA-SISB	•
HPI-MOV-FT-1115C	•	SIS-ACT-FA-SISA	•
HPI-MOV-FT-1115D	•	OEP-DGN-FR-6HDG3	•
HPI-MOV-FT-1115E	•	HPI-CKV-FT-CV225	•
HPI-CKV-OO-CV258	•	HPI-CKV-FT-CV410	•
HPI-MDP-FR-1A24H	•	HPI-CKV-FT-CV25	•
LPR-MOV-FT-1860A	•	RMT-ACT-FA-RMTSB	•
LPR-MOV-FT-1860B	•	RMT-ACT-FA-RMTSA	•
LPR-MOV-FT-1862A	•	AFW-TDP-FR-2P6HR	•
LPR-MOV-FT-1862B	•	ACC-CKV-FT-CV147	•
LPR-MOV-FT-1890A	•	ACC-CKV-FT-CV145	•
LPR-MOV-FT-1890B	•	ACC-CKV-FT-CV130	•
AFW-CKV-OO-CV142	•	ACC-CKV-FT-CV128	•
AFW-TDP-FS-FW2	•	AFW-ACT-FA-PMP3B	•
HPI-MDP-FR-1A6HR	•	AFW-ACT-FA-PMP3A	•
AFW-CKV-OO-CV157	•	HPI-MOV-FT-1867D	•
AFW-CKV-OO-CV172	•		
AFW-MDP-FS-FW3A	•		
AFW-MDP-FS-FW3B	•		
HPI-MOV-FT-1350	•		
SIS-ACT-FA-SISA	•		

TABLE 20. ABSOLUTE ORDERING OF THE COMPONENT CONTRIBUTORS: COMBINATION OF THE CASES

Contributor Above 1E-3	Contributor Above 1E-5
HPI-CKV-FT-CV225	LPR-MOV-FT-1862A
HPI-CKV-FT-CV410	PPS-MOV-FT-1536
HPI-CKV-FT-CV25	PPS-MOV-FT-1535
	HPI-MOV-FT-1115B
Contributor Above 1E-4	HPI-MOV-FT-1115C
	HPI-MOV-FT-1115D
ACC-CKV-FT-CV147	HPI-MOV-FT-1115E
ACC-CKV-FT-CV145	LPR-MOV-FT-1860A
ACC-CKV-FT-CV130	LPR-MOV-FT-1860B
ACC-CKV-FT-CV128	LPR-MOV-FT-1862A
HPI-MOV-FT-1115E	LPR-MOV-FT-1862B
HPI-MOV-FT-1115D	LPR-MOV-FT-1890A
HPI-MOV-FT-1115C	LPR-MOV-FT-1890B
HPI-MOV-FT-1115B	LPI-MDP-FS-SI1B
HPI-MDP-FR-1A24H	LPI-MDP-FS-SI1A
HPI-CKV-OO-CV258	LPI-CKV-OO-CV58
LPR-MOV-FT-1890B	LPI-CKV-OO-CV50
LPR-MOV-FT-1890A	MSS-SRV-OO-SGSRV
LPR-MOV-FT-1862B	HPI-MOV-FT-1350
LPR-MOV-FT-1862A	OEP-DGN-FS-DG01
LPR-MOV-FT-1860B	CPC-MDP-FR-SWA24
LPR-MOV-FT-1860A	CPC-CKV-OO-CV113
AFW-TDP-FS-FW2	LPI-MDP-FR-B21HR
AFW-CKV-OO-CV142	LPI-MDP-FR-A21HR
HPI-MDP-FR-1A6HR	OEP-DGN-FR-6HDG1
AFW-MDP-FS-FW3B	OEP-DGN-FS-DG03
AFW-MDP-FS-FW3A	OEP-DGN-FS-DG02
AFW-CKV-OO-CV172	OEP-DGN-FR-6HDG2
AFW-CKV-OO-CV157	

6. IDENTIFICATION OF RISK-DIRECTED AGING MANAGEMENT STRATEGIES

6.0 Introduction

Once the aging contributors are prioritized with regards to their risk contributions, then aging management strategies can be focused on those contributors which are assessed to be relatively high. This chapter illustrates how such risk-directed aging management strategies can be identified and can be evaluated. The prioritized aging contributors obtained in the previous chapter will be used as a demonstration. In many cases, the risk-directed aging strategies need not necessarily involve large resources since the aging controls can be pinpointed on the relatively few, top ranked contributors to the core damage frequency increase caused by aging. The risk-directed aging management strategies which are investigated involve scheduled replacement of the high aging contributors and implementation of more frequent or more effective surveillance tests on these high contributors. Since there are relatively few high contributors which have been identified, the additional resources involved would not necessarily be large. Furthermore, the additional resources required could be trade-off against less frequent testing on the risk-unimportant components. The last section of the chapter further investigates the impacts of replacing operational tests with condition-monitoring tests.

6.1 Risk-Directed Aging Management Strategies

We shall consider the base case prioritization results obtained in the previous chapter. The same approaches would be used for the other results obtained using the different data bases. In the previous chapter, Tables 12A and 12B give the dominant aging contributors which are obtained for the base case. These tables are reproduced as Tables 21A and 21B on the following two pages. These contributors constitute approximately 99% of the increase in core damage frequency due to aging.

From Tables 21A and 21B, the top contributors consists of the motor operated valves (MOVs) in the Emergency Core Cooling System (HPI/LPR). There are 14 motor operated valves involved. The base case testing program involved testing the valves every 18 months and replacing the valves at failure. The first risk-directed aging management strategy investigated involves replacing the valves every 5 years

TABLE 21A. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: BASE CASE, SINGLE CONTRIBUTIONS

Plant A: Single Contributions
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 1.8E-04 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq1	ΔC (/year)
1	LPR-MOV-FT-1862A	1.5E-04	3.6E-06	167	30	2.6E-01	3.9E-05
2	LPR-MOV-FT-1860A	1.5E-04	3.6E-06	167	30	2.6E-01	3.9E-05
3	LPR-MOV-FT-1890A	1.4E-04	3.6E-06	167	30	2.6E-01	3.5E-05
4	HPI-MOV-FT-1350	6.7E-05	3.6E-06	167	30	2.6E-01	1.7E-05
5	LPR-MOV-FT-1862B	2.1E-05	3.6E-06	167	30	2.6E-01	5.4E-06
6	OEP-DGN-FS-DG01	3.8E-04	3.6E-06	72	4	1.4E-02	5.3E-06
7	LPR-MOV-FT-1860B	2.0E-05	3.6E-06	167	30	2.6E-01	5.3E-06
8	OEP-DGN-FR-6HDG1	3.4E-04	3.6E-06	72	4	1.4E-02	4.8E-06
9	OEP-DGN-FS-DG03	2.0E-04	3.6E-06	72	4	1.4E-02	2.8E-06
10	OEP-DGN-FS-DG02	2.0E-04	3.6E-06	72	4	1.4E-02	2.8E-06
11	OEP-DGN-FR-6HDG3	1.9E-04	3.6E-06	72	4	1.4E-02	2.7E-06
12	OEP-DGN-FR-6HDG2	1.7E-04	3.6E-06	72	4	1.4E-02	2.5E-06
13	PPS-MOV-FT-1535	9.5E-06	3.6E-06	167	30	2.6E-01	2.4E-06
14	HPI-CKV-FT-CV225	2.1E-03	4.0E-09	720	11	4.8E-04	1.7E-06
15	HPI-CKV-FT-CV25	2.1E-03	4.0E-09	720	11	4.8E-04	1.7E-06
16	HPI-CKV-FT-CV410	2.1E-03	4.0E-09	720	11	4.8E-04	1.7E-06
17	HPI-MOV-FT-1115C	5.7E-06	3.6E-06	167	30	2.6E-01	1.5E-06
18	HPI-MOV-FT-1115D	5.7E-06	3.6E-06	167	30	2.6E-01	1.5E-06
19	HPI-MOV-FT-1115B	5.7E-06	3.6E-06	167	30	2.6E-01	1.5E-06
20	HPI-MOV-FT-1115E	5.7E-06	3.6E-06	167	30	2.6E-01	1.5E-06
21	LPR-MOV-FT-1890B	4.5E-06	3.6E-06	167	30	2.6E-01	1.2E-06
22	PPS-MOV-FT-1536	3.4E-06	3.6E-06	167	30	2.6E-01	8.8E-07
23	HPI-MOV-FT-1867D	2.9E-06	3.6E-06	167	30	2.6E-01	7.5E-07
24	OEP-DGN-FR-DG01	5.0E-05	3.6E-06	72	4	1.4E-02	7.2E-07
25	SIS-ACT-FA-SISA	1.8E-05	3.0E-07	720	6	1.8E-02	5.4E-07

TABLE 21B. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: BASE CASE, DOUBLE CONTRIBUTIONS

Plant A: Double Contributions
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 7.6E-04 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq1	Component Name	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq2	ΔC (/year)
1	HPI-MOV-FT-1115B	1.9E-03	3.6E-06	167	30	2.6E-01	HPI-MOV-FT-1115D	3.6E-06	167	30	2.6E-01	1.3E-04
2	HPI-MOV-FT-1115C	1.9E-03	3.6E-06	167	30	2.6E-01	HPI-MOV-FT-1115E	3.6E-06	167	30	2.6E-01	1.3E-04
3	LPR-MOV-FT-1890A	1.5E-03	3.6E-06	167	30	2.6E-01	LPR-MOV-FT-1890B	3.6E-06	167	30	2.6E-01	1.0E-04
4	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	167	30	2.6E-01	LPR-MOV-FT-1860B	3.6E-06	167	30	2.6E-01	1.0E-04
5	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	167	30	2.6E-01	LPR-MOV-FT-1860B	3.6E-06	167	30	2.6E-01	1.0E-04
6	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	167	30	2.6E-01	LPR-MOV-FT-1862B	3.6E-06	167	30	2.6E-01	1.0E-04
7	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	167	30	2.6E-01	LPR-MOV-FT-1862B	3.6E-06	167	30	2.6E-01	1.0E-04
8	SIS-ACT-FA-SISB	6.5E-03	3.0E-07	720	6	1.8E-02	SIS-ACT-FA-SISA	3.0E-07	720	6	1.8E-02	5.9E-06
9	RMT-ACT-FA-RMTSA	1.5E-03	3.0E-07	720	6	1.8E-02	RMT-ACT-FA-RMTSB	3.0E-07	720	6	1.8E-02	1.4E-06
10	OEP-DGN-FR-6HDG3	5.6E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG1	3.6E-06	72	4	1.4E-02	1.1E-06
11	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FS-DG02	3.6E-06	72	4	1.4E-02	9.9E-07
12	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FS-DG03	3.6E-06	72	4	1.4E-02	9.9E-07
13	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG2	3.6E-06	72	4	1.4E-02	8.1E-07
14	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG3	3.6E-06	72	4	1.4E-02	8.1E-07
15	OEP-DGN-FS-DG02	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG1	3.6E-06	72	4	1.4E-02	8.1E-07
16	OEP-DGN-FR-6HDG1	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG2	3.6E-06	72	4	1.4E-02	8.1E-07
17	OEP-DGN-FS-DG03	3.9E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG1	3.6E-06	72	4	1.4E-02	7.8E-07
18	OEP-DGN-FS-DG01	5.0E-03	3.6E-06	72	4	1.4E-02	MSS-SRV-OO-SGSRV	7.0E-07	22	22	3.4E-03	2.4E-07
19	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1862A	3.6E-06	167	30	2.6E-01	2.3E-07
20	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1860B	3.6E-06	167	30	2.6E-01	2.3E-07
21	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1860A	3.6E-06	167	30	2.6E-01	2.3E-07
22	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1862B	3.6E-06	167	30	2.6E-01	2.3E-07
23	OEP-DGN-FR-6HDG1	4.6E-03	3.6E-06	72	4	1.4E-02	MSS-SRV-OO-SGSRV	7.0E-07	22	22	3.4E-03	2.2E-07
24	PPS-MOV-FC-1536	2.9E-06	3.6E-06	167	30	2.6E-01	PPS-MOV-FC-1535	3.6E-06	167	30	2.6E-01	1.9E-07
25	OEP-DGN-FS-DG03	9.1E-04	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-DG01	3.6E-06	72	4	1.4E-02	1.8E-07

(60 months) and improving the test and increasing the test frequency so that the effective test interval is 6 months.

Tables 22A and 22B give the new results for this first risk-directed aging management strategy. This enhanced aging management strategy results in an average core damage frequency increase due to aging of $3.8 \times 10^{-5} + 1.9 \times 10^{-5} = 5.7 \times 10^{-5}$ per year. This compares to the base case core damage frequency increase of $1.8 \times 10^{-4} + 7.6 \times 10^{-4} = 9.4 \times 10^{-4}$ per year. The risk-directed aging management strategy thus results in a factor of 16 reduction in the core damage frequency increase due to aging. A significant reduction in risk effects due to aging is thus achieved by focusing on the 14 risk-important motor operated valves.

In addition to the motor operated valves, the prioritized aging contributors for the base case in Tables 21A and 21B also identify as important risk contributors the diesel generators (DGN), the three check valves (CKV) in the High Pressure Injection (HPI) System, and the four Actuation Trains (ACT). Thus, a second risk-directed aging management strategy is identified which involves carrying out the MOV tests and replacements in the first strategy plus improving the test efficiency on the three diesels so that the effective test interval is 1 month, replacing the three check valves every 20 years (240 months) and replacing the four actuation trains every 20 years. (The necessary requirements to improve the diesel test efficiency was assessed by personnel knowledgeable of the test.)

Tables 23A and 23B give the new values for the aging contributors corresponding to the second risk-directed aging management strategy. This second enhanced aging management strategy results in an average core damage frequency increase from aging of $1.8 \times 10^{-5} + 5.1 \times 10^{-6} = 2.3 \times 10^{-5}$ per year, which represents a factor of 41 reduction as compared to the base case. Thus, by focusing on relatively few additional, risk important aging contributors the core damage frequency increase due to aging is further significantly reduced.

As a summary of strategies evaluated, Figure 7 illustrates the core damage frequency increase due to aging for the base case, the first risk-directed aging management strategy, and the second risk-directed aging management strategy. Instead of the absolute increases, the relative core damage frequency increases due to aging may be of more interest where the relative increase is the absolute increase divided by the original core

TABLE 22A. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: FIRST RISK-DIRECTED STRATEGY, SINGLE CONTRIBUTIONS

Plant A: Single Contributions
First Aging Control Strategy
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 3.8E-05 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq1	ΔC (/year)
1	OEP-DGN-FS-DG01	3.8E-04	3.6E-06	72	4	1.4E-02	5.3E-06
2	OEP-DGN-FR-6HDG1	3.4E-04	3.6E-06	72	4	1.4E-02	4.8E-06
3	LPR-MOV-FT-1862A	1.5E-04	3.6E-06	60 *	6 *	1.9E-02	2.9E-06
4	LPR-MOV-FT-1860A	1.5E-04	3.6E-06	60 *	6 *	1.9E-02	2.9E-06
5	OEP-DGN-FS-DG02	2.0E-04	3.6E-06	72	4	1.4E-02	2.8E-06
6	OEP-DGN-FS-DG03	2.0E-04	3.6E-06	72	4	1.4E-02	2.8E-06
7	OEP-DGN-FR-6HDG3	1.9E-04	3.6E-06	72	4	1.4E-02	2.7E-06
8	LPR-MOV-FT-1890A	1.4E-04	3.6E-06	60 *	6 *	1.9E-02	2.6E-06
9	OEP-DGN-FR-6HDG2	1.7E-04	3.6E-06	72	4	1.4E-02	2.5E-06
10	HPI-CKV-FT-CV225	2.1E-03	4.0E-09	720	11	4.8E-04	1.7E-06
11	HPI-CKV-FT-CV25	2.1E-03	4.0E-09	720	11	4.8E-04	1.7E-06
12	HPI-CKV-FT-CV410	2.1E-03	4.0E-09	720	11	4.8E-04	1.7E-06
13	HPI-MOV-FT-1350	6.7E-05	3.6E-06	60 *	6 *	1.9E-02	1.3E-06
14	OEP-DGN-FR-DG01	5.0E-05	3.6E-06	72	4	1.4E-02	7.2E-07
15	SIS-ACT-FA-SISA	1.8E-05	3.0E-07	720	6	1.8E-02	5.4E-07
16	LPR-MOV-FT-1862B	2.1E-05	3.6E-06	60 *	6 *	1.9E-02	4.0E-07
17	LPR-MOV-FT-1860B	2.0E-05	3.6E-06	60 *	6 *	1.9E-02	3.9E-07
18	PPS-MOV-FT-1535	9.5E-06	3.6E-06	60 *	6 *	1.9E-02	1.8E-07
19	HPI-MOV-FT-1115B	5.7E-06	3.6E-06	60 *	6 *	1.9E-02	1.1E-07
20	HPI-MOV-FT-1115D	5.7E-06	3.6E-06	60 *	6 *	1.9E-02	1.1E-07
21	HPI-MOV-FT-1115C	5.7E-06	3.6E-06	60 *	6 *	1.9E-02	1.1E-07
22	HPI-MOV-FT-1115E	5.7E-06	3.6E-06	60 *	6 *	1.9E-02	1.1E-07
23	LPR-MOV-FT-1890B	4.5E-06	3.6E-06	60 *	6 *	1.9E-02	8.5E-08
24	PPS-MOV-FT-1536	3.4E-06	3.6E-06	60 *	6 *	1.9E-02	6.5E-08
25	HPI-MOV-FT-1867D	2.9E-06	3.6E-06	60 *	6 *	1.9E-02	5.6E-08

* - Control Value

TABLE 22B. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS
PLANT A: FIRST RISK-DIRECTED STRATEGY: DOUBLE CONTRIBUTIONS

Plant A: Double Contributions
Second Aging Control Strategy
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 5.1E-06 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq1	Component Name	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq2	ΔC (/year)
1	HPI-MOV-FT-1115C	1.9E-03	3.6E-06	60	6	1.9E-02	HPI-MOV-FT-1115E	3.6E-06	60	6	1.9E-02	6.8E-07
2	HPI-MOV-FT-1115B	1.9E-03	3.6E-06	60	6	1.9E-02	HPI-MOV-FT-1115D	3.6E-06	60	6	1.9E-02	6.8E-07
3	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	60	6	1.9E-02	LPR-MOV-FT-1862B	3.6E-06	60	6	1.9E-02	5.4E-07
4	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	60	6	1.9E-02	LPR-MOV-FT-1860B	3.6E-06	60	6	1.9E-02	5.4E-07
5	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	60	6	1.9E-02	LPR-MOV-FT-1862B	3.6E-06	60	6	1.9E-02	5.4E-07
6	LPR-MOV-FT-1890A	1.5E-03	3.6E-06	60	6	1.9E-02	LPR-MOV-FT-1890B	3.6E-06	60	6	1.9E-02	5.4E-07
7	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	60	6	1.9E-02	LPR-MOV-FT-1860B	3.6E-06	60	6	1.9E-02	5.4E-07
8	SIS-ACT-FA-SISB	6.5E-03	3.0E-07	240 *	6	6.0E-03	SIS-ACT-FA-SISA	3.0E-07	240 *	6	6.0E-03	2.3E-07
9	OEP-DGN-FR-6HDG3	5.6E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FR-6HDG1	3.6E-06	72	1 *	3.9E-03	8.6E-08
10	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FS-DG03	3.6E-06	72	1 *	3.9E-03	7.5E-08
11	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FS-DG02	3.6E-06	72	1 *	3.9E-03	7.5E-08
12	OEP-DGN-FS-DG01	5.0E-03	3.6E-06	72	1 *	3.9E-03	MSS-SRV-OO-SGSRV	7.0E-07	22	22	3.4E-03	6.7E-08
13	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FR-6HDG2	3.6E-06	72	1 *	3.9E-03	6.2E-08
14	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FR-6HDG3	3.6E-06	72	1 *	3.9E-03	6.2E-08
15	OEP-DGN-FS-DG02	4.0E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FR-6HDG1	3.6E-06	72	1 *	3.9E-03	6.2E-08
16	OEP-DGN-FR-6HDG1	4.6E-03	3.6E-06	72	1 *	3.9E-03	MSS-SRV-OO-SGSRV	7.0E-07	22	22	3.4E-03	6.1E-08
17	OEP-DGN-FR-6HDG1	4.0E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FR-6HDG2	3.6E-06	72	1 *	3.9E-03	6.1E-08
18	OEP-DGN-FS-DG03	3.9E-03	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FR-6HDG1	3.6E-06	72	1 *	3.9E-03	6.0E-08
19	RMT-ACT-FA-RMTSA	1.5E-03	3.0E-07	240 *	6	6.0E-03	RMT-ACT-FA-RMTSB	3.0E-07	240 *	6	6.0E-03	5.4E-08
20	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1862B	3.6E-06	60	6	1.9E-02	1.7E-08
21	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1860A	3.6E-06	60	6	1.9E-02	1.7E-08
22	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1862A	3.6E-06	60	6	1.9E-02	1.7E-08
23	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1860B	3.6E-06	60	6	1.9E-02	1.7E-08
24	OEP-DGN-FS-DG03	9.1E-04	3.6E-06	72	1 *	3.9E-03	OEP-DGN-FR-DG01	3.6E-06	72	1 *	3.9E-03	1.4E-08
25	PPS-MOV-FC-1536	2.9E-06	3.6E-06	60	6	1.9E-02	PPS-MOV-FC-1535	3.6E-06	60	6	1.9E-02	1.1E-09

* - Control Value

TABLE 23A. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: SECOND RISK-DIRECTED STRATEGY, SINGLE CONTRIBUTIONS

Plant A: Single Contributions
Second Aging Control Strategy
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 1.8E-05 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq1	ΔC (/year)
1	LPR-MOV-FT-1862A	1.5E-04	3.6E-06	60	6	1.9E-02	2.9E-06
2	LPR-MOV-FT-1860A	1.5E-04	3.6E-06	60	6	1.9E-02	2.9E-06
3	LPR-MOV-FT-1890A	1.4E-04	3.6E-06	60	6	1.9E-02	2.6E-06
4	OEP-DGN-FS-DG01	3.8E-04	3.6E-06	72	1 *	3.9E-03	1.5E-06
5	OEP-DGN-FR-6HDG1	3.4E-04	3.6E-06	72	1 *	3.9E-03	1.3E-06
6	HPI-MOV-FT-1350	6.7E-05	3.6E-06	60	6	1.9E-02	1.3E-06
7	OEP-DGN-FS-DG02	2.0E-04	3.6E-06	72	1 *	3.9E-03	7.8E-07
8	OEP-DGN-FS-DG03	2.0E-04	3.6E-06	72	1 *	3.9E-03	7.8E-07
9	OEP-DGN-FR-6HDG3	1.9E-04	3.6E-06	72	1 *	3.9E-03	7.5E-07
10	OEP-DGN-FR-6HDG2	1.7E-04	3.6E-06	72	1 *	3.9E-03	6.8E-07
11	LPR-MOV-FT-1862B	2.1E-05	3.6E-06	60	6	1.9E-02	4.0E-07
12	LPR-MOV-FT-1860B	2.0E-05	3.6E-06	60	6	1.9E-02	3.9E-07
13	HPI-CKV-FT-CV225	2.1E-03	4.0E-09	240 *	11	1.6E-04	3.4E-07
14	HPI-CKV-FT-CV410	2.1E-03	4.0E-09	240 *	11	1.6E-04	3.3E-07
15	HPI-CKV-FT-CV25	2.1E-03	4.0E-09	240 *	11	1.6E-04	3.3E-07
16	OEP-DGN-FR-DG01	5.0E-05	3.6E-06	72	1 *	3.9E-03	2.0E-07
17	PPS-MOV-FT-1535	9.5E-06	3.6E-06	60	6	1.9E-02	1.8E-07
18	HPI-MOV-FT-1115B	5.7E-06	3.6E-06	60	6	1.9E-02	1.1E-07
19	HPI-MOV-FT-1115E	5.7E-06	3.6E-06	60	6	1.9E-02	1.1E-07
20	HPI-MOV-FT-1115D	5.7E-06	3.6E-06	60	6	1.9E-02	1.1E-07
21	HPI-MOV-FT-1115C	5.7E-06	3.6E-06	60	6	1.9E-02	1.1E-07
22	SIS-ACT-FA-SISA	1.8E-05	3.0E-07	240 *	6	6.0E-03	1.1E-07
23	LPR-MOV-FT-1890B	4.5E-06	3.6E-06	60	6	1.9E-02	8.5E-08
24	PPS-MOV-FT-1536	3.4E-06	3.6E-06	60	6	1.9E-02	6.5E-08
25	HPI-MOV-FT-1867D	2.9E-06	3.6E-06	60	6	1.9E-02	5.6E-08

* - Control Value

TABLE 23B. CORE DAMAGE FREQUENCY INCREASE FROM AGING ACTIVE COMPONENTS PLANT A: SECOND RISK-DIRECTED STRATEGY, DOUBLE CONTRIBUTIONS

Plant A: Double Contributions
First Aging Control Strategy
TIRGALEX Aging Rates
TIRGALEX Testing Efficiencies

Total ΔC: 1.9E-05 /year

Rank	Component Name	Sensitivity Coefficient	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq1	Component Name	Aging Rate (/hr/yr)	MTBF (months)	Test Interval (months)	Δq2	ΔC (/year)
1	SIS-ACT-FA-SISB	6.5E-03	3.0E-07	720	6	1.8E-02	SIS-ACT-FA-SISA	3.0E-07	720	6	1.8E-02	5.9E-06
2	RMT-ACT-FA-RMTSA	1.5E-03	3.0E-07	720	6	1.8E-02	RMT-ACT-FA-RMTSB	3.0E-07	720	6	1.8E-02	1.4E-06
3	OEP-DGN-FR-6HDG3	5.6E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG1	3.6E-06	72	4	1.4E-02	1.1E-06
4	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FS-DG02	3.6E-06	72	4	1.4E-02	9.9E-07
5	OEP-DGN-FS-DG01	4.9E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FS-DG03	3.6E-06	72	4	1.4E-02	9.9E-07
6	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG2	3.6E-06	72	4	1.4E-02	8.1E-07
7	OEP-DGN-FS-DG01	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG3	3.6E-06	72	4	1.4E-02	8.1E-07
8	OEP-DGN-FS-DG02	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG1	3.6E-06	72	4	1.4E-02	8.1E-07
9	OEP-DGN-FR-6HDG1	4.0E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG2	3.6E-06	72	4	1.4E-02	8.1E-07
10	OEP-DGN-FS-DG03	3.9E-03	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-6HDG1	3.6E-06	72	4	1.4E-02	7.8E-07
11	HPI-MOV-FT-1115B	1.9E-03	3.6E-06	60 *	6 *	1.9E-02	HPI-MOV-FT-1115D	3.6E-06	60 *	6 *	1.9E-02	6.8E-07
12	HPI-MOV-FT-1115C	1.9E-03	3.6E-06	60 *	6 *	1.9E-02	HPI-MOV-FT-1115E	3.6E-06	60 *	6 *	1.9E-02	6.8E-07
13	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	60 *	6 *	1.9E-02	LPR-MOV-FT-1860B	3.6E-06	60 *	6 *	1.9E-02	5.4E-07
14	LPR-MOV-FT-1862A	1.5E-03	3.6E-06	60 *	6 *	1.9E-02	LPR-MOV-FT-1862B	3.6E-06	60 *	6 *	1.9E-02	5.4E-07
15	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	60 *	6 *	1.9E-02	LPR-MOV-FT-1862B	3.6E-06	60 *	6 *	1.9E-02	5.4E-07
16	LPR-MOV-FT-1860A	1.5E-03	3.6E-06	60 *	6 *	1.9E-02	LPR-MOV-FT-1860B	3.6E-06	60 *	6 *	1.9E-02	5.4E-07
17	LPR-MOV-FT-1890A	1.5E-03	3.6E-06	60 *	6 *	1.9E-02	LPR-MOV-FT-1890B	3.6E-06	60 *	6 *	1.9E-02	5.4E-07
18	OEP-DGN-FS-DG01	5.0E-03	3.6E-06	72	4	1.4E-02	MSS-SRV-OO-SGSRV	7.0E-07	22	22	3.4E-03	2.4E-07
19	OEP-DGN-FR-6HDG1	4.6E-03	3.6E-06	72	4	1.4E-02	MSS-SRV-OO-SGSRV	7.0E-07	22	22	3.4E-03	2.2E-07
20	OEP-DGN-FS-DG03	9.1E-04	3.6E-06	72	4	1.4E-02	OEP-DGN-FR-DG01	3.6E-06	72	4	1.4E-02	1.8E-07
21	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1862B	3.6E-06	60 *	6 *	1.9E-02	1.7E-08
22	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1862A	3.6E-06	60 *	6 *	1.9E-02	1.7E-08
23	LPI-MDP-FS-SI1B	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1860A	3.6E-06	60 *	6 *	1.9E-02	1.7E-08
24	LPI-MDP-FS-SI1A	1.5E-03	2.0E-07	86	2	5.8E-04	LPR-MOV-FT-1860B	3.6E-06	60 *	6 *	1.9E-02	1.7E-08
25	PPS-MOV-FC-1536	2.9E-06	3.6E-06	60 *	6 *	1.9E-02	PPS-MOV-FC-1535	3.6E-06	60 *	6 *	1.9E-02	1.1E-09

* - Control Value

FIGURE 7. CORE DAMAGE FREQUENCY INCREASE DUE TO AGING: MINIMAL MAINTENANCE VERSUS RISK-DIRECTED CONTROL

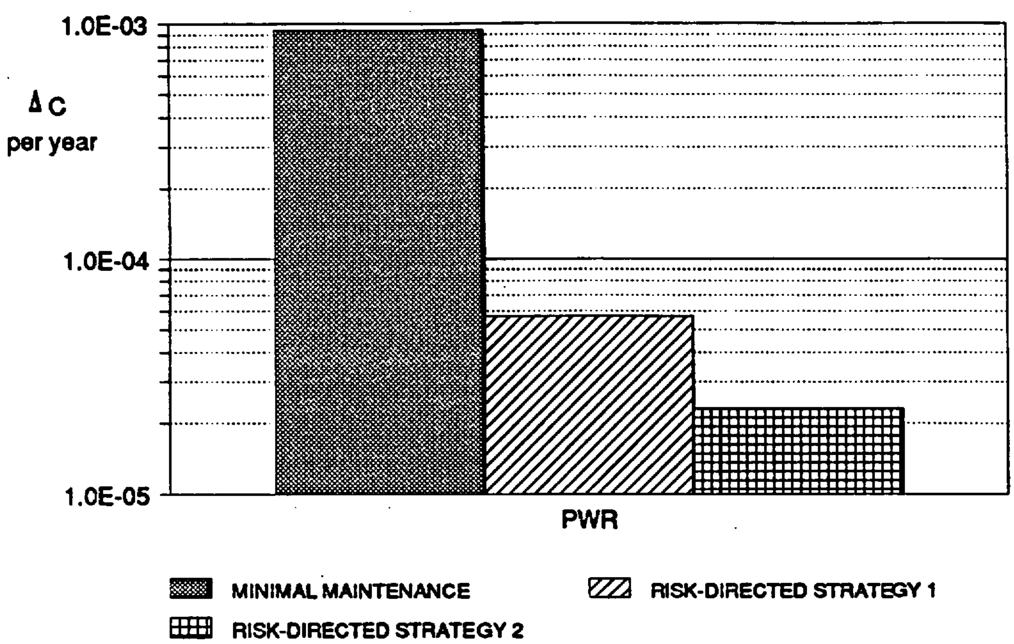
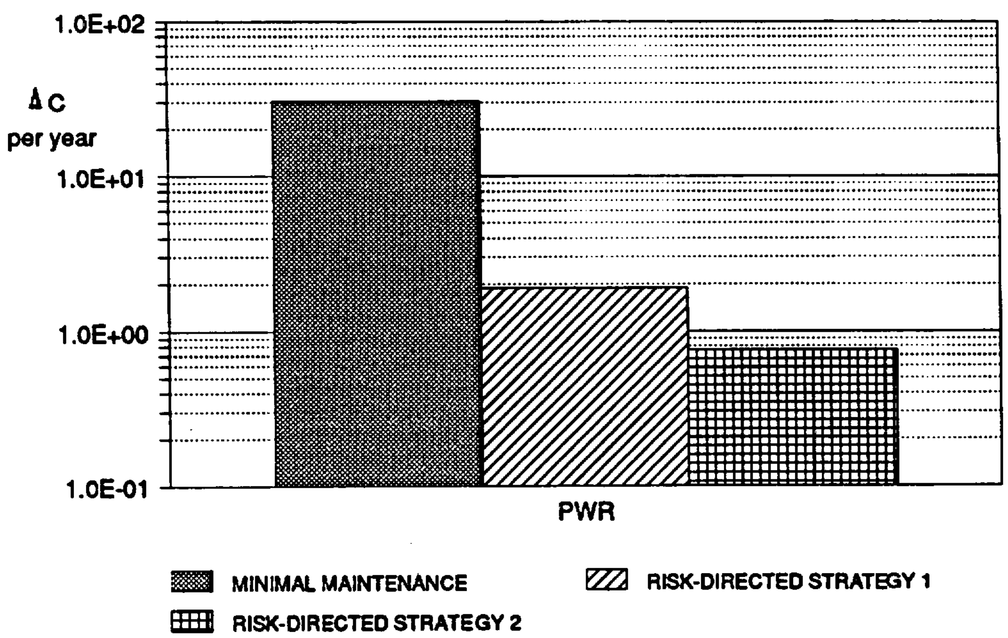


FIGURE 8. RELATIVE CORE DAMAGE FREQUENCY INCREASE DUE TO AGING: MINIMAL MAINTENANCE VERSUS RISK-DIRECTED CONTROL



damage frequency increase in the standard PSA. Figure 8 illustrates the relative core damage frequency increase due to aging for the base case and the risk-directed aging management strategies. (The tables of aging contributions can be simply changed to relative contributions by dividing by the original PSA core damage frequency). Figures 7 and 8 again illustrate the significant control of aging effects which can be achieved by focusing on the risk important aging contributors.

Other alternative aging management strategies directed toward the risk important contributors could be evaluated by using the appropriate test and maintenance models to calculate the aging effects Δq and the subsequent core damage frequency impact ΔC. The core damage importances S_i, S_{ij} would remain the same and would not need to be recalculated. The formulas and approaches which have been presented allow these alternative evaluations to be straightfowardly carried out.

7. TIME DEPENDENT AGING EVALUATIONS

7.0 Introduction

In evaluating the risk effects of aging, either the average effects of aging or the time dependent effects of aging can be calculated. The previous two chapters focused on evaluations of the average risk effects of aging. Determining the average effects of aging involves averaging the time dependent component unavailabilities over the period between replacements of the component or over given time periods (such as the plant lifetime). The average component unavailabilities or unavailability increases are then used in the PSA model to determine the average increase in core damage frequency and other average risk effects. These average aging contributions are straightforward to calculate and generally have reduced uncertainties due to the time averaging effect.

When time dependent aging effects are determined then time dependent component unavailabilities (or unreliabilities) are utilized. The time dependent component unavailabilities are input to the PSA to obtain the time dependent core damage frequency with aging or the time dependent increase in core damage frequency due to aging. The average aging contribution can also be obtained by time averaging the results over appropriate periods of time. The time dependent aging results provide more detailed information, however they involve more detailed calculations and have larger uncertainties due to the additional details.

This chapter demonstrates how time dependent aging results can be obtained using the models and approaches given in the previous chapters. Basically, to obtain time dependent aging results, the aging contributions at a given time are used in the formulas, e.g. Equation (45), instead of the average aging contributions. The calculations are repeated at different time points with the appropriate time dependent component unavailabilities used at each time point. The core damage frequency which is obtained at each time point then provides a time track of the effects of aging which can be used for monitoring and predicting aging effects. However, more accurate component aging failure rates are required for these time dependent evaluations.

7.1 Basic Time Dependent Equations

We shall again consider the risk importance approach for the APSA approach, however the general time dependent models we present apply to any APSA approach used. For the risk importance approach, the increase in core damage frequency ΔC due to aging is again from Equation (45) of Section 3.3

$$\Delta C = \sum_{i} S_i \Delta q_i + \sum_{j>i} S_{ij}..\Delta q_i \Delta q_j + ... + \sum S_{12...n} \Delta q_1 ... \Delta q_n \quad (63)$$

S_i, S_{ij}, etc. are again the core damage frequency importances determined from the standard PSA. The increases in component unavailability Δq_i due to aging are now the time dependent unavailability increases. Now, from standard reliability theory, and as also given in the appendix, the time dependent unavailability q(t) at given time t is generally

$$q(t) = 1 - \exp(- \int_{(t_T - t_R)^+}^{t-t_R} \lambda(w)dw) \quad (64)$$

where

$$\lambda(w) = \text{the age dependent component failure rate at age w} \quad (65)$$

$$t_R = \text{the time of the last replacement or renewal of the component} \quad (66)$$

and

t_T = the time of the last operational surveillance test (good as old test) of the component (67)

the symbol $(t_T - t_R)^+$ denotes the maximum of zero and $(t_T - t_R)$, i.e.

$$(t_T - t_R)^+ = t_T - t_R; \; t_T > t_R \quad (68)$$

$$= 0 \qquad ; t_T \leq t_R . \tag{69}$$

Thus, in Equation (64) if the last renewal is before the last test ($t_T > t_R$), the age of the component at the start of the test is $t_T - t_R$. If the renewal occurs after the test ($t_T \leq t_R$) then the age starts again at zero.

The time dependent increase in component unavailability Δq due to aging is the difference between the time dependent component unavailability with aging q(t) and the time dependent unavailability without aging $q_o(t)$

$$\Delta q = q(t) - q_o(t) \tag{70}$$

where

$$q_o(t) = 1 - \exp(-\lambda(t - t_T)) \tag{71}$$

and where λ is the constant component failure rate. Note that the last time of renewal t_R does not enter $q_o(t)$ since aging and hence renewal is not considered. The average value of $q_o(t)$ over a test interval is the average component unavailability used in a standard PSA. The average value of $\Delta q(t)$ over a renewal interval is the average increase in component unavailability due to aging which was utilized in the applications discussed in the previous two chapters along with the assumption of a linear aging failure rate.

7.2 Time Dependent Equations for a Linear Aging Failure Rate

We will consider the linear aging failure rate with no threshold and will describe how the threshold age can be later incorporated into the results. The linear aging failure rate with no threshold is again

$$\lambda(w) = \lambda + aw \tag{72}$$

where λ is the constant failure rate, a is the aging rate and w is the age of the component. Substituting the linear aging failure rate into the general formula for q(t), Equation (64), gives

$$q(t)=1-\exp\left[-\int_{(t_T-t_R)^+}^{t-t_R}(\lambda+aw)dw\right] \quad (73)$$

We shall consider the case when $t_R<t_T$ and hence $(t_T - t_R)^+ = t_T - t_R$. When $t_R \geq t_T$ then the results which are obtained will apply by assuming $t_T=t_R$ since the time of last renewal also then serves as a the time of the last equivalent surveillance test. For $t_R<t_T$

$$q(t)=1-\exp\left[-\int_{t_T-t_R}^{t-t_R}(\lambda+aw)dw\right] \quad (74)$$

or

$$q(t)=1-\exp\left[-\lambda(t-t_T)-\frac{1}{2}a\left((t-t_R)^2-(t_T-t_R)^2\right)\right] \quad (75)$$

The difference in availability $\Delta q(t)$ is then

$$\Delta q(t)=1-\exp\left[-\lambda(t-t_T)-\frac{1}{2}a\left((t-t_R)^2-(t_T-t_R)^2\right)\right]-\left[1-\exp(-\lambda(t-t_T))\right]. \quad (76)$$

Expanding the exponential to first order gives the simple result

$$\Delta q(t)\cong\frac{1}{2}a\left((t-t_R)^2-(t_T-t_R)^2\right) \quad (77)$$

This first order equation gives accurate results to at least two significant figures when $\Delta q(t) \leq 0.1$ otherwise, the exact equation, Equation (76), can be used. A threshold age can be incorporated into Equation (76) or (77) by subtracting the threshold age from t; the squared terms in the Equations(76) and (77) will then only be nonzero if they are larger then the threshold age.

If the component is tested at intervals of T and is replaced or renewed at intervals of L then

$$t_T = \left[\frac{t}{T}\right]T \qquad (78)$$

and

$$t_R = \left[\frac{t}{L}\right]L \qquad (79)$$

where "[x]" denotes the greatest integer function, e.g. [9.34] = 9. For periodic testing and renewal, Equations (78) and (79) can then be substituted into Equations (76) or (77) for $\Delta q(t)$.

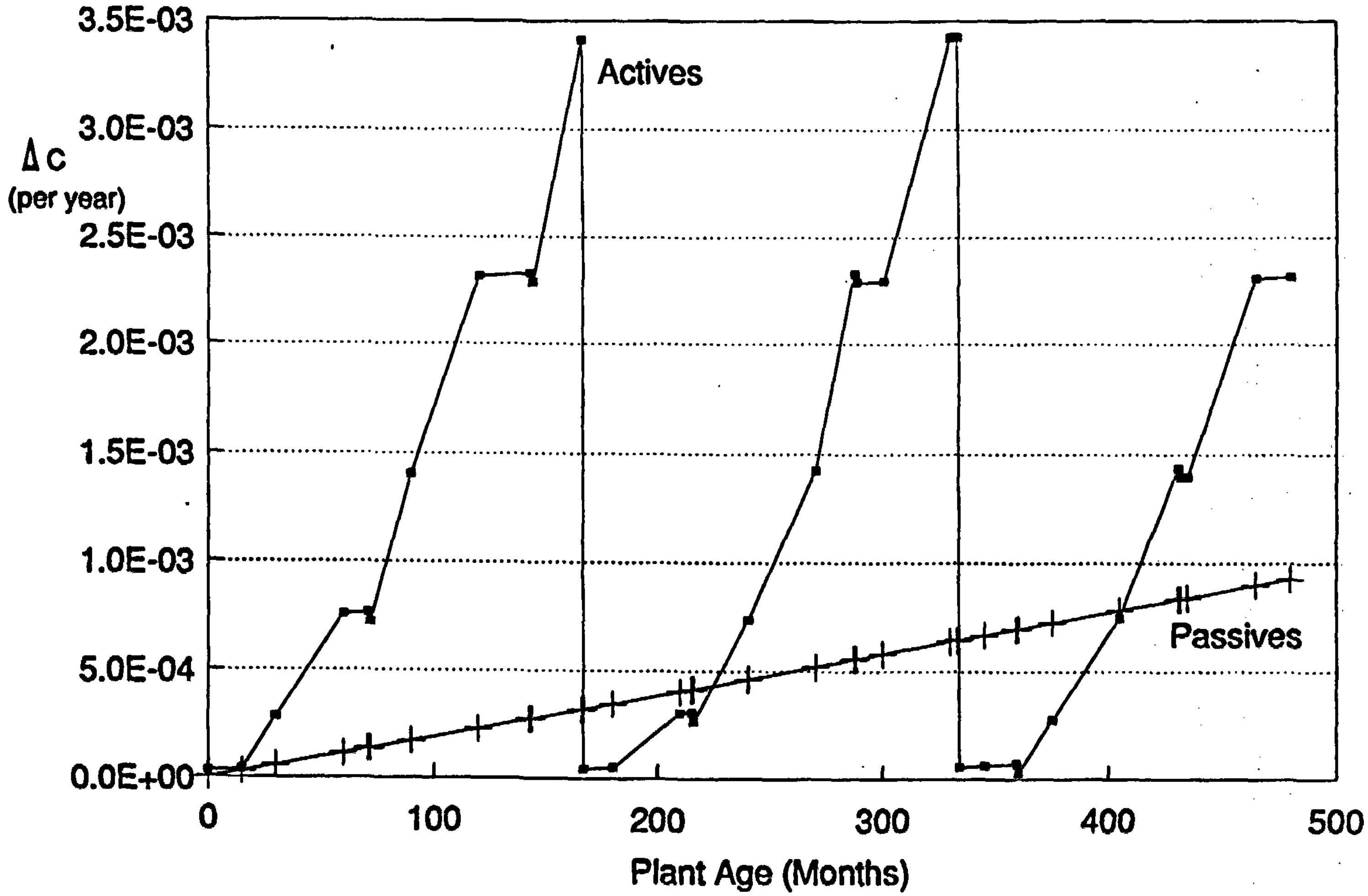
7.3 Applications of the Time Dependent, Linear Aging Failure Rate Equations

For a given application, $\Delta q(t)$ can be determined at a given time point for each aging component using Equation (76) or (77). The $\Delta q(t)$ for each aging component can then be substituted into Equation (63) for the time dependent core damage frequency due to aging $\Delta C = \Delta C(t)$. These calculations are then repeated for the time points of interest. Note that the core damage frequency S_i, S_{ij} ,etc. are not dependent on time and need to be computed only once from the standard PSA.

Figure 9 shows the time dependent core damage frequency increase $\Delta C(t)$ due to aging that is calculated for the basic case evaluation carried but in Chapter 5. The same base case data is used as in Chapter 5, except that time dependent aging effects are calculated instead of time-averaged aging effects. As in Chapter 5, the renewal interval for each component is assumed to be the component's mean time to failure. In Figure 9, the time points are selected to correspond to the test times for each component. The components with the same test interval are assumed to be tested at the same time, sequentially so as not to violate technical specifications.

A more general evaluation of $\Delta q(t)$ can be obtained by using the equations in Appendix which can account for nonlinear aging effects and for the randomness of failure times when components are only replaced at failure. Figure 9 is useful for showing the time tracking information which is obtained from time dependent evaluations. The total core damage frequency at any given plant age is then $\Delta C(t)$ plus the baseline value in the

FIGURE 9. TIME DEPENDENT CORE DAMAGE FREQUENCY INCREASE ΔC DUE TO AGING



PSA. The sudden drops in the core damage frequency increase ΔC(t) in Figure 9 occur when the motor operated valves in the Emergency Core Cooling System are replaced at failure. The high peaks in ΔC indicate that replacement only at failure for these critical components is not adequate, and more frequent replacement or overhaul of the dominant failure contributors is needed. This is a similar result as found in Chapter 5 where average aging effects were utilized. Calculations of the time dependent aging effects provides useful information on the growth of the aging effects, indicating the times at which the aging effects become significant.

8. SENSITIVITY AND UNCERTAINTY EVALUATIONS

8.0 Introduction

One of the most useful applications of an APSA is for sensitivity and uncertainty studies. Both sensitivity studies and uncertainty analyses involve systematically changing variables in the APSA and then determining the core damage frequency changes. An uncertainty analysis differs from a sensitivity study in that probability distributions are also assigned to the variables which represent the probabilities for the different values which a variable may assume . Using uncertainty propagation techniques, a probability distribution is then determined for the core damage frequency, which gives the probabilities for the different core damage frequency values. A sensitivity study does not utilize probability distributions but simply changes the input values and determines the resulting change in the core damage frequency.

The variables which are changed in a sensitivity study or uncertainty study can not only be data values, but can also be models and assumptions. In an APSA, sensitivity or uncertainty studies can be performed for different possible aging behaviors for the components, for alternative maintenance effects, alternative test effects, or alternative repair effects. By designing appropriate sensitivity or uncertainty studies, the capability of a given test and maintenance program to control aging risk effects over a range of plausible alternatives can be systematically evaluated. These evaluations can help guide and focus aging management activities.

This chapter illustrates uncertainty and sensitivity analyses which can be carried out using an APSA. The following section first shows an application of uncertainty analysis by assigning uncertainty distributions to the data used in an APSA. The subsequent sections illustrate sensitivity analyses which can be carried out to evaluate the risk sensitivities to aging and to maintenance strategies.

8.1 Uncertainty Analysis of Data Used in an APSA

The uncertainty analysis which is described is also described in NUREG-1362 (9). Further information is provided here on the basic principles and applications of such an analysis. An uncertainty analysis is carried out in an APSA to assess the uncertainties one has in the aging results and to identify the dominant contributors to the uncertainty.

A data uncertainty analysis involves assigning error ranges to the data used in an APSA. The error range assigned to a data input represents the different possible values the data input may have because of uncertainties associated with collecting and estimating the data. The probability distribution associated with the error range gives the probability that the data will have any of the specific values in the range.

In a standard PSA, the input data which are assigned associated uncertainties include the initiating event frequencies, component failure rates, test and maintenance intervals and downtimes, and human error rates. For an APSA, the additional input data which have uncertainties include the component aging failure rates, and test and maintenance data describing the aging control effects of the test or maintenance. The component aging failure rates will generally have the largest uncertainties.

To illustrate a data uncertainty analysis performed for an APSA, uncertainties are determined for the aging impacts calculated in Chapter 5 which utilized the risk importance approach and the linear aging failure rate model. Error ranges are assigned to the data used for the base case evaluation. Error ranges are specifically assigned to the component aging rates which are used, to the component mean times to failure (MTBF) which are used as the component replacement times, and to the TIRGALEX testing efficiencies which are used. Error ranges are also assigned to the risk importance coefficients S_i, S_{ij} coming from the PSA.

An error ranges is generally defined in a PSA by assigning an error factor to a midpoint data value. The upper value of the error range is defined as the data value times the error factor and the lower value is the data value divided by the error factor. The data value is thus the midpoint value of the range. This error range is generally defined to be a 90% error range with the upper value being a 95% value and the lower value being a 5% value. There is thus a 90% probability that the data value will lie in the defined range.

The error factors assigned to each piece of data for the APSA uncertainty analyses are given below:

Data Type	Error Factor
Component aging rate	10
Surveillance test efficiency	2
Component MTBF	2
Risk importance coefficient	5

The assignment of the above error factors is described in NUREG-1362 (9) and also in NUREG/CR-5510 (7). Basically, the error factor of 10 on each component aging rate covers uncertainties and plant specific variations that were observed by comparing the TIRGALEX aging rate values with values estimated using plant failure data for selected components. The error factor of 2 for each test efficiency basically gives test efficiency values from 0 to 1 (the efficiencies are truncated at 1). The error factors for each component MTBF and each risk importance coefficient (S_i and S_{ij}) are assigned based on PSA uncertainties.

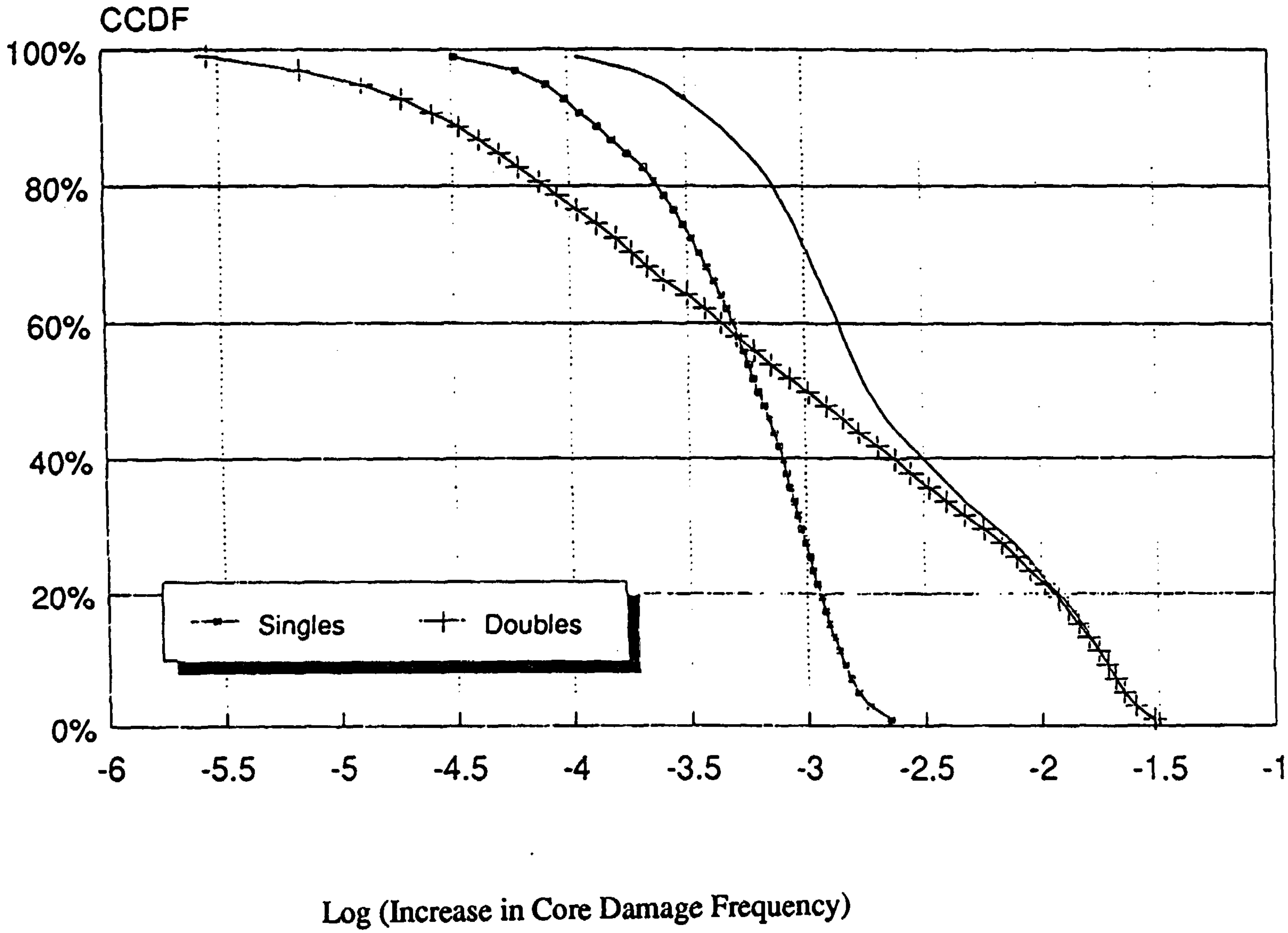
The probability distribution assumed for each error range is a log uniform distribution with the given upper and lower values. The log uniform distribution is a flat distribution on a log scale. The log uniform is used in PSA uncertainty analyses when any factor increase in the data value or any factor decrease in the value, within the range of possible values, is equally likely. The log uniform distribution is thus a nonpreferential distribution.

Before using the error ranges and probability distributions, one must decide whether different data values are independent or are correlated with one another. Recent PSAs assume data for a similar components to be totally correlated. (See for example Reference (1).) For example, failure rates for all motor operated valves are assumed to be totally correlated. When data are totally correlated then the data follow the same probability distribution and are not independent with separate, similar distributions. To be consistent with PSA approaches, all aging rates, MTBFs, and testing efficiencies for a given type of component (eg. motor operated valves) are assumed to be totally correlated. Further details are given in NUREG/CR-5510.

The error ranges and probability distributions for the data are then propagated through the APSA calculations to obtain the error ranges and probability distributions on the APSA results. Standard Monte Carlo simulation approaches are used in the PSA for this propagation and these same approaches can be applied to the APSA. References (1) through (3), as well as NUREG/Cr-5510 (7), describe the simulation approaches and computer codes which are available to automatically carry out the calculations once the data error ranges and probability distributions are assigned.

Figure 10 shows the output of the uncertainty analyses in terms of the probability distribution obtained for the core damage frequency (CDF) increase due to aging.

FIGURE 10. UNCERTAINTY ANALYSIS OF AGING EFFECTS: PLANT A



The y-axis of the figure is the probability that the CDF increase exceeds a given value on the x-axis. The x-axis is the log to the base 10 of the CDF increase; the x-axis is thus the exponent of 10 of the CDF increase. The curve of the probability distribution on these axes is termed a complementary cumulative distribution function, or ccdf, in standard PSA terminology.

In the figure, ccdf curves are given for the single component contribution to the CDF increase, for the double component interaction contribution, and for the total CDF increase due to aging. The ccdf curves can be used to obtain error ranges for the output results. For example, a 90% error range for the total CDF increase has a lower value of approximately $1 \times 10^{-3.5} = 3 \times 10^{-4}$ per year (corresponding to a y-value of 95%) and an upper value of approximately $1 \times 10^{-1.5} = 3 \times 10^{-2}$ per year (corresponding to a y-value of 5%). More accurate values can be obtained from the associated tables which are produced as part of the uncertainty analysis. Error ranges for the single and double contributions can be obtained in a similar manner.

Uncertainty ccdfs and associated error ranges can be obtained for every aging contributor, in addition to the sum totals for the singles and doubles shown in Figure 10. These ccdfs and error ranges can be used to describe the uncertainties and confidences which are associated with quantifying the CDF effects of aging. The lower end point of an error range (eg. the lower bound) can be used to define the minimal aging effect and the upper end point (the upper bound) can be used to define the maximum aging effect which account for data uncertainties. The ccdf curves themselves can also be used in more formal decision approaches for cost-benefit and optimization studies.

8.2 Sensitivity Studies of the Effects of Different Aging Rates

Sensitivity studies differ from uncertainty analyses in that no probability distribution is assigned to the input variables which are changed. Only input values are changed. By appropriately designing a sensitivity study and by systematically varying selected variables, a significant amount of information can be obtained on the sensitivities of risks to aging effects and to test and maintenance practices.

To investigate the sensitivity of the core damage frequency effects to aging , a very useful and straightforward sensitivity study to carry out is to vary component aging failure rates over a plausible range and then determine the resulting core damage frequency effects under given maintenance practices. To aid in the interpretation of the results, the component aging failure rates can be expressed in a relative form which indicates the relative size of the aging occurring. For the linear aging failure rate model, the component aging rate is thus expressed as a relative percentage increase per year in the baseline component failure rate.

If a is the component linear aging failure rate, then expressing a as a relative fraction of the constant, baseline component failure rate λ_0, we have

$$a = r\lambda_0 \tag{80}$$

or

$$r = \frac{a}{\lambda_0} \tag{81}$$

In percentage (%) terms

$$r(\text{in }\%) = \frac{a}{\lambda_0} \text{x}\,100 \tag{82}$$

If the aging rate a has units of the failure rate change per year as in Table 8 in Chapter 5 then r has the units of per year. Thus, r gives the percentage increase in the component failure rate per year due to aging. Note, that r can be larger than 100% per year.

Expressing the aging rate of the component as a relative percentage increase per year has several advantages for aging sensitivity studies. The aging rate of a component can be systematically varied by varying r from 0% through 100%. Higher values of r can also be used. The aging rates of a group of components can also be simultaneously varied by varying the one parameter r. For example, assigning r = 10% to all the motor operated valves in the Emergency Core Cooling System describes the situation where all the valves are aging with a relative increase in their failure rates of 10% per year.

Another important advantage in focusing on the relative aging behavior is that component aging can then be classified into different engineering categories which represent different degrees of aging, such as a small degree of aging, a moderate degree of aging , or a severe degree of aging. The risk impact , eg. CDF increase, which results from different degrees of aging can then be evaluated for given test and maintenance practices to assess the adequacy of the practices in controlling aging effects. Table 24 gives one categorization of different degrees of aging along with the corresponding percentage increase in the failure rate. Also given is the associated time period in which the baseline failure rate doubles due to the aging. These values are consistent with aging that has been observed in samples of data that have been evaluated (see for example NUREG/CR-5510 (7)), with the significant aging corresponding to harsh environment effects such as due to unpurified water environments or high temperatures. These relative values appear to be applicable for a range of absolute aging rates and baseline failure rates.

As a demonstration aging sensitivity studies, Figure 11 shows the core damage frequency increase for a plausible range of aging behaviors up to significant aging. The plant analyzed is the same one as analyzed in Chapter 5 for the prioritization analyses. For the present sensitivity study, monthly testing (good as old testing) of all active components is assumed. Failed components are assumed to be replaced with new components. No burn-in problems are assumed (ie. the replaced components are good as new).

Figure 11 shows the average core damage frequency increase (per year) between replacements versus annual percentage increase in component failure rate due to aging of all active components. All the active components are assumed to be aging with the same relative percentage increase in their failure rate (The baseline failure rate for each component is that defined in the baseline PSA.). Aging of passive components and structures is not considered in this particular sensitivity study.

The baseline core damage frequency for the plant is approximately $3x10^{-5}$ per year from the standard PSA. This sensitivity study thus shows that aging effects are controlled over a range of plausible aging for the given plant under the policy of monthly testing and replacement at failure with new components. Even with a relative aging of 100%, where all component failure rates are doubled each year, the core damage frequency increase due to aging is still held to approximately $3x10^{-5}$ per year which is still comparable to the baseline core damage frequency of $3x10^{-5}$ per year. For moderate to minor aging, the

TABLE 24. RELATIVE AGING FAILURE RATE CATEGORIES

Category	Relative Failure Rate Increase (per year)	Failure Rate Doubling Period (yrs)
Minor aging	10%	10 yrs
Moderate aging	30%	3 yrs
Significant aging	100%	1 yr

aging effects on the core damage frequency are controlled to be significantly less than the baseline core damage frequency.

The aging control which is exhibited in Figure 11 is due to monthly testing with replacement at failure. Failed components are not down for significant times until detected by a monthly test, and failed components are replaced with new components, removing all previous aging effects. Other policies which involve less frequent testing or which do not replace all failed components, but only the most important contributors, could also achieve effective aging control. Prioritization of the dominant contributors similar to that performed in Chapter 5 would identify the components which are most important to test and replace to control aging impacts. The dominant contributors would now need to be obtained for the range of aging rates that are defined to be plausible.

8.3 Sensitivity Studies of the Effects of Different Test and Replacement/Repair Policies

Sensitivity studies can also be usefully carried out to evaluate different aging management policies for their control of aging effects on risk. Figure 12 shows the average core damage frequency increase per year due to aging under two different surveillance test intervals. The PSA is again the same as that used in the previous sections. Replacement at failure is again assumed and only active component aging is considered. All active components again are assumed to be aging with the same relative aging rate.

The monthly testing line (T = 1 month) is the same result as given in the previous section in Figure 11. The semi-annual testing line (T = 6 months) corresponds to semi-annual testing of all active components. With semi-annual testing the core damage frequency increase due to aging is considerably higher and becomes larger than the baseline core damage frequency with moderate aging (20% - 30%). Thus, monthly testing of the key contributors is important if no additional scheduled maintenance is performed. The prioritization of contributors as done in Chapter 5 would show those components for which it is important to control the test interval to be 1 month.

Finally, as a sensitivity study Figure 13 shows the impact of a policy of replacement of failed components versus a policy of repair of failed components. The replacement curve is the same as in Figure 11 (but on a log scale). For a replacement policy again, failed components are

FIGURE 11. CORE DAMAGE FREQUENCY INCREASE FOR A PLAUSIBLE RANGE OF AGING REPLACEMENT AT FAILURE: MONTHLY TESTING

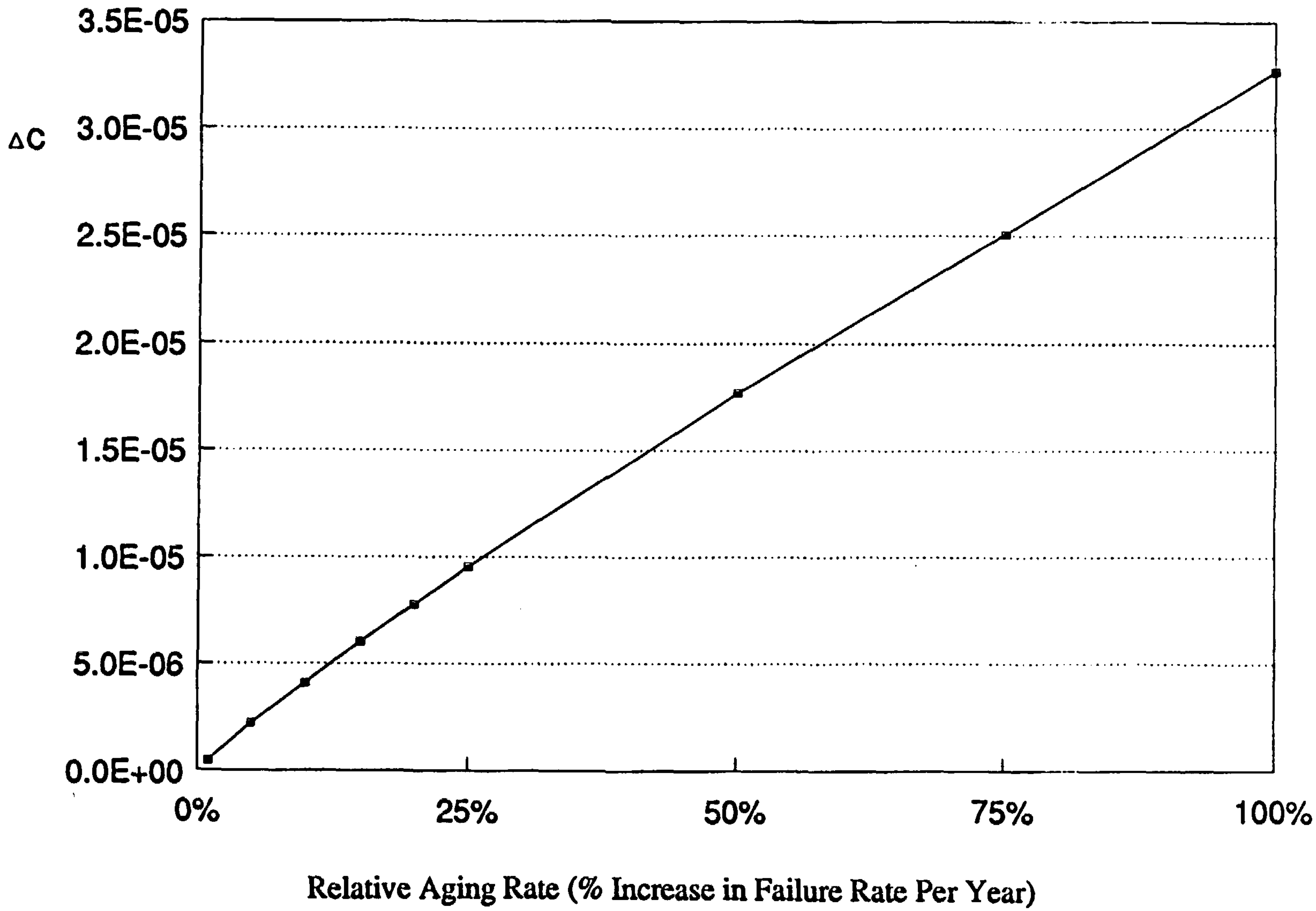


FIGURE 12. CORE DAMAGE FREQUENCY INCREASE FOR A PLAUSIBLE RANGE OF AGING: REPLACEMENT AT FAILURE: TWO DIFFERENT TEST INTERVALS

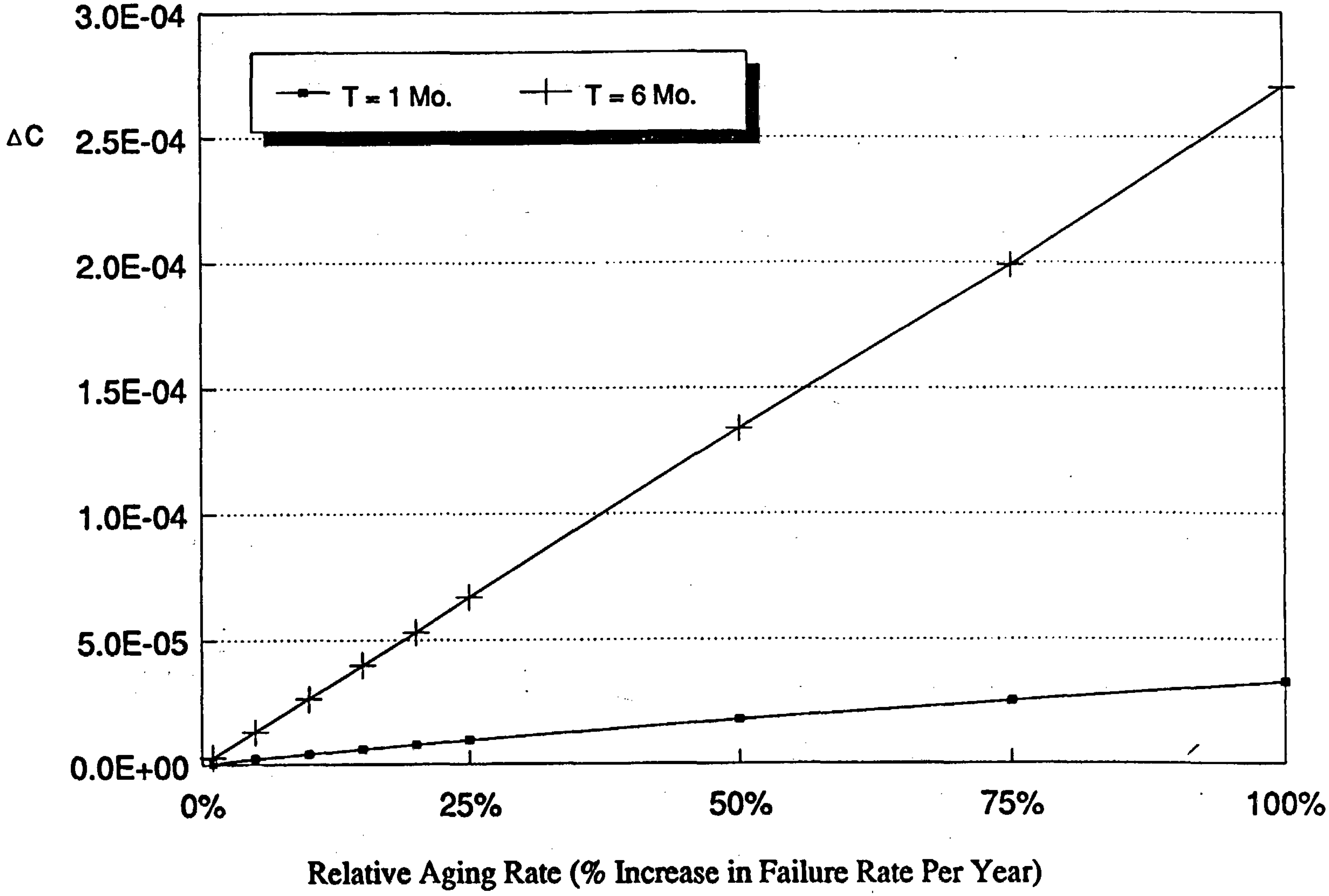
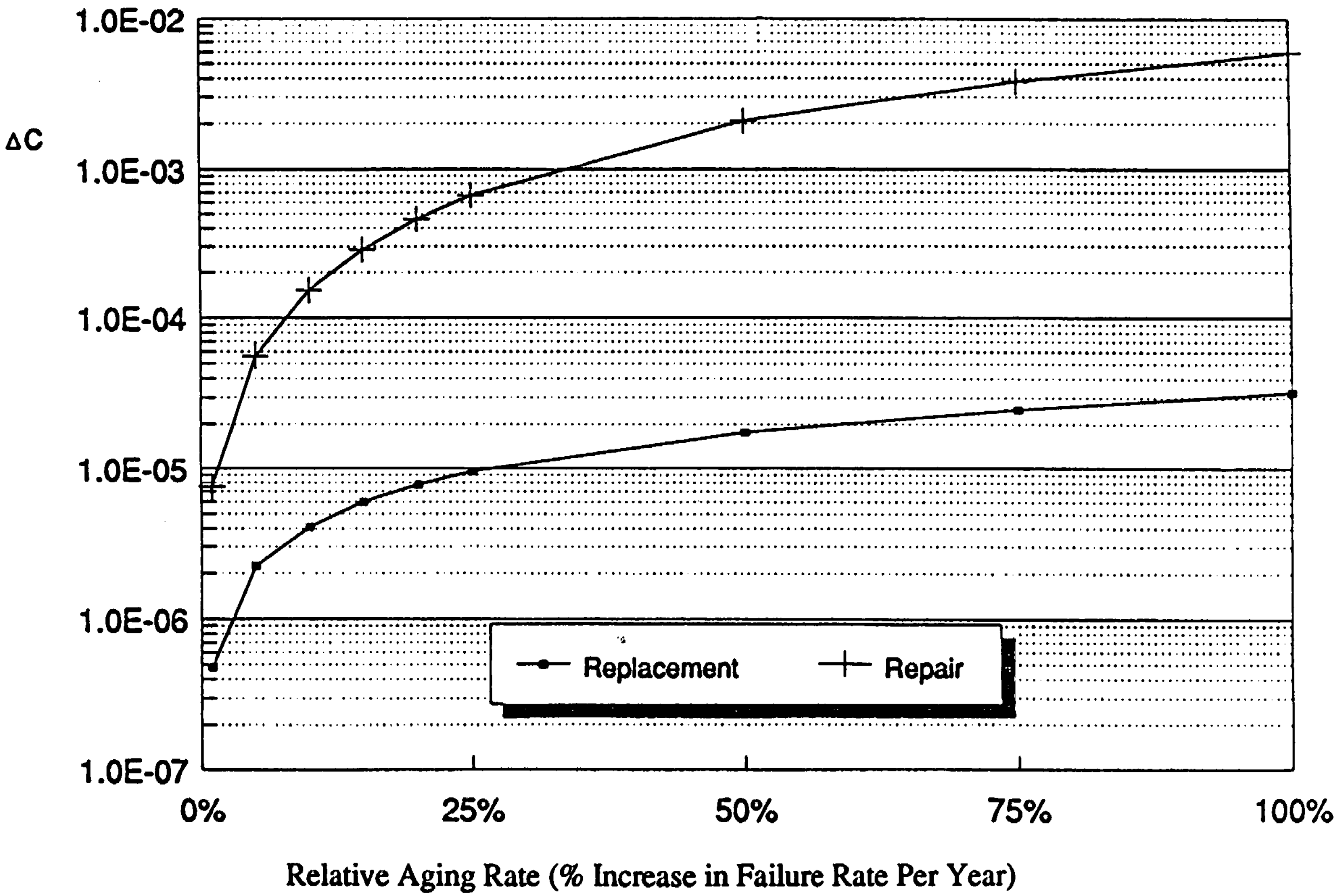


FIGURE 13. CORE DAMAGE FREQUENCY INCREASE FOR A PLAUSIBLE RANGE OF AGING: REPLACEMENT AT FAILURE VERSUS REPAIR AT FAILURE: MONTHLY TESTING



replaced with new components. For the repair policy, it is assumed that failed components are restored to an operational status but are not replaced with new components. Aging effects are thus not significantly removed. The repair is thus treated to be as good as old. The repair curve is very much higher than the replacement curve, showing significant core damage frequency effects from aging even at minor component aging (5% - 10%). It is thus extremely important to replace or overhaul the dominant components instead of repairing them to control aging impacts on the core damage frequency. Prioritization of the components would again identify those components which need to be focused on for aging management.

9. CONSIDERATIONS IN USING A PSA TO EVALUATE THE RISK EFFECTS FROM AGING OF PASSIVE COMPONENTS.

9.0 Introduction

To use the PSA for evaluation of risk effects from aging of passive components, it is first of all important that a plant specific PSA be constructed to evaluate and quantify the core damage frequency associated with the plant's design and procedures. For the most comprehensive PSA, all major passive components should be incorporated, otherwise it will not be possible to explicitly evaluate the risk effects from aging of these passive components. In this final chapter, important concepts and considerations are discussed involving the reliability modeling of passive components and their aging effects. As part of the risk evaluation of aging work, a separate report is planned which will discuss the special points involved in modeling passive component aging in greater detail.

9.1 The Role and Use of PSA to Evaluate the Reliability of Passive Components and Their Risk Impacts

PSAs have not generally included the detailed risk contributions from passive components and structures (e.g. pipes, vessels, containments). The passive contributions which can be analyzed in greater detail include:

(a) Initiating events
- Primary circuit failures
- Pressure shell failures
- Steam generator tube ruptures

(b) System related contributions
- control rod failures
- pipe breaks
- vessel failures
- missile generation and impact
- pipe whip phenomena

(c) Containment contributions
- steel shell
- closures

Most of these contributions are presently incorporated into a PSA in only a general way using failure rates based on generic information or expert judgement.

In particular cases there have been more formal analyses to derive a failure probability for specific components. When more formal analyses are carried out then a probabilistic fracture mechanics (PFM) model is often used to model the probability distributions of various parameters including:

- flaw size and location
- failure to detect particular flaw sizes
- material property variations
- changes of material properties through life

These probability distributions are then combined to evaluate, for example, the probability of the vessel exceeding its design criteria. The analyses are used to determine, among other things,

- the probabilities of failure of the passive components
- the important inspection activities which have an impact on the failure probabilities

In principle, detailed models could be developed for all major passive components and associated failure probabilities derived.

For systems analyses performed in PSAs, as was observed from the previous demonstrations, typically the active components (e.g., pumps, valves) are only considered in detail. The reason is that relatively small failure rates are used for the passive components. Also, expert judgement tends to limit the importance of passive component contributions. As a consequence, interactions between active and passive components (e.g., different loads as a consequence of various failure modes) are generally incorporated in only a limited way. Aging can cause these contributions to be more important.

One example of an interaction between active and passive components is the safety issue related to pressurized thermal shock. In this event scenario, the thermal loads (stresses) at the primary piping and reactor pressure vessel (RPV) are strongly dependent on the function and/or malfunction of the active components in the emergency core cooling system (ECCS) and other systems. Conversely, the failure modes of the passive components influence the failures of the actives in this scenario. This interacting process can be modeled in an age dependent PSA.

A PSA can thus represent a framework and an analysis tool to integrate the behavior of active and passive components, prioritizing the importance (contribution) of each involved component to the overall risk. The traditional deterministic safety analysis process generates limited insights regarding the risk importances of passive components and structures. The PSA (or PRA) can show the risk importance of different assumptions (e.g., break location or parameters, e.g., load cycles, critical stress intensity factor) used in these safety analyses. By incorporating probabilistic models of passive component failures into a PSA, one can then generate answers as to not only where breaks are most likely, but where they most effect the core damage frequency or risk. This stochastic modeling - PSA integration combines design, manufacturing and operating aspects and allows a risk prioritization of the contributors and associated parameters.

9.2 Aging Component Reliability Models Required for PSA Aging Evaluations.

In aging evaluations of a plant, one is confronted with four basic phenomena causing time dependent changes in material behavior of passive components:

- Fatigue
- Embrittlement
- Crack Growth
- Surface degradation (friction, erosion, corrosion)

Passive component modeling for PSA applications need therefore to focus on these basic phenomena.

A passive component reliability analysis can be demonstrated where a loading stress interacts with strength. Consider a state function S of the form,

$$S = \text{strength} - \text{stress} \quad (83)$$

If both the stress and the strength are random variables with defined probability distributions, S will also be a random variable with a defined probability distribution. When $S>0$, the passive component is said to be in the safe state. Failure occurs when $S \leq 0$ (when loading and therefore stress is larger than strength). If S is normally distributed, then the ratio of S-E(S), where E(S) is the expected value, and $\Theta(S)$ where $\Theta(S)$ is the standard deviation is a standard normal random variable.

More generally, the probability can be computed that the structure will fail i.e., that $S \leq 0$. The state function can furthermore be extended to multiple controlling variables, with different distributions,

$$S = S\,(x_1, x_2, \ldots x_n). \quad (84)$$

These types of models need to be utilized when evaluating passive component failure probabilities (unreliabilities) to insert into the equation for the core damage frequency increase, such as Equation (45).

9.3 The Crack Growth Phenomenon.

A probabilistic fracture mechanics crack growth analysis can be expressed in terms of a multi-variate state function, i.e. Equation (84). The result from a crack growth analysis can be the probability versus time that the crack will propagate and cause component failure, i.e., $S \leq 0$. To carry out the reliability analysis, an initial crack size distribution and a probability distribution for detecting a given crack size by non destructive inspection (NDI) can be used. The effect of NDI can be explicitly incorporated using Bayesian updating,

$$P(F/I) = \frac{P(F)P(I/F)}{P(I)} \quad (85)$$

where P(F/I) is the updated structural failure probability given that an inspection has been carried out. P(F) is the structural failure probability before the inspection, P(I) is the NDI reliability, and P(I/F) is the probability of detection given the failure.

Instead of calculating failure probabilities, an alternative procedure is to update the crack size only. NDI can be considered as providing new information on current crack sizes, and can be used to constrain the updating to specific crack sizes. Bayesian approaches can again be used to obtain associated probabilities.

9.4 The Corrosion Phenomenon

The deterioration process due to corrosion generally affects the reliability of passive components. The corrosive effects depend on the loading process and on the environmental conditions in the systems to which the component is exposed. Due to the uncertainties inherent in the loading process, as well as in the manufacturing and operating process, a variety of variables need to be considered as being random. Because of the non-normal properties of these variables and the non-linear characteristics of the state function, general simulation methods need to be used to estimate the failure probability of the passive components due to corrosion effects. Normally the deterioration process of fatigue is analyzed utilizing models that describe the crack growth rate per load cycle.

To explicitly consider the deterioration process of corrosion, a corrosion factor C_c is often introduced. This factor depends on the loading process and the environmental conditions to which the passive component is exposed. Based on data, the corrosion factor C_c can be approximated by a function of the stress intensity factor, the frequency of loads and the stress ratio, and the applied loading process. Corrosion can significantly decrease the structural reliability of passive components versus time and therefore it can be important to consider such effects in an age dependent PSA.

9.5 Stochastic Analysis as a Complement to Deterministic Crack Growth Analysis

In the design process, and the safety assessment of operating strategies of passive components, typically a deterministic crack growth approach (DCGA) is often used. The DCGA provides a single value prediction for crack size at a given service time for a single structural detail, but it does not quantity structural reliability and the importance of different contributors. Over the past years reliable passive reactor components have been obtained based on DCGA, good design/analysis methods and practices, quality manufacturing, and effective inspection and quality control. However, in view of the benefits of using a PSA, and the special issues associated with aging, a PSA approach can be applied to complement existing deterministic practice (e.g. DCGA) to estimate the failure probabilities of passive components and the importances of different passive components as risk contributors. Passive components and interactions between passive components and active components can then be prioritized in the same detail as active components can. With appropriate probabilistic failure models which can include those aging failure rate models in Chapter 2 and by expanding the PSA to include passive component contributors, the risk effects of aging from passive components can thus be analyzed and be prioritized in the same manner as active components are.

10. SUMMARY AND CONCLUSIONS

An age-dependent PSA, or an APSA, is different from a standard PSA in that an APSA explicitly evaluates the risk effects of aging. Age dependent component failure rates are utilized, and test and maintenance activities are explicitly analyzed for their control of aging effects. Specific models have been presented for different aging failure rate behaviors and for different effects of tests and maintenances in controlling aging. These models can be incorporated into a PSA to explicitly evaluate aging effects.

Different approaches can actually be used to incorporate the aging models and to transform a PSA to an APSA. Three basic approaches were described in detail along with their specific features. These descriptions and the detailed models presented allow any PSA to be transformed to an APSA.

Different applications of an APSA were described which include bottom-line evaluations, evaluations of maintenance effectiveness, prioritization analyses, and sensitivity and uncertainty analyses. These different applications were reviewed in light of aging failure data which is available, test and maintenance data which is available, PSA information which is available, and meaningful results which can be obtained.

Specific applications were then demonstrated involving prioritizations of aging contributors, identification of risk-directed aging management strategies, evaluation of time dependent aging effects, data uncertainty analyses, sensitivity analyses of the risk impacts of aging, and sensitivity analyses of the effectiveness of different test and maintenance practices in controlling the risk impacts from aging. These studies illustrate the significant amount of useful information which is obtainable from an APSA even if accurate aging failure rate data is not available. Finally, specific considerations were discussed in determining the time dependent and age dependent failure probabilities for passive components which can then be utilized in the general formulas for the aging impacts on risk.

REFERENCES

1. NUREG/CR-4550, "Analysis of Core Damage Frequency from Internal Events", Volume 1, September 1987.

2. NUREG/CR-4350, "Probabilistic Risk Assessment Course Documentation", Volumes, 1-7, August 1985.

3. NUREG/CR-2300, "PRA Procedures Guide", Volume 1, January 1983.

4. H. Ascher and H. Feingold, Repairable Systems Reliability, Marcel Dekker, New York, 1984.

5. M.S. Abdel-Hammeed, E. Cinlar, and J. Quinn, eds, Reliability Theory and Models, Academic Press, New York, 1984.

6. B.V. Gnedenko, Mathematical Methods of Reliability Theory, Academic Press, New York, 1969.

7. NUREG/CR-5510, "Evaluations of Core Melt Frequency Effects Due to Component Aging and Maintenance", June 1990.

8. NUREG/CR-5248, "Prioritization of TIRGALEX-Recommended Components for Further Aging Research", October 1988.

9. NUREG-1362, "Regulatory Analysis for Proposed Rule on Nuclear Power Plant License Renewal", July 1990.

APPENDIX: GENERAL FORMULAS FOR AGING COMPONENT UNRELIABILITIES AND UNAVAILABILITIES

APPENDIX: GENERAL FORMULAS FOR AGING COMPONENT UNRELIABILITIES AND UNAVAILABILITIES

Let $\lambda(w)$ be the age dependent component failure rate, where $\lambda(w)$ can be any form and can include a threshold age. The component can be either an active component or passive component. The *component unreliability* is the probability that the component fails to operate successively for a given interval. The component unreliability can be calculated from the following formulas depending upon the initial conditions:

$$1-\exp\left(-\int_0^w \lambda(w')dw'\right)$$ = the probability of failure before age w given the component was known to be last up at age zero: (1)

$$1-\exp\left(-\int_{w_a}^w \lambda(w')dw'\right)$$ = the probability of failure before age w given the component was known to be last up at age w_a. (2)

When the component was last checked will depend upon the testing schedule. The above formulas can be transformed to time dependent formulas by using the age of the component at the given time $w = w(t)$.

The *component unavailability* is the probability that the component is down and is unable to function. The component unavailability can be calculated from the following formulas depending upon the initial conditions:

$$1-\exp\left(-\int_0^w \lambda(w')dw'\right)$$ = the probability that the component is down at age w given that the component was last known to be up at age zero: (3)

$$1-\exp\left(-\int_{w_a}^w \lambda(w')dw'\right)$$ = the probability that the component is down at age w given the component was last known to be up at age w_a. (4)

Note that formulas (3) and (4) are similar in form to formulas (1) and (2). The difference is that *operating failure rates* are generally used in formulas (1) and (2) while *standby failure rates* are used in formulas (3) and (4).

When a maintenance or restoration is performed on the component then formulas (3) and (4) still apply with the component age measured from the last maintenance or restoration on the component. For a restoration where the age is reset to zero then formulas (3) and (4) apply with the age w being the age since the last restoration. For a maintenance involving a partial restoration which resets the component age to a value w_1 then formulas (3) and (4) apply with the age w being the age of the component since the last partial restoration where the age begins at w_1.

Associated time dependent formulas for the unavailability can be obtained by using the ages that correspond to given times. For example, if the component was renewed at t_o with no subsequent checking or maintenance then the unavailability q(t) at time t is

$$q(t) = 1 - \exp\left(- \int_{0}^{t-t_o} \lambda(w')dw' \right) \tag{5}$$

where the component age at time t is t-t_o.

If the component was last known to be up at time t_a ,i.e. last tested at t_a , then the component unavailability q(t) is

$$q(t) = 1 - \exp\left(- \int_{t_a-t_o}^{t-t_o} \lambda(w')dw' \right) \tag{6}$$

where t_a - t_o is the age w_a at the last test or check. Similar transformations can be used for the component unreliabilities in Equations (1) and (2).

Finally, for average component unavailabilities the above age dependent or time dependent component unavailabilities are averaged over given time intervals. Averages over intervals between tests give the average unavailability between tests and averages over intervals between replacements give the average unavailability between replacements. Differences from the baseline PSA unavailabilities give the increases in unavailability (or unreliability) due to aging, either for time dependent or for averaged results.

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-5587
SAIC-92/1137

2. TITLE AND SUBTITLE

Approaches for Age-Dependent Probabilistic Safety Assessments with Emphasis on Prioritization and Sensitivity Studies

3. DATE REPORT PUBLISHED

MONTH	YEAR
August	1992

4. FIN OR GRANT NUMBER

L1072

5. AUTHOR(S)

W.E. Vesely

6. TYPE OF REPORT

Technical

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 name and mailing address.)

Science Applications International Corporation
655 Metro Place South, Suite 745
Dublin, OH 43017

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 Engineering
Office of Nuclear Regualtory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Approaches are described for incorporating component aging reliability models into a probabilistic safety assessment (PSA), or probabilistic risk assessment (PRA), of a nuclear power plant. These approaches and procedures are described from a technical standpoint and are not to be interpreted as having any regulatory implications. Component aging failure rate models and test and maintenance aging control models are presented for utilization. Different approaches for carrying out the aging evaluations are given. Demonstrations are given involving prioritizing aging contributors, evaluating maintenance effectiveness, carrying out time dependent evaluations, and carrying out uncertainty and sensitivity analyses of aging effects.

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

Probabilistic Safety Assessment
Probabilistic Risk Assessment
Aging Evaluations
Component Reliability 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)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

A65617-00006 2
USNRC
J. VORA
217B N/LS

SPECIAL FOURTH-CLASS RATE
POSTAGE AND FEES PAID
USNRC
PERMIT NO. G-67