NUREG/CR-6415
BNL-NUREG-52488

Applications of Reliability Degradation Analysis

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Prepared for
U.S. Nuclear Regulatory Commission

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Manuscript Completed: January 1996
Date Published: February 1996

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NRC Job Code A3270

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ABSTRACT

Reliability degradation analysis is the analysis of the occurrences of degradations and the times of maintenance to determine their reliability and risk implications. A program is presented for applying reliability degradation analyses to maintenance data collected at nuclear power plants. As a specific part of the program, time trending of maintenance data is illustrated. Maintenance data on residual heat removal (RHR) pumps and service water (SW) pumps at selected boiling water reactor (BWR) plants are evaluated to show how trends in maintenance data, which generally do not involve failures, can be used to understand effectiveness of maintenance. These trends also are translated to specific impacts on pump unavailability and on core-damage frequency (assuming that the trends in failure rate are the same as those observed for the degradation rate). The second application shows the use of reliability degradation analysis to quantitatively evaluate the effect of maintenance, i.e., the quantitative change in component unavailability when no maintenance is performed. Assessment of these impacts are important since they measure the reliability and risk impacts of maintenance and can be fed back to the maintenance program to improve its effectiveness.

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EXECUTIVE SUMMARY

Reliability degradation analysis is the analysis of maintenance and degradation data to determine the reliability and risk implications of the maintenances undertaken. Maintenance data generally include the times of maintenance and the associated actions that are taken when it is conducted. Generally, the pieceparts that are maintained also are identified, but the root causes of the problems are not recorded. Since failure occurrences are rare, reliability degradation analysis focuses on using the times of maintenance and associated information on degradation to determine reliability and risk implications.

In this report, we summarize the concept of reliability degradation analyses, focussing on aspects of its application. These discussed aspects are based on the techniques for reliability degradation modeling that were discussed in NUREG/CR-5612* and NUREG/CR-5967.** We define and give examples of component degraded states relevant for the reliability degradation analyses, and discuss practical considerations of extracting occurrences of degradations from available databases. We also demonstrate applications to analyze time trends in degradation data, and to evaluate the effect of maintenance on components' performances. These kinds of analyses can be carried out using maintenance data as they provide useful information about the maintenances being performed on a component.

In the first application, the times of occurrences of degradations are analyzed to observe trends in degradation rate. The degradation rate is the same as the maintenance rate when degradation is defined for each corrective maintenance. In the example application for residual heat removal (RHR) pumps, the degradation rate shows a distinct increase as a function of the pump's age. This trend is statistically significant. Such component-specific analysis has use in judging and improving maintenance to avoid increase in the component's failure rate.

In the second application, the Markov models described in NUREG/CR-5967 are used to quantitatively evaluate the impact of maintenance on components' unavailability. The impact includes both the unavailability due to maintenance downtime and that due to failure. We demonstrate the steps involved, the input data, and the results obtained. In the example discussed, the effect of no maintenance would be to increase failure unavailability by a factor of 7, but to decrease the overall unavailability of the component. Intent in such an application is to define maintenance practices that are more effective in controlling both the failure unavailability and the total component unavailability.

Finally, we discuss how and under what engineering assumptions and considerations trends in times of degradations can be translated to associated trends in component failure rates. The latter trends can be used to evaluate implications on component unavailability and plant risk.

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*NUREG/CR-5612, "Degradation Modeling with Application to Aging and Maintenance Effectiveness Evaluations," March 1991.

**NUREG/CR-5967, "Development and Application of Degradation Modeling to Define Maintenance Practices," June 1994.

1. CONCEPTS AND APPROACHES FOR RELIABILITY DEGRADATION ANALYSIS

1.1 Introduction

The concepts of reliability degradation analysis were originally introduced in NUREG/CR-5612 (Ref. 1), "Degradation Modeling with Application to Aging and Maintenance Effectiveness Evaluations" and were expanded in NUREG/CR-5967 (Ref. 2), "Development and Application of Degradation Modeling to Define Maintenance Practices". NUREG/CR-5612 focused on developing technical methods to evaluate times of degradations and maintenances for time trends and for measures of the efficiency of maintenance. NUREG/CR-5967 focused on developing Markov models to quantify the probabilities of safety system components being in various degraded states.

NUREG/CR-5612 and NUREG/CR-5967 thus focused on developing technical methods. The objective of this document is to describe and demonstrate how methods of degradation analysis can be incorporated into an applications program to determine the reliability and risk effects of the maintenances undertaken. We note that in this document the term "reliability degradation analysis" is used instead of "degradation analysis" as in the previous NUREG/CRs. The modifier "reliability" has been added to specifically denote that the purpose of all the degradation analyses described here, and in the previous NUREGs, is to evaluate the reliability implications of the degradations.

This first chapter summarizes the basic concepts of reliability degradation analysis; its applications are presented in later chapters. The approaches are described in terms of their objectives and results, but not in terms of their technical details which were given earlier in NUREG/CR-5612 and NUREG/CR-5967. The second chapter presents the definition of component degradation used in reliability degradation analysis and gives examples from our review of component maintenance data. Here, the considerations involved in identifying occurrences of degradation from component databases are discussed. The third chapter demonstrates two applications of reliability degradation analysis: a) the analysis of time trends of degradations, and b) the assessment of the effect of maintenance on the components' performance. The final chapter summarizes and discusses the findings.

1.2 Basic Definition of Reliability Degradation Modeling

Reliability degradation modeling is the modeling of the reliability implications of degradation phenomena. In this modeling, the occurrences of degradations of components are explicitly considered to understand the need for, and the effect of, maintenance on the component. Typically, degradations occur more frequently than failures, and valuable information can be gleaned from these occurrences. Reliability degradation modeling aims to extract such information on components' performances. It differs from other types of degradation modeling and analyses in that the effect of the components' degradation on component reliability is evaluated. We discuss here applications that can be carried out with data currently available. Reliability degradation modeling can be further broadened where quantitative models are developed showing the relationships between the characteristics of the degradation and the resulting impacts on reliability. The explicit relationships between them can be used to obtain the time-dependent reliability of the component which then can be input to Probabilistic Risk Assessments (PRAs) to determine the risk effects of the degradations and the maintenance practices. However, data for developing explicit relationships between the characteristics of degradations and components' reliability usually are not available.

1.3 Application Approaches for Carrying Out Reliability Degradation Modeling

The following applications of reliability degradation modeling are discussed here:

- analysis of time trends of degradations
- analysis of the effect of maintenance on components' performances.

These two applications are supported by the kind of data which can be gathered with reasonable resources from existing databases. Below, we briefly describe each of them.

Analysis of Time Trends of Degradations

The analysis of time trends of degradations involves evaluating the rate at which the degradation progresses and the increases in its severity. If corrective maintenances are carried out when degradation exceeds a given severity value, then the times between corrective maintenances can be used as a measure of times between the occurrences of degradation. Decreasing times indicate an increasing degradation rate and hence, ineffectiveness in maintenance in controlling this behavior. Statistical techniques can be used to determine the time trend from a set of recorded measurements and its associated statistical significance.

Analysis of the Effect of Maintenance on Component Performance

Usually, corrective maintenances are undertaken when a component is detected in a degraded state. It is reasonable to assume that, if corrective maintenances are not performed, then the component will fail. A component's failures are those that occur in spite of the corrective maintenances made. In reliability degradation modeling, the performance states of a component are defined, and then the transition rates between states can be used to predict the reliability and time to failure of the component using standard Markov modeling (see NUREG/CR-5967, June 1994). Then, the component's performance when no maintenance is done can be simulated by disallowing all transitions to the maintenance state. Hence, the effect of maintenance of the component can be evaluated. This is a powerful application of the reliability degradation modeling since there are no data on components when no maintenance is performed.

In addition to the above two applications, another useful application will be to relate the performance of a degraded component to its reliability performance. Once the effect of the occurrence of degradation is translated into the component's failure rate, then the failure rate can be an input into the PRA to obtain its risk impact. An example is given in the appendix where the component failure rate is assumed to have the same behavior as its degradation rate.

2. COMPONENT STATES FOR RELIABILITY DEGRADATION ANALYSIS

2.1 Definitions of Component States

In reliability degradation analysis, the performance of a component is defined in terms of four states: operational (o), degraded (d), maintenance (m), and failure (f). Table 2.1 identifies and briefly describes these states. These states allow the progression to failure from the operational state through the degraded state. The definition of a maintenance state allows the effects of maintenance on the progression of aging to be modeled explicitly. The effects of maintenance include its benefits in correcting degradations before they progress to failure. Maintenance effects also include its negative effects involving downtime and errors, and inefficiencies.

For extended models, a surveillance test state and a repair state also can be defined, to allow the fraction of time the component is in a test state or in the repair state to be determined. These additional states are not identified, but instead, the effects of testing and repair are included in the transition rates between the four defined states.

These transitions are the state-to-state changes which can occur in the component during operation or standby. Table 2.2 identifies the possible one-step transitions, or state changes, for the four-state model. Transitions from one state to the same one are not defined because they are not changes.

When the initial state is an operational one, a transition can occur to either a maintenance, a degraded, or a failed state (Table 2.2). The transition from an operational state directly to a failed state represents a catastrophic failure occurring without first an intermediate degraded state (for example, a catastrophic failure due to a human error). When the component is in a degraded state, then it can proceed to a maintenance state or to a failed state, if the component cannot be maintained

Table 2.1 Component States For Reliability Degradation Analysis

COMPONENT STATE	DESCRIPTION
Operational State, o	The normal designed performance of the component, above the degradation threshold.
Degraded State, d	Minimal functional performance of the component, above the failure threshold, but below the degradation threshold.
Maintenance State, m	The component is down for maintenance, and hence, is unavailable.
Failed State, f	The component is functionally failed and thus, unavailable.

in time to correct the degradation. A transition from a degraded state to an operational state cannot occur without the component first going through a maintenance state, which is why there is no such transition.

After maintenance, a component can be restored to an operational state or can be left in a degraded or a failed state. Thus, the possibility of ineffective maintenance is considered. Similarly, when the component is in a failed state, then, after repair, it can be in an operational state or can be left in a degraded state. Transitions from a failed state to another failed state are not considered because this is not a change.

It is important to realize that the transition matrix shown in Table 2.2 defines the possible one-step changes. The component may progress from one state to any other state, but this requires a series of transitions or steps. For example, the component may progress from a degraded state to an operational state by first moving to a maintenance state and from there to an operational state. Alternatively, the component may progress from a degraded state to a failed state, and thence, to the operational state.

When there are several possible one-step transitions from a given state, then transitions may occur to any one of these alternative states. Thus, Table 2.2 defines the basic process by which degradations, aging, and maintenance progress.

Table 2.2 Possible One-Step Transitions Between States

	Transition State			
Initial State	o	d	m	f
o	No	Transition to a degraded state	Maintenance performed on an operational component	Failure occurrence without passing through a degraded state
d	No	No	Maintenance performed on a degraded component	Failure from a degraded state
m	The component restored to an operational state after maintenance	The component left in a degraded state after maintenance	No	The component left in a failed state after maintenance
f	The component restored to an operational state after repair	The component left in a degraded state after repair	No	No

o = Operational State
d = Degraded State
m = Maintenance State
f = Failed State

Figure 2.1 shows the possible state-to-state transitions. The solid lines indicate the transitions which would occur if maintenance were perfectly effective; any degradation would be corrected by maintenance before failure occurred and the component would be restored to an operational state. The dotted lines identify those transitions which are associated with less than perfectly effective maintenances.

2.2 Degraded State of a Component

In a reliability degradation analysis, the occurrences of degradation of a component are identified, which requires evaluating the records of a component's performance kept as part of the maintenance and/or reliability databases. Usually, failures of components have been identified in developing a PRA database, but not the occurrences of degradation. Identifying the occurrence of degradation is the additional evaluation needed for applying reliability degradation analysis.

For reliability degradation analysis, the degraded state of a component is defined at a gross level, i.e., a component is described as degraded whenever any deterioration occurs which does not cause loss of function. One example of identifying component degradations at a gross level is to look at the times when corrective maintenances are required, but the component has not failed. A specific example is an oil leak by the gasket due to deterioration of the gasket for an air compressor, or the build up of corrosion by the after cooler in the jacket heat exchanger of the air compressor. Using detailed analyses involves associating a degraded state with a given range of characteristics defining the component's performance. For example, a detailed degraded state of a pump may be defined based on the time needed to reach full flow, or for circuit breakers it can be based on defined ranges for pick-up/drop-out voltages, in rush/holding current. Determining degraded states using detailed analyses is time consuming and in many cases, cannot be supported by available data. For the types of applications discussed in this report, the gross definition is adequate.

Figure 2.1. Flow chart for the possible state-to-state transitions

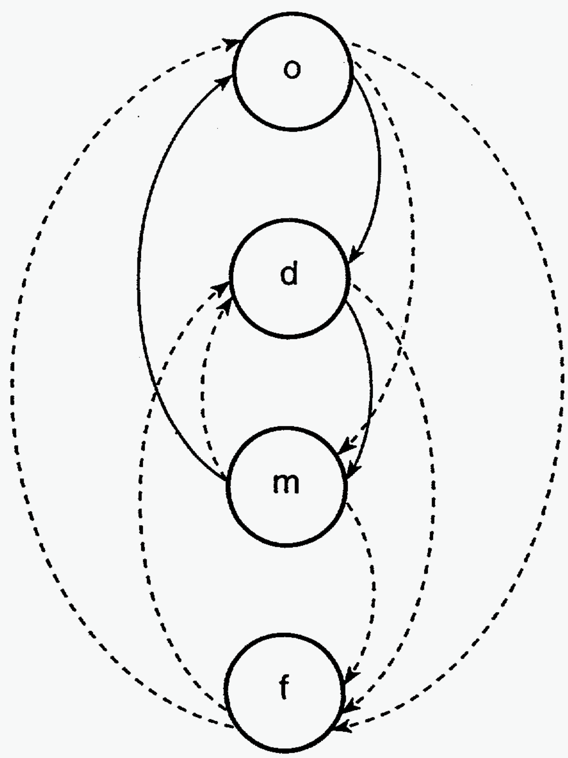

Table 2.3 Examples of Degraded Component States

COMPONENT	DESCRIPTION OF DEGRADATION (Action Taken)
SW Pump	Pump was operating at a decreased flow and pressure. The cause was attributed to normal erosion of the pump internals causing leakage past the impeller to the suction side of the pump.
SW Pump	A small leak on the pump's coupling was noted. The cause of the leak was a hole in the coupling cooling water line. The cool coil was removed and repaired.
RHR Pump	The mechanical seal of the pump was required to be rebuilt. New "o" rings and seal faces were installed.
Air Compressor	Mechanical debris was noted in the Jacket Heat Exchanger. This resulted in corrosion deposits by the after cooler.
Air Compressor	Mechanical vibration was noted due to a fractured stud on the spacer.
Air Compressor ·	Oil leak was noted. The cause was identified to be deterioration of the gasket which was replaced.

Table 2.3 presents examples identifying degradations for residual heat removal (RHR) pumps, service water (SW) pumps, and air compressors. As the descriptions show, there are definite indications that the components condition has degraded, and it was noted that the component is not failed, but corrective maintenance was performed.

2.3 Practical Considerations in Evaluating Component Databases for Identifying Component Degradations

To identify occurrences of the degradation, database maintained for the component being analyzed is reviewed. Two types of databases usually are useful: Work maintenance records at specific plant sites, and the Nuclear Plant Reliability Data System (NPRDS) maintained by the Institute of Nuclear Power Operations. Work maintenance records contain records of every maintenance on the components, and hence, many minor routine maintenances may need to be screened out in extracting occurrences of degradations; scanning these work records is time consuming, and at times, difficult because only minimal descriptive information is kept in a computerized work maintenance record. NPRDS is less time-consuming to evaluate, but requires care in evaluating individual records. In some cases, NPRDS data may need to be supplemented by work maintenance records since cases of degradations, as defined for reliability degradation analysis, may not be reported. (The "Incipient" failure category in NPRDS may contain component-degraded states. Reporting this category is not required in NPRDS.) Below, we discuss some observations on using NPRDS and work maintenance records that should be considered in identifying degradation occurrences for reliability degradation analyses.

1. The NPRDS should be used to obtain a listing of the component's records which then should be used to identify occurrences of degradations. This listing should include the reported data for all three severity levels: catastrophic, degraded, and incipient. All three categories should be evaluated to identify occurrences of degradations.

2. Care should be taken to assure that the component's definition being used for reliability degradation analysis is the same as that in the NPRDS database. Sometimes a catastrophic failure identified in an NPRDS record may relate to a piece-part of the component and not the component itself that is being analyzed. Thus, the catastrophic failure of the piece-part may or may not be a catastrophic failure of the component, and accordingly, the definition of the component should be considered in identifying the data for degradation analyses.

3. The NPRDS definition of severity levels; catastrophic, degraded, and incipient, cannot be directly used to identify occurrence of degradations, i.e., only the records classified as degraded cannot be selected to identify occurrences of degradations. Many reports in the incipient category can qualify as a degradation of the component, as defined in this report for reliability degradation analysis. Similarly, many reports in the degraded category qualify as failures, and some in the catastrophic category actually may be a degradation because the catastrophic failure referred to a piece-part of the component. Thus, the detailed description of reports in all three categories should be reviewed to identify the occurrences of degradations.

4. Several NPRDS reports may be generated corresponding to one maintenance performed in response to requests for the maintenance at different times. Usually, all the reports have the same "end date" as defined in the NPRDS database signifying the time when the maintenance was completed, but have a different "start date" signifying different requests for maintenance. These reports should be carefully reviewed to identify specific occurrences of degradation, and to avoid multiple counting of a degradation. In most cases, these multiple reports combine into one degradation occurrence corresponding to the time when maintenance was performed.

5. In identifying the occurrences of degradation, minor degradations which may remain in the component and do not cause a failure unless their severity increases with time, should be ignored. One way to judge these minor degradations is to look at the date when they were noted and maintenance was requested, and the date when the maintenance was performed. Usually, when the time difference is large (e.g., more than one month), then degradation may be a minor one and can be ignored.

3. DEMONSTRATIONS OF APPLICATIONS OF RELIABILITY DEGRADATION ANALYSIS

This chapter demonstrates the applications of reliability degradation analyses. First, analyses of time-trends in degradation data is presented, and then, an application evaluating the effect of maintenance on a component's performance is discussed.

3.1 Analyses of Times of Maintenances and Failures and Associated Trend Analysis

The application focusses on establishing time-trends in degradations which can be used to identify needed enhancements to the maintenance program. Appendix A discusses how these trends in the maintenance data can be translated into unavailability implications and risk implications so as to assess the effects of the maintenance program on reliability and risk.

The applications presented here are those carried out for pumps in the residual heat removal (RHR) system and in the service water (SW) system. The primary data are the times of degradations at which maintenances were performed. Data for the RHR pump were collected from work maintenance records, whereas the SW pump data were gleaned from the NPRDS database. The root causes of the degradations generally are not identified so this maintenance data represents the minimal type of information for which reliability degradation analyses can be performed.

Tables 3.1 and 3.2 show the times of maintenance and repair for RHR pumps and SW pumps. This data basically reproduces the information in NUREG/CR-5612 but is again presented for the readers' convenience. In NUREG/CR-5612, this data was used to demonstrate trending analyses that can be carried out on the data. Tables 3.1 and 3.2 are more or less self-explanatory with "Age" denoting the age at which maintenance occurred, measured from the beginning of the data record. Since it is the intervals between maintenances which are important, the starting point (origin) for the age measurement is not critical. The "Age Interval" is the age since the last maintenance: this is the critical information for reliability degradation applications. The failure data are not used in this analysis except that in calculating the "age interval" for a degradation following a failure, the interval is measured from the failure date when repair was performed; the reason why those data are kept in the table. As NUREG/CR-5612 indicates, one over the age interval, 1/(Age Interval), is an empirical estimate of the maintenance rate, or equivalently, the degradation rate, at the given age. We note that the ages are in units of quarter years (e.g. multiply by 91 days per quarter to obtain ages in days). Degradation as defined in the database is a component condition requiring maintenance. Hence, for this definition, the degradation rate and maintenance rate are synonymous. Thus, we shall use the terms interchangeably.

Figures 3.1 and 3.2, taken from NUREG/CR-5612, plot the empirical maintenance rates (or degradation rates) versus age for the RHR and SW pump data. The maintenance rates show a distinct increasing trend with age.

Tables 3.3 and 3.4, also from NUREG/CR-5612, show the results of applying standard regression analysis to the empirical maintenance rates versus age. As described in NUREG/CR-5612, the time trend model for the maintenance rate or degradation rate $\lambda(t)$ is:

$$\ln\lambda(t) = a + bt \quad (1)$$

or

$$\lambda(t) = e^{a+bt} \quad (2)$$

where t is the age and a and b are constants. If there is no time trend in the maintenance rate or degradation rate, then b=0. Based on the plots, Tables 3.3 and 3.4 divide the pump ages into two periods: for RHR pumps, 0-20 quarters and 21-40 quarters, and for SW pumps, 0-23 quarters and 24-55 quarters. Table 3.3 contains two sets of results based on whether RHR pump data from all plants is used (Method 1), or whether only statistically similar data is pooled together (Method 2). The results are similar. For the SW pump, all data were combined. The results in Tables 3.3 and 3.4 represent standard statistical analysis which can be done on the data and were obtained using standard statistical models (Cox's model), as described in NUREG/CR-5612.

The boxes which are highlighted in Tables 3.3 and 3.4 are the important results for reliability degradation analysis. In Table 3.3 for an RHR pump, depending upon whether Method 1 or Method 2 is used, the time-trend parameter for the maintenance rate is 0.105 or 0.095 respectively, in age period of 20 to 40 quarters. This finding means that after 20 quarters, the maintenance rate on the pump increases at a relative rate of 10.5% per quarter, or 9.5% per quarter depending upon whether Method 1 or 2 is used for combining the data. We shall use the time trend parameter obtained by Method 2, i.e. 9.5%, since the population is more homogeneous; however, the trends obtained from the two methods are basically the same considering the uncertainties.

Table 3.1 Maintenance Times on RHR Pumps (3 Nuclear Units, 4 Pumps Per Unit)

Maintenance/Repair Date								
Mo	Dy	Yr	Plant	Component ID	Severity*	Age**	Age Interval**	1/ (Age Interval)
5	1	80	1	a	D	1.33	1.33	0.750
1	15	81	1	a	D	4.21	2.88	0.347
3	16	82	1	a	D	8.94	4.73	0.211
10	28	82	1	a	D	11.41	2.47	0.405
9	8	83	1	a	D	14.91	3.50	0.286
2	17	84	1	a	D	16.73	1.82	0.549
7	1	84	1	a	D	18.22	1.49	0.672
7	26	85	1	a	D	22.56	4.33	0.231
5	12	80	1	b	D	1.46	1.46	0.687
1	15	81	1	b	D	4.21	2.76	0.363
3	16	82	1	b	D	8.94	4.73	0.211
10	28	82	1	b	D	11.41	2.47	0.405
3	17	83	1	b	D	13.01	1.60	0.625
4	18	84	1	b	F	17.41	4.40	0.227
7	26	85	1	b	D	22.56	5.14	0.194
3	10	86	1	b	D	25.10	2.54	0.393
1	9	87	1	b	F	28.48	3.38	0.296
5	10	88	1	b	D	33.88	5.40	0.185
6	7	80	1	c	D	1.73	1.73	0.577
1	15	82	1	c	F	8.27	6.53	0.153
3	16	82	1	c	D	8.94	0.68	1.475
10	28	82	1	c	D	11.41	2.47	0.405
9	8	83	1	c	D	14.91	3.50	0.286
6	8	84	1	c	D	17.97	3.06	0.327
8	7	84	1	c	D	18.62	0.66	1.525
7	26	85	1	c	D	22.56	3.93	0.254
2	2	87	1	c	D	28.73	6.18	0.162
4	25	80	1	d	D	1.27	1.27	0.789

* D = degradation; F = failure

** Age in quarter years

Table 3.1 Continued

Maintenance/Repair Date Mo	Dy	Yr	Plant	Component ID	Severity*	Age**	Age Interval**	1/ (Age Interval)
5	12	80	1	d	D	1.46	0.19	5.294
3	16	82	1	d	D	8.94	7.49	0.134
10	28	82	1	d	D	11.41	2.47	0.405
12	15	82	1	d	D	11.93	0.52	1.915
3	17	83	1	d	D	13.01	1.08	0.928
4	18	84	1	d	F	17.41	4.40	0.227
5	5	84	1	d	D	17.60	0.19	5.294
6	29	84	1	d	D	18.20	0.60	1.667
7	26	85	1	d	D	22.56	4.36	0.230
7	28	86	1	d	D	26.63	4.08	0.245
1	4	83	2	a	D	0.03	0.03	30.000
8	25	83	2	a	F	2.60	2.57	0.390
11	8	83	2	a	D	3.41	0.81	1.233
2	2	84	2	a	D	4.40	0.99	1.011
8	7	84	2	a	F	6.46	2.06	0.486
5	8	85	2	a	F	9.52	3.07	0.326
1	16	86	2	a	D	12.33	2.81	0.356
4	19	88	2	a	F	21.48	9.14	0.109
1	4	83	2	b	D	0.03	0.03	30.000
7	28	83	2	b	D	2.30	2.27	0.441
11	8	83	2	b	D	3.41	1.11	0.900
6	19	84	2	b	F	5.92	2.51	0.398
8	2	84	2	b	F	6.40	0.48	2.093
1	30	86	2	b	D	12.49	6.09	0.164
2	11	86	2	b	D	12.61	0.12	8.182
3	24	87	2	b	D	17.14	4.53	0.221
12	17	87	2	b	D	20.07	2.92	0.342
2	4	88	2	b	D	20.64	0.58	1.731

* D = degradation; F = failure
** Age in quarter years

Table 3.1 Continued

Maintenance/Repair Date Mo	Dy	Yr	Plant	Component ID	Severity*	Age**	Age Interval**	1/ (Age Interval)
1	4	83	2	c	D	0.03	0.03	30.000
2	1	83	2	c	D	0.33	0.30	3.333
3	4	83	2	c	D	0.70	0.37	2.727
5	25	83	2	c	D	1.60	0.90	1.111
9	27	83	2	c	D	2.96	1.36	0.738
2	16	84	2	c	D	4.56	1.60	0.625
5	16	84	2	c	D	5.56	1.00	1.000
8	15	84	2	c	F	6.54	0.99	1.011
3	7	85	2	c	D	8.84	2.30	0.435
2	3	89	2	c	F	24.69	15.84	0.063
1	4	83	2	d	D	0.03	0.03	30.000
1	11	83	2	d	D	0.11	0.08	12.857
4	12	83	2	d	D	1.12	1.01	0.989
3	5	84	2	d	F	4.77	3.64	0.274
8	2	84	2	d	D	6.40	1.63	0.612
8	15	84	2	d	F	6.54	0.14	6.923
9	20	84	2	d	F	6.93	0.39	2.571
3	7	85	2	d	D	8.84	1.91	0.523
12	17	87	2	d	D	20.07	11.22	0.089
8	1	74	3	a	D	1.00	1.00	1.000
12	5	74	3	a	F	2.38	1.38	0.726
12	15	75	3	a	D	6.54	4.17	0.240
9	20	76	3	a	D	9.66	3.11	0.321
11	21	76	3	a	D	10.33	0.68	1.475
12	26	76	3	a	D	19.11	0.39	0.119
1	16	79	3	a	D	19.11	8.39	0.119
3	16	82	3	a	D	31.94	12.83	0.078
6	3	82	3	a	D	32.80	0.86	1.169

* D = degradation; F = failure
** Age in quarter years

Table 3.1 Continued

Maintenance/Repair Date Mo	Dy	Yr	Plant	Component ID	Severity*	Age**	Age Interval**	1/ (Age Interval)
10	23	82	3	a	D	34.36	1.56	0.643
2	25	83	3	a	D	35.77	1.41	0.709
3	3	85	3	a	D	43.97	8.20	0.122
7	1	86	3	a	D	49.33	5.37	0.186
4	23	75	3	b	F	3.97	3.97	0.252
12	18	78	3	b	D	18.74	14.78	0.068
3	10	82	3	b	D	31.88	13.13	0.076
4	4	82	3	b	D	32.14	0.27	3.750
5	1	82	3	b	D	32.44	0.30	3.333
6	8	82	3	b	D	32.86	0.41	2.432
8	1	82	3	b	D	33.44	0.59	1.698
10	23	82	3	b	D	34.36	0.91	1.098
2	9	83	3	b	D	35.59	1.23	0.811
3	1	85	3	b	D	43.94	8.36	0.120
4	23	82	3	c	D	32.36	32.36	0.031
10	23	83	3	c	D	38.41	6.06	0.165
3	1	85	3	c	D	43.94	5.53	0.181
9	14	74	3	d	F	1.48	1.48	0.677
3	18	76	3	d	D	7.63	6.16	0.162
11	4	76	3	d	D	10.14	2.51	0.398
5	1	82	3	d	D	32.44	22.30	0.045
10	23	82	3	d	D	34.36	1.91	0.523
12	1	82	3	d	D	34.78	0.42	2.368
1	1	83	3	d	D	35.17	0.39	2.571
1	1	84	3	d	D	39.22	4.06	0.247
3	1	85	3	d	D	43.94	4.72	0.212

* D = degradation; F = failure
** Age in quarter years

Table 3.2 Maintenance Times on SW Pumps (7 Nuclear Units)

Maintenance/Repair Date Mo	Dy	Yr	Plant	Component ID	Severity*	Age**	Age Interval**	1/(Age Interval)
3	7	74	4	d	D	0.18	0.18	5.625
3	7	74	4	a	F	0.18	0.18	5.625
8	14	86	5	g	F	0.37	0.37	2.727
1	12	84	3	a	F	0.51	0.51	1.957
7	10	74	4	c	D	1.54	1.54	0.647
7	10	74	4	a	D	1.54	1.37	0.732
7	10	74	4	d	D	1.54	1.37	0.732
12	4	86	5	g	F	1.59	1.22	0.818
3	8	80	7	d	D	2.09	2.09	0.479
3	15	86	7	b	F	2.42	2.42	0.413
7	17	86	7	b	D	3.78	1.36	0.738
5	15	86	5	a	D	4.01	0.80	1.250
11	22	83	5	h	D	5.79	5.79	0.173
5	11	81	7	a	F	6.84	6.84	0.146
10	22	85	2	b	F	7.68	7.68	0.130
6	14	87	11	i	D	7.82	7.82	0.128
2	25	76	4	g	F	8.16	8.16	0.123
12	13	85	3	c	D	8.24	1.08	0.928
3	3	86	3	c	D	9.19	0.94	1.059
5	15	86	3	d	F	9.99	9.99	0.100
5	23	86	3	e	D	10.08	10.08	0.099
3	14	82	7	c	D	10.27	10.27	0.097
8	8	86	2	d	D	10.91	10.91	0.092
5	12	82	7	d	D	10.91	8.82	0.113
3	3	85	5	c	D	11.02	11.02	0.091
10	28	86	2	c	D	11.80	2.17	0.462
6	3	85	5	d	F	12.02	0.41	2.432

* D = degradation; F = failure
** Age in quarter years

Table 3.2 Continued

Maintenance/Repair Date Mo	Dy	Yr	Plant	Component ID	Severity*	Age**	Age Interval**	1/ (Age Interval)
4	17	86	5	b	F	15.57	15.57	0.064
7	24	78	4	h	F	17.92	17.92	0.056
12	18	86	5	b	D	18.24	2.68	0.373
6	21	87	5	d	D	20.32	8.30	0.120
8	6	85	7	d	D	24.01	13.10	0.076
10	16	80	4	e	F	26.94	12.80	0.078
5	31	86	7	a	F	27.34	4.18	0.239
6	22	86	7	c	F	27.58	17.31	0.058
1	1	87	7	g	D	29.73	5.56	0.180
5	12	87	7	c	F	31.19	3.61	0.277
3	25	88	7	d	D	34.72	10.71	0.093
6	2	85	6	a	F	38.23	4.72	0.212
6	25	82	11	h	D	43.48	0.04	22.500
4	4	88	2	a	D	44.79	10.17	0.098
5	11	87	6	a	D	46.11	7.88	0.127
8	27	85	4	e	D	46.68	11.99	0.083
8	28	87	6	c	F	47.30	10.66	0.094
11	14	85	4	b	D	47.53	4.66	0.215
7	30	86	4	b	D	50.43	2.90	0.345
7	1	88	6	c	D	50.72	3.42	0.292
1	18	87	4	b	D	52.36	1.92	0.520
6	10	87	4	b	D	53.93	1.58	0.634
6	17	85	11	d	D	55.56	12.69	0.079
10	5	85	11	f	D	56.76	14.06	0.071

* D = degradation; F = failure
** Age in quarter years

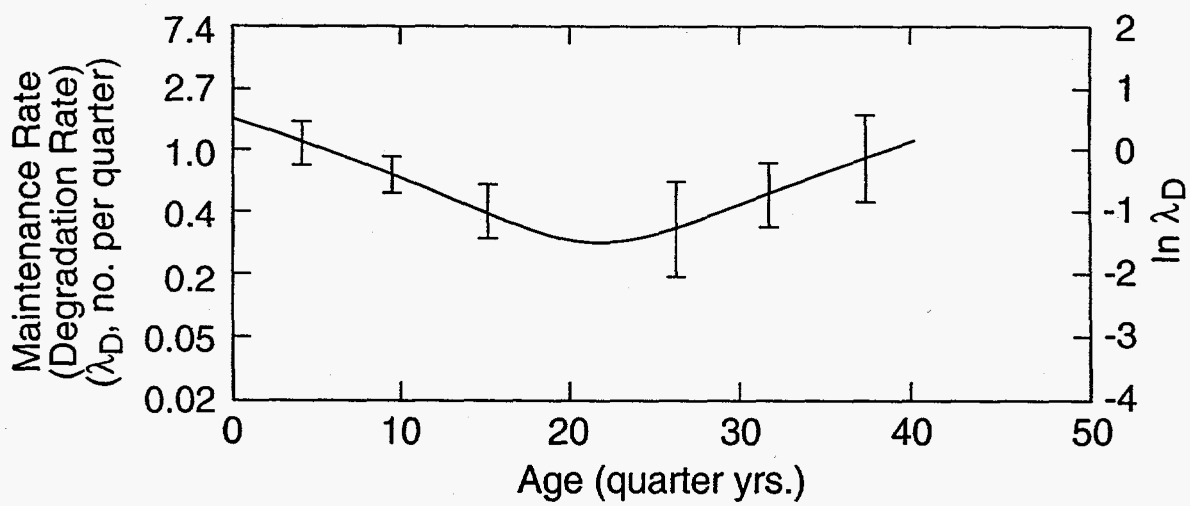

Figure 3.1 Age-dependent maintenance rate for RHR pumps (3 plants)

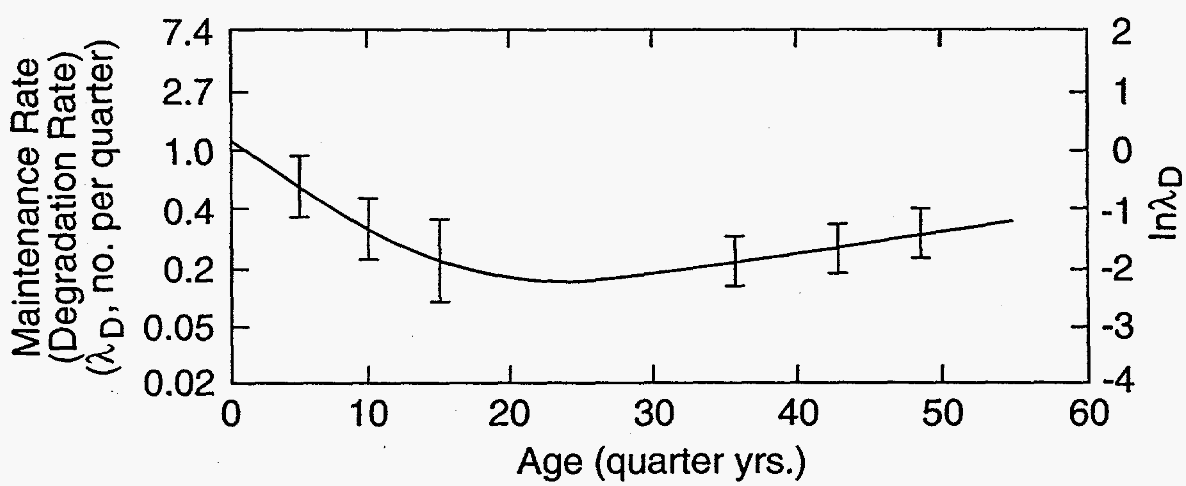

Figure 3.2 Age-dependent maintenance rate for SW pumps (7 plants)

Table 3.3 Results of Trend Analysis on the Maintenance Times: RHR Pumps

Data Aggregation Method	Pump Age	Time Trend b			Constant ln a		
		Estimated Value	Statistical Significance Level	90% Uncertainty Range	Estimated Value	Statistical Significance Level	90% Uncertainty Range
Method 1: Data Combining	0-20 (quarters)	-0.095	99.9	L: -0.1395 U: -0.05086	0.541	97.5	L: 0.06661 U: 1.0149
	21-40 (quarters)	0.105	95.4	L: 0.00223 U: 0.207	-4.161	98.8	L: -7.325 U: -0.9975
Method 2: Data Pooling	0-20 (quarters)	-0.0285	86.8	L: -0.0659 U: 0.00887	0.365	94.0	L: -0.0247 U: 0.7549
	21-40 (quarters)	0.095	97.2	L: 0.0113 U: 0.1777	-3.111	98.2	L: -5.633 U: -0.5882

U = Upper (95%) range
L = Lower (5%) range

Table 3.4 Results of Trend Analysis on the Maintenance Times: SW Pumps

Data Aggregation Method	Pump Age	Time Trend b			Constant ln a		
		Estimated Value	Statistical Significance Level	90% Uncertainty Range	Estimated Value	Statistical Significance Level	90% Uncertainty Range
Data Combining	0-23 (quarters)	-0.1527	-0.0001	L: -0.2207 U: -0.0848	0.1698	0.589	L: -0.4669 U: -0.8065
	24-55 (quarters)	0.0365	0.0285	L: 0.00438 U: 0.0686	-3.2534	0.0001	L: -4.578 U: -1.9287

From Table 3.4, the time-trend parameter for the maintenance rate for SW pumps from 24 to 55 quarters is 0.0365. This value means the maintenance rate increases at a relative rate of 3.65% per quarter, or to two significant figures at a rate of 3.6% per quarter, after 23 quarters. The significance levels and uncertainty ranges in Tables 3.3 and 3.4 show that these aging rates for the RHR pumps and SW pumps are statistically significant.

Determining the time trends in the maintenance rates and degradation rates for the RHR and SW pumps is an important application of reliability degradation analyses. Consequently, the results obtained are highlighted in the table below. The associated uncertainties in the time trends, i.e. the 90% upper and lower confidence bounds, also are shown.

TIME TRENDS IN MAINTENANCE RATES AND DEGRADATION RATES

RHR PUMPS:	9.5% per quarter increase in the rate after a pump age of 20 quarters. [(1.1%, 17.8%) confidence bounds for the trend.]
SW PUMPS:	3.6% per quarter increase in the rate after a pump age of 23 quarters [(0.4%, 6.9%) confidence bounds on the aging trend.]

3.2 Analyses of Maintenance Effects Using Degradation Modeling

An application of reliability degradation modeling is to assess the effect of maintenance on the failure probability of a component and on its unavailability (including the failure probability and the unavailability due to maintenance downtime). In the standard evaluation used in PRAs the effect of maintenance on failure probability is not separated out (only the maintenance downtime contribution is given separately), so that the full effect of maintenance cannot be delineated. Using the reliability degradation modeling can estimate the overall effect of maintenance. NUREG/CR-5967 describes the details of the degradation modeling, provides example analysis, and also sensitivity analyses to compare different alternatives. Here, we describe the steps involved in carrying out the application, the data needed, the assumption involved, and the results which will be obtained.

The following are the steps in the application process:

1. Selecting the model's parameters
2. Estimating the transition rates
3. Calculating the state probabilities
4. Estimating state probabilities if there is no maintenance
5. Comparing unavailability (maintenance vs. no maintenance cases)

Step 1. Selecting the Model's Parameters

In this first step, the parameters of the model are defined. These parameters define the characteristics of the component being evaluated and contribute significantly to the final results. We briefly define each parameter, the source of information for estimating the parameter, and indicate where expert judgments are needed. The details of the model are given in NUREG/CR-5967.

1. Total Component Failure Rate, λ_f: Typically, this is the failure rate used in PRA studies. It also can be directly estimated from the component's database using the observed number of failures over a certain period.

2. Rate of Transition from Operating State to Failed State, λ_{of}: The rate includes those transitions that do not pass through the degraded state. This term is expressed as some fraction q_{of} of λ_f.

$$\lambda_{of} = q_{of} \cdot \lambda_f$$

   The term q_{of} is the fraction of failures which do not pass through a degraded state. The estimate of this parameter may need to be based on expert judgments. For many mechanical components, q_{of} is small, i.e., between 0 and 0.1, whereas for certain electronic equipment it can be large, i.e., greater than 0.5. It is expected that the application carried out involves components that usually become degraded before failing and accordingly, q_{of} will be small.

3. Rate of Transition from Operating State to Degraded State, λ_{od}: The rate can be expressed as some factor r_{od} times λ_f. r_{od} can be estimated from the occurrences of degradations identified in a component database. r_{od} is the ratio of number of occurrences of degradations to the number of failures observed.

4. Rate of Transition from Degraded State to Failed State, λ_{df}: This rate, also, can be expressed as some factor r_{df} time $_f\lambda$. Expert judgement may be needed to estimate r_{df}, based on an understanding of the component's characteristics. Usually, r_{df} is greater than 1, and is expected to be between 3 and 10. Sensitivity evaluations can be undertaken for a range of r_{df} values if this parameter is difficult to estimate.

5. Average Downtime for Maintenance, d_m: The average downtime for maintenance can be obtained from the downtimes associated with the maintenances performed for the degradations. The repair times, associated with the failures of the component, are not included here.

6. Surveillance Test Interval, T: The surveillance test intervals usually is defined in the technical specification (TS) and is usually followed. Unless there is evidence that the component was tested at different intervals, the interval defined in the TS can be used.

7. Average Repair Time, r: The average time to repair the component is obtained from the time spent in repairing the component after its failure. The downtimes associated with the maintenance of the degraded component are not included here (they are included in item 5, above).

8. Average Time to Detect and Repair a Failure T_f: The average time to detect and repair a failure, T_f, is obtained from the surveillance test interval, T, and the average repair time, r. For a standby component, as in our application, T_f is expressed as (T/2+r).

9. Maintenance Efficiencies: The maintenance efficiency parameters are p_{mo}, p_{md}, and p_{mf}. p_{mo} defines the fraction of the maintenances restoring the components to operational state. p_{md} defines the fraction of maintenances where the component is left in a degraded state, and p_{mf} defines the remaining fraction where the component remains in failed state due to some maintenance-caused error ($p_{mo} + p_{md} + p_{mf} = 1$). These parameters are difficult to estimate from data, but may be estimated with expert judgments. p_{mf} is similar to the human error of restoration following test or maintenance and is of the order of 0.01. p_{mo} and p_{md} depend on the maintenance policy, i.e., if the component is restored to almost good-as-new condition following each maintenance, then $p_{mo} \rightarrow 1$, and $p_{md} \rightarrow 0$. These parameters can be estimated from discussions with maintenance personnel. Usually (p_{mo}, p_{md} p_{mf}) are in the range (0.9-1.0, 0.1-0, 0.01-0). Sensitivity analyses can address variation in these parameters.

10. Repair Efficiencies: The repair efficiency parameters are p_{of} and p_{fd}. Similar to the maintenance efficiency parameters, p_{of} is the fraction of failures that are returned to operational state, and p_{fd} is the fraction of failures that end up in a degraded state following repair. Here, expert judgments also are needed to estimate these parameters. Usually (p_{of}, p_{fd}) are in the range (0.8-1.0, 0.0-0.2).

11. Maintenance Interval, T_m: The interval at which maintenances are performed can be obtained from plant maintenance records; usually it ranges from 3 months to 1 year.

Step 2. Estimating the Transition Rates

When the input parameters are defined, the transition-rate parameters of the model can be derived using the equations given below. (These equations are given in page 4-3 of NUREG/CR-5967). Considering an example component with characteristic parameters, we can obtain the transition rates discussed above. Table 3.5 includes input parameters for an example component, and also the values of the transition rate parameters based on the values of the input parameters,

$$\lambda_{od} = r_{od}\lambda_f$$
$$\lambda_{om} = \frac{\exp(-(\lambda_{of}+\lambda_{od})T_m)}{T_m}$$
$$\lambda_{of} = q_{of}\lambda_f$$
$$\lambda_{dm} = \frac{\exp(-\lambda_{df}T_m/2)}{(T_m/2)}$$
$$\lambda_{df} = r_{df}\lambda_f$$
$$\lambda_{mo} = p_{mo}/d_m$$
$$\lambda_{md} = p_{md}/d_m$$
$$\lambda_{mf} = p_{mf}/d_m$$
$$\lambda_{fo} = p_{fo}/T_f$$
$$\lambda_{fd} = p_{fd}/T_f$$

Step 3. Calculating the State Probabilities

Once the transition rates have been obtained, the probability can be estimated that the component is in each of four states: p_o, p_m, p_d and p_f. To get these probabilities, it is necessary to solve the balance equations (see pp. 3-7 to 3-10, and Appendix A of NUREG/CR-5967).

One method for solving the balance equations is to use a numerical equation solving routine, such as LSARG as we did in our example. LSARG is a precise routine for solving systems of linear equations, and is part of the International Mathematical and Statistical Subroutine Library (IMSL).

Table 3.5 Input Model Parameters and Transition Rates for an Example Component

MODEL PARAMETERS			TRANSITION RATE	
Parameter	**Explanation**	**Value**	**Parameter**	**Value**
λ_f	Failure Rate	1E-06/hr	λ_{od}	3.0E-06
q_{of}	Fraction of failures not passing through a degraded state	0.1	λ_{om}	4.6E-04
r_{od}	Ratio of degradation rate to failure rate	3	λ_{of}	1.0E-07
r_{df}	Ratio of λ_{df} to λ_f	3	λ_{dm}	9.3E-04
d_m	Average maintenance downtime	24 hrs.	λ_{df}	3.0E-06
T	Surveillance test parameter	730 hrs. (1 month)	λ_{mo}	3.8E-02
r	Average repair downtime	72 hrs.	λ_{md}	4.2E-03
p_{mo}, p_{md}, p_{mf}	Maintenance efficiencies	(0.9,0.1,0)	λ_{mf}	0
p_{fd}, p_{of}	Repair efficiencies	(0.8,0.2)	λ_{fo}	1.8E-03
T_m	Maintenance interval	2160 hrs. (3 months)	λ_{fd}	4.6E-04

The balance equations are solved numerically to obtain the state probabilities for our example component.

p_o, the probability that the component is in operating state = 0.9339

p_d, the probability that the component is in degraded state = 0.0545

p_m, the probability that the component is in maintenance = 0.0115

p_f, the probability that the component is in failed state = 0.000112

In this example, the probability that the component is in failed state is about .0001, which is much smaller compared to the probability that the component is in degraded state, .05. This is because frequent maintenances, with high efficiencies, are being performed on the component. The probabilities of being in maintenance is large, .0115, increasing the total component unavailability. The comparison of component unavailabilities with or without maintenance is discussed in step 5.

Step 4. Estimating State Probabilities if There is No Maintenance

The no-maintenance situation can be simulated by setting to zero the five model parameters that reflect maintenance practices. These five maintenance parameters; λ_{om}, λ_{dm}, λ_{mo}, λ_{md}, and λ_{mf}, are the transition rates from operation to maintenance, degradation to maintenance, maintenance to operation, maintenance to degradation, and maintenance to failure, respectively. Table 3.6 shows the parameters that were selected for our example. For the no-maintenance condition, the five maintenance-related parameters were set to zero.

Using the parameter choices above, the balance equations were solved in each of the four cases. Table 3.7 shows the steady state values of p_o, p_d, p_m , p_f , and the unavailability. Neglecting maintenance greatly decreases the probability that the component will be in the operating state, and increases the probability of degradation. However, neglecting maintenance reduces the total unavailability from roughly .012 to .0007 in the standby case. This increase in unavailability is due to the time required to perform maintenance.

Table 3.6. Transition Parameters for Two Maintenance Conditions

Parameter	Test Interval = 730 Hours	
	Maintenance	No Maintenance
λ_{od}	3.0E-06	3.0E-06
λ_{om}	4.6E-04	0
λ_{of}	1.0E-07	1.0E-07
λ_{dm}	9.3E-04	0
λ_{df}	3.0E-06	3.0E-06
λ_{mo}	3.8E-02	0
λ_{md}	4.2E-03	0
λ_{mf}	0	0
λ_{fo}	1.8E-03	1.8E-03
λ_{fd}	4.6E-04	4.6E-04

Table 3.7 Steady State Solutions for Maintenance vs. No Maintenance Conditions

State Probability	Maintenance	No Maintenance
p_o	.9339	.4425
p_d	.0545	.5568
p_m	.0115	0
p_f	.0001	.0007
Unavailability	.0116	.0007

Step 5. Comparing Unavailability (Maintenance vs. No Maintenance Cases)

A comparison of state probabilities, for our example analysis, shows that the component spends a significantly large fraction of time in a degraded state when no maintenance is performed. Also, the probability of being in a failure state is larger by a factor of 7. But, since maintenance downtime is avoided, the total unavailability (failed unavailability plus maintenance unavailability) is lower when no maintenance is undertaken. Thus, in this example, maintenance shows significant benefit in avoiding degradation of the component and in reducing its failure. These benefits, along with the unavailability due to maintenance, are considered to define the frequency and duration of maintenances for the component.

4. CONCLUSIONS AND RECOMMENDATIONS

This report presents specific applications of reliability degradation analyses that can be carried out, based on data on a component's performance. These data include occurrences of failures and degradations, repair and maintenance downtimes, and surveillance test frequency. Except for the data on occurrences of degradations, other relevant data are collected as part of probabilistic risk assessments (PRAs) for a nuclear power plant.

In this report, we summarize the concept of reliability degradation analyses focussing on aspects of application. These aspects are based on the reliability degradation modeling techniques discussed in NUREG/CR-5612 and NUREG/CR-5967. We define and give examples of component degraded states, and discuss the practicalities of extracting occurrences of component degradations from available databases. We also demonstrate applications to analyze time trends in degradation data, and to evaluate the effect of maintenance on a component's performance. These kinds of analyses can be carried out using maintenance data as they have useful information about maintenances undertaken on a component.

Additional developments of reliability degradation modeling may focus on developing relationships between degradations and failures, expanding the model to include time-dependency in degradation rates, and in defining optimal frequencies for maintenance. Further work on these areas can be pursued, and procedures may be written to expand on the use and applications of reliability degradation analyses.

5. REFERENCES

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

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APPENDIX A

Trends in Core-damage Frequency Using Information on Component Degradation

In this appendix, we describe the steps involved in converting the component degradation data into trends in core-damage frequency. To do such evaluations, we need to develop trends in a component's failure rate from its degradation rate, but detailed data are not easily available to establish the relationship between the two. However, under certain assumptions and conditions, a component's failure rate can be assumed to show the same behavior as the degradation rate. Here, we describe those assumptions and considerations, and also the steps in obtaining the risk trends (measured in terms of core-damage frequency) from occurrences of degradations. Specifically, the application steps presented here consist of the following analyses:

1. The times of maintenances are analyzed for trends as presented in the main body of the report.

2. The engineering assumptions and considerations are given which are needed to translate the trends in the times of maintenances to the associated trends in failure rates. The associated trends in a component's failure rates are needed to determine the reliability implications.

3. The implied trends in a component's failure rate are used to determine the time trends in its unavailability. These latter are very important since they define how maintenance is affecting unavailabilities. The unavailability time-trends also can be used to determine when more complete maintenances and overhauls are needed.

4. The trends in pump unavailability then are used to determine the associated trends in core damage frequency (CDF) using information from a Probabilistic Risk Assessment (PRA). The PRA is not the plant-specific PRA for any of the plants whose data is analyzed. However, the PRA illustrates how the unavailability trends determined in the previous step can be translated to risk information. These results also are very important since they define how maintenance is affecting risk. The risk trends also can be used to determine when more complete maintenances and overhauls are needed.

A.1 Necessary Engineering Assumptions to Translate the Trends in Maintenance Rates and Degradation Rates to Trends in Component and Piecepart Failure Rates

The time trends determined in Chapter 3 from basic maintenance-log data give the trends in the maintenance rate and equivalent degradation rate, i.e. give the trends in the times of maintenances. These trends in the maintenance rate need to be translated to associated trends in the component's unavailability, i.e. in the RHR pump unavailability and SW pump availability so that the implications of present maintenance practices on pump unavailability can be quantified. This is important since this defines the effect of maintenance on a component's reliability performance. Also, the trends in pump unavailability can be input to Probabilistic Risk Assessment (PRA) models to determine the trends and implications in risk from present maintenance activities.

Using the concepts presented in NUREG/CR-5612 and NUREG/CR-5967, the relative trends in the maintenance rate and degradation rate determined in the previous section can be translated directly to the same relative trends in the component or piecepart failure rate using the following engineering assumptions:

1. Corrective maintenance is carried out on the component or component piecepart when its state of degradation exceeds some threshold which can be fuzzy or ill-defined. Equivalently, this assumption can be stated as: corrective maintenance is carried out on the component or component piecepart when the performance level degrades below some minimal performance level.

2. The degradation level or performance level at which corrective maintenance is triggered can vary with the piecepart, but for a given piecepart is fixed and does not vary because of changes in the maintenance program.

3. The failure rate of the component or piecepart is dominated by causes which progress through a degradation stage which potentially can be detected by maintenance.

4. When failure occurs in a component's piecepart or subsystem for which maintenance data is recorded, then the component subsequently fails. Thus, maintenances are recorded for major pieceparts of the component.

5. After a corrective maintenance or repair after failure, the component or piecepart state may only be partially restored and does not need to be "good as old" or "good as new". However, on average, the same restoration is carried out when a corrective maintenance is performed as when a failure is repaired.

The above assumptions imply certain conditions in the maintenance data and activities which are recorded for trend analysis. Assumption 1 implies the times of maintenances which are analyzed are the times of corrective, and not preventive, maintenances; this appears to apply to the RHR and SW pump maintenance data. Assumption 2 implies a fixed maintenance policy and not one whose criteria or procedures change with the age of the component or piecepart; again, this appears to apply to the RHR and SW data.

Assumption 3 states that component failures are not dominated by sudden catastrophic failures but are dominated by age-related and degradation-related causes, e.g. wear, corrosion, erosion, and brittle fracture. For pumps, and particularly RHR and SW pumps, this is a reasonably valid assumption. Assumption 4 states that recorded maintenance data used for trending generally involve the pieceparts and subsystems of the components which, if they fail, cause the component to fail. That is, the maintenances for which data are recorded are not those performed on minor, incidental pieceparts but on pieceparts which can cause the component to fail. Examining the pieceparts maintained, which is particularly documented in Table 3 for the SW pumps, shows this to be a reasonably valid assumption for the RHR and SW pump data.

Assumption 5 states that restorations after a maintenance or repair do not have to be complete but have to be generally the same for the same piecepart whether a corrective maintenance is carried out or a failure is repaired. This says that, as a policy, replacements or major overhauls are not carried out only after a failure. They can be carried out after a failure but they also can be carried out at a corrective maintenance. This appears to be a reasonable assumption for the RHR and SW pump maintenance data.

Making these assumptions, a failure of a component or piecepart can be viewed as a limit of a degradation process. Since the degradation process must pass through the corrective-maintenance state level, relative trends in the maintenance rate will be reflected as the same relative trends in the component's or piecepart's failure rate. These assumptions can be more formally shown to give the same relative trends in the failure rates using cumulative damage models, which will not be done here.

Thus, based on checks of the above assumptions, we can reasonably conclude that the relative trends in the component failure rates are the same as the relative trends in the maintenance rates on the components. Thus, we can reproduce the trends in the maintenance rates of RHR and SW pumps and call them trends in failure rates:

TIME TRENDS IN COMPONENT FAILURE RATES	
RHR PUMPS:	9.5% [1.1%, 17.8%] per quarter after 20 quarters of age.
SW PUMPS:	3.6% [0.4%, 6.9%] per quarter after 23 quarters of age.

A.2 Translation of Trends in Component Failure Rates to Trends in Component Unavailability

From NUREG/CR-5510 (Ref. 3) and NUREG/CR-5587 (Ref. 4), let α be the relative linear time-trend increase in the component's failure rate. Then, the corresponding relative time-trend increase γ in the component's unavailability is

$$\gamma = \alpha(t-t_0): t > t_0 \qquad \text{(A.1)}$$

where t is the age of the component, and t_0 is the age of the component at which the trend begins. From Equation (A.1), the trend γ in unavailability is simply the trend in component failure rate α times the aging period $t-t_0$. Now, from Equation (A.1), the trend in the maintenance rate is not linear but exponential. However, for small relative trend values, the exponential trend is approximately the same as the linear trend.* Thus, the relative trends in the maintenance rates can be interpreted as the relative linear increases in the component's failure rate. Thus, we can reproduce the previous table, give the component failure rate trends, and call the trends linear increase trends:

RELATIVE LINEAR INCREASE TRENDS IN COMPONENT FAILURE RATE

RHR PUMPS:	9.5% [1.1%, 17.8%] per quarter after 20 quarters of age.
SW PUMPS:	3.6% [0.4%, 6.9%] per quarter after 23 quarters of age.

We can now use Equation (A.1) to calculate the trend in the pump unavailability as a function of age. Figures A.1 and A.2 plot the relative increase in the RHR and SW pump unavailability as a function of their age which is determined from the maintenance data. Figures A.3 and A.4 plot the same relative increase also showing the confidence limits. Thus, in Figure A.1 at an age of 30 quarters (7.5 years), the unavailability of the RHR pump increases by approximately 100% over the baseline value. For the SW pump in Figure A.2, after 33 quarters its unavailability increases by approximately 35% over its baseline value.

The plots in Figures A.1 through A.4 are very important because they determine the implications of the component's unavailability from the times of recorded maintenances. No failure data are used to obtain these results. As stated in NUREG/CR-5612, the failure data on the RHR and SW pumps are too sparse to determine any trending. However, the maintenance data provide sufficient information to identify trends in maintenances, which can be translated to trends in the component's failure rates and trends in unavailabilities, as shown here.

Because of the time-trends in the pump's unavailabilities, more complete overhauls on the pumps will be needed after they reach a given age. The times of more complete overhauls can be determined from the unavailability trend plots shown in Figures A.1 through A.4. For example, to limit the increase unavailability to below 100%, overhauls are needed within 30 quarters (7.5 years) for the RHR pumps. The SW pumps start approaching a 100% increase in unavailability after 43 quarters (approximately 11 years). In actual applications, the analyses shown here would be supplemented by plant-specific assessments and considerations. It is important to note that the time trends in maintenances and associated unavailabilities do not necessarily imply that the maintenances are inefficient. They may be the most efficient possible with the given resources and operational constraints, including technical specification constraints. The results indicate, however, that a more complete maintenance or overhaul will be required, and they are valuable in providing information on when this is needed.

*Expanding the exponential to first order, $e^{b(t-t_0)} \cong 1 + b(t-t_0)$ and hence b is also the relative linear trend increase.

A.3 Translation of Trends in Component Unavailabilities to Trends in Core Damage Frequency

Finally, the unavailability time-trends can be translated to the associated time trends caused in the core-damage frequency and risk. To determine these time-trends, the plant-specific PRA information is required. Such information was not available for the plants containing the RHR and SW pumps, so we use a NUREG-1150 PRA that was employed for demonstrations in NUREG/CR-5510 (Ref. 3).

If φ is the relative increase in the core-damage frequency due to a time trend γ in the unavailability of a given type of component, then φ is given by the formula:

$$\varphi = c_1\gamma + c_2\gamma^2 \qquad \text{(A.2)}$$

where c_1 is the risk importance coefficient for the single component trend effects, and c_2 is the coefficient for the double component trend effects. The above formula accounts for a maximum redundancy of two components, e.g., two redundant RHR pumps. Other terms can be added for higher redundancies. We consider the trend including single component contributions and double component interactions.

From NUREG/CR-5510, the generic importance coefficients, c_1 and c_2, can be determined for pumps:

$$c_1 = 6.9 \times 10^{-2} \qquad \text{(A.3)}$$

$$c_2 = 3.3 \times 10^{-4}. \qquad \text{(A.4)}$$

We will use these coefficients for both RHR and SW pumps. For these coefficient values, the relative increase in pump unavailability γ is given as a percent increase, as previously shown in Figures A.1 through A.4. The relative increase in core-damage frequency, φ, then also is given as a percentage using Equation (A.2). For a given plant specific PRA, c_1 and c_2 would be determined for the particular RHR and SW pumps, as defined in Appendix A of NUREG/CR-5510.

Figures A.5 through A.8 show separately the resulting trends φ in core-damage frequency (CDF) using the determined trends in unavailabilities for the RHR and SW pumps; these can be added to obtain the approximate total trend due to both. The contribution from the interactions between the RHR and SW pump trends also can be included. The separate CDF trend plots for the RHR pump maintenance data and for the SW pump maintenance data are important since they show the way maintenance data can be translated to risk implications, in this case, core-damage frequency. These CDF trend plots show the effects of current maintenances on risk. Like the unavailability plots, the trend plots for core-damage frequency can be used to help determine the age of the pump at which overhauls or more complete maintenances will be required.

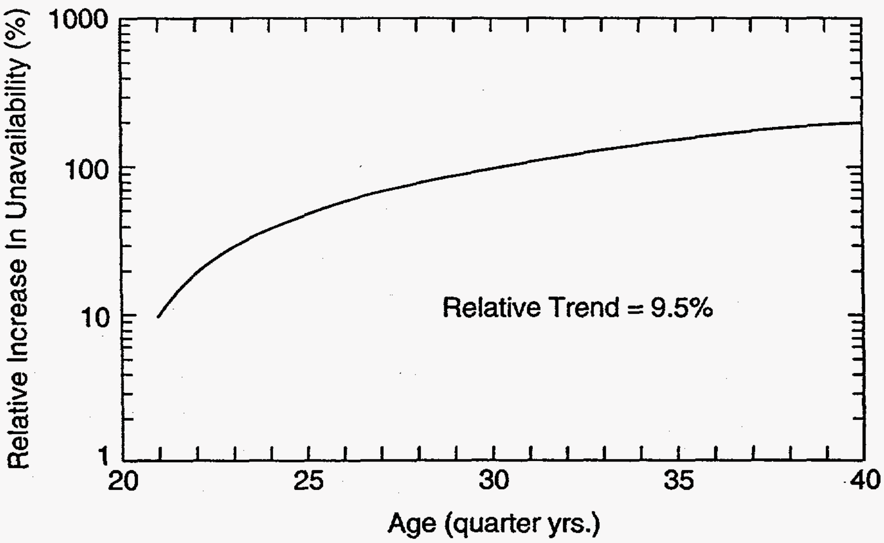

Figure A.1 Relative increase in RHR pump unavailability inferred from maintenance trends: best estimate

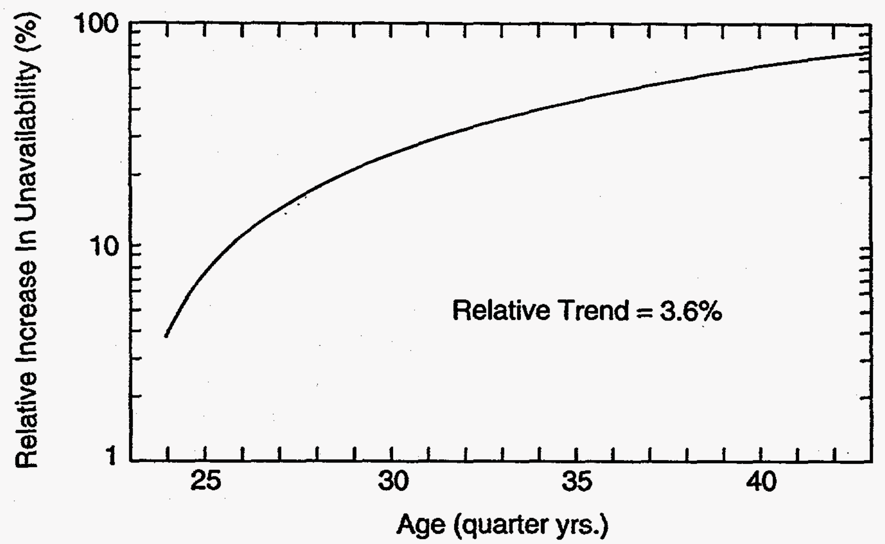

Figure A.2 Relative increase in SW pump unavailability inferred from maintenance trends: best estimate

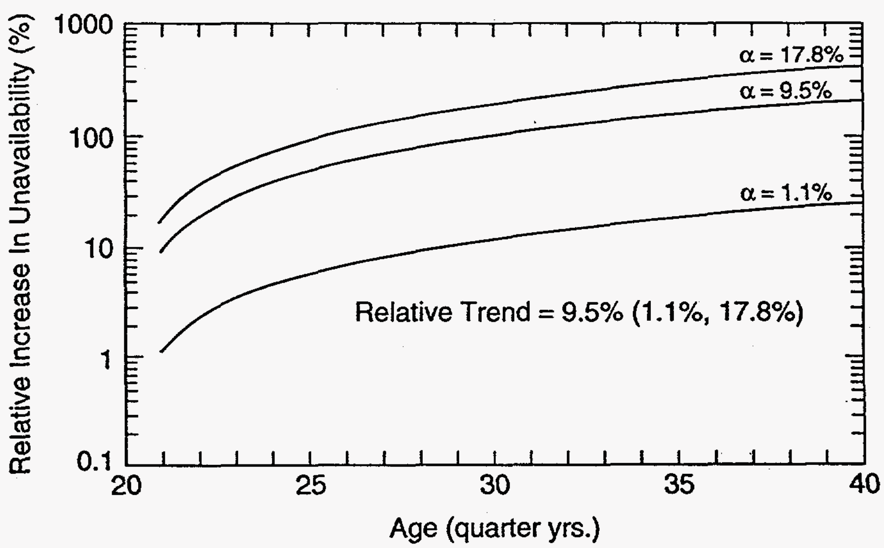

Figure A.3 Relative increase in RHR pump unavailability inferred from maintenance trends, with uncertainties

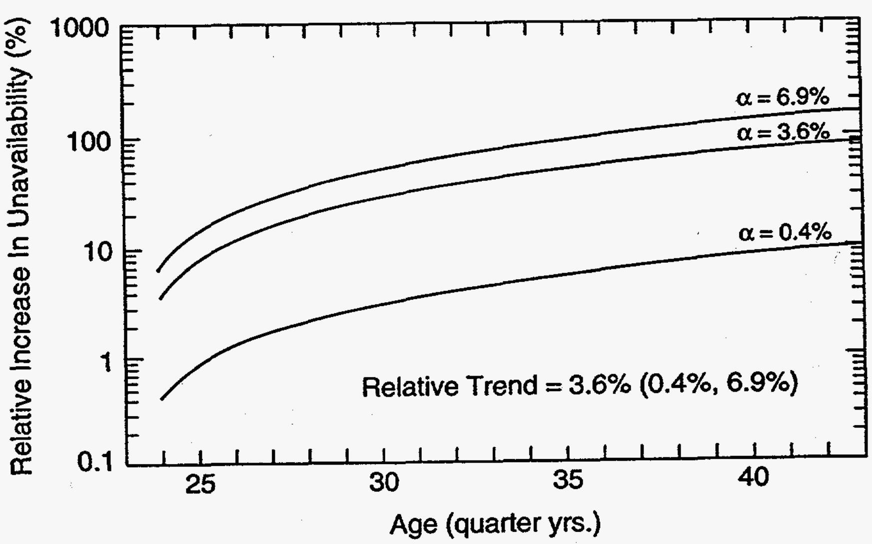

Figure A.4 Relative increase in SW pump unavailability inferred from maintenance trends, with uncertainties

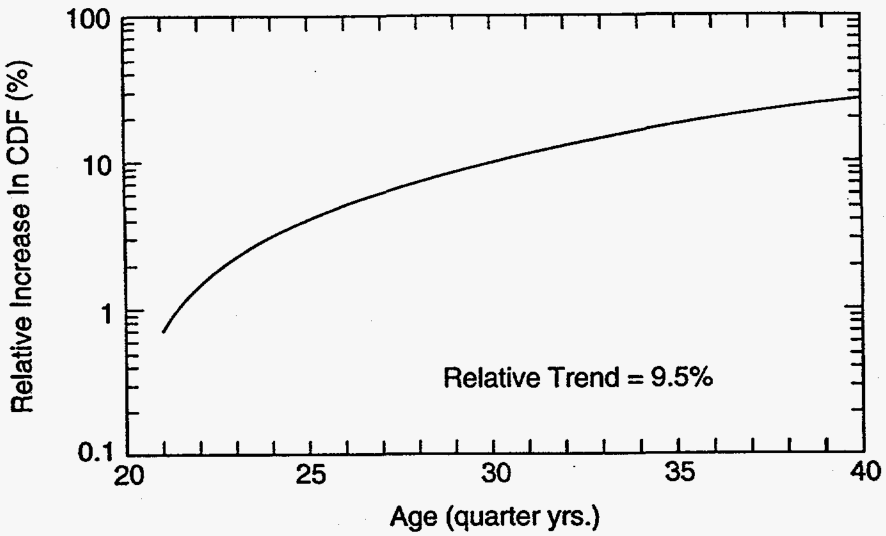

Figure A.5 Relative increase in core-damage frequency due to RHR pump trends

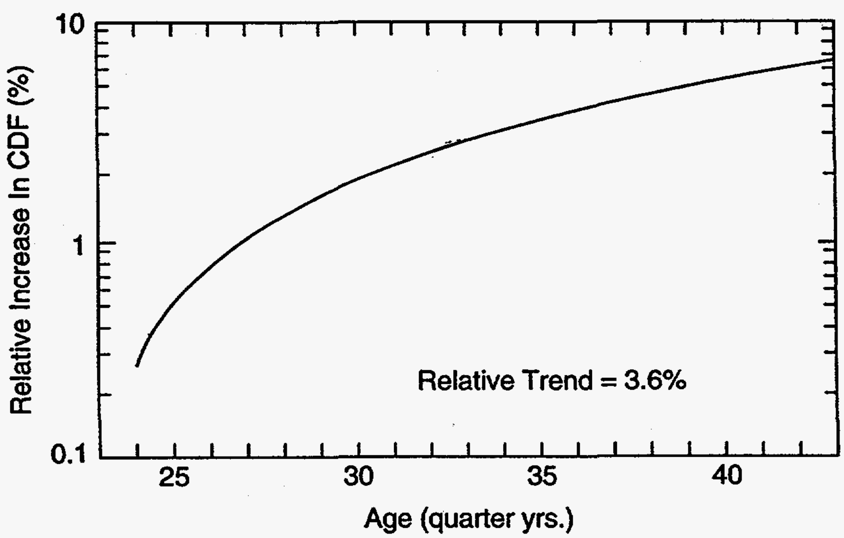

Figure A.6 Relative increase in core-damage frequency due to SW pump trends

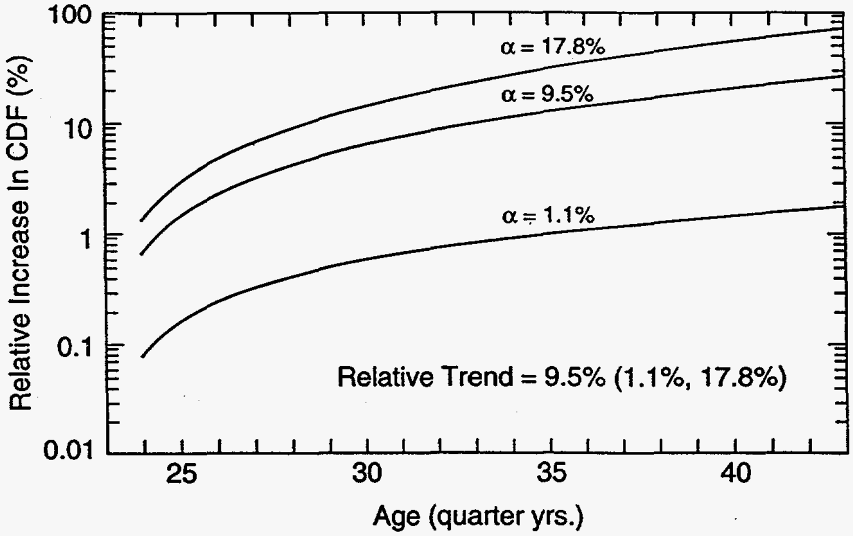

Figure A.7 Relative increase in core-damage frequency due to RHR pump trends, with uncertainties

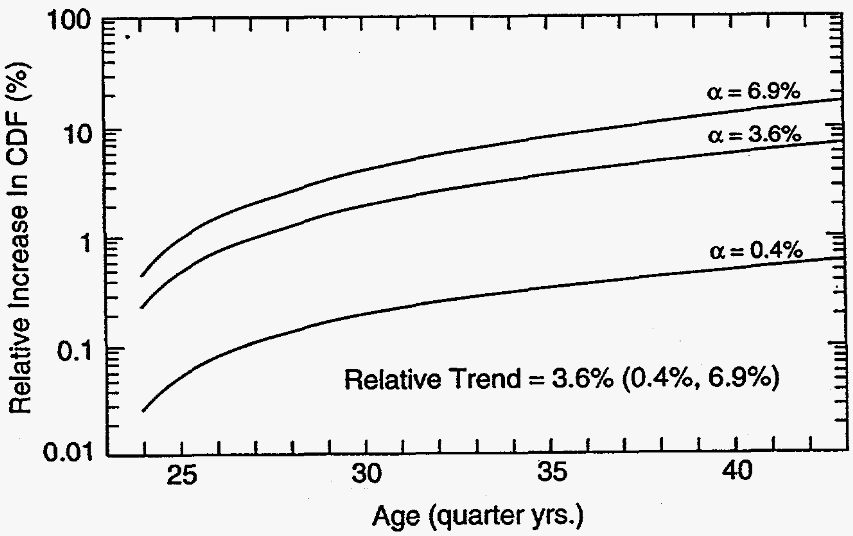

Figure A.8 Relative increase in core-damage frequency due to SW pump trends, with uncertainties

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-6415
BNL-NUREG-52488

2. TITLE AND SUBTITLE

Applications of Reliability Degradation Analysis

3. DATE REPORT PUBLISHED

MONTH	YEAR
February	1996

4. FIN OR GRANT NUMBER

A3270

5. AUTHOR(S)

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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.)*

Brookhaven National Laboratory
Upton, NY 11973-5000

*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 Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

Reliability degradation analysis is the analysis of the occurrences of degradations and the times of maintenance to determine their reliability and risk implications. A program is presented for applying reliability degradation analyses to maintenance data collected at nuclear power plants. As a specific part of the program, time trending of maintenance data is illustrated. Maintenance data on residual heat removal (RHR) pumps and service water (SW) pumps at selected boiling water reactor (BWR) plants are evaluated to show how trends in maintenance data, which generally do not involve failures, can be used to understand effectiveness of maintenance. These trends also are translated to specific impacts on pump unavailability and on core-damage frequency (assuming that the trends in failure rate are the same as those observed for degradation rate). The second application shows the use of reliability degradation analysis to quantitatively evaluate the effect of maintenance, i.e., the quantitative change in component unavailability when no maintenance is performed. Assessment of these impacts are important since they measure the reliability and risk impacts of maintenance and can be fed back to the maintenance program to improve its effectiveness.

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

reactor components - aging, BWR type reactors - reactor components, PWR type reactors - reactor components, failures, mathematical models, reactor maintenance, reliability, Markov process, systems analysis, probability, service life, risk assessment

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE