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AGE-DEPENDENT RISK QUANTIFICATION USING STANDARD MAINTENANCE RECORDS[a]

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INTRODUCTION

The risk associated with the operation of many individual nuclear power plants has been calculated using Probabilistic Risk Assessment (PRA) techniques. To date, PRA calculations have used time-averaged unreliabilities and unavailabilities as inputs such that the calculated risks are a time-average and say nothing of the risk trends. This lack of knowledge of the age-dependent risk and trends has become a source of concern with the recognition of the potential for operation of plants for years beyond the original 40 year license period. The calculation of an age-dependent risk is a fairly simple matter given the age-dependent inputs. The development of valid age-dependents inputs is not such a simple matter. It involves the reduction of large masses of information, which were not recorded for the purposes of PRA, into failure time-histories, and the representation of these time-histories by a model. The results must then be tested to check certain assumptions that are made when the model is applied to the data.

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The specific methodology developed for the reduction of the information and the application and testing of the model is outlined in a stepwise fashion in this paper. Results of the application of the methodology to the Maintenance Records from the Auxiliary Feedwater (AFW) System of an older Pressurized Water Reactor (PWR) are used throughout the paper to demonstrate the methodology. In addition, a very brief discussion of the AFW system is presented to allow better understanding of the application.

AUXILIARY FEEDWATER SYSTEM: A BRIEF DESCRIPTION

The basic function of the Auxiliary Feedwater (AFW) System is to remove heat from a nuclear power plant core through heat exchange in the steam generators which are the interface between the primary (nuclear) water system and the secondary (steam) water system. The system function is performed during normal plant start-ups and shutdowns and during emergencies following loss of the main feedwater system. The system operates an average of 100 hours each year. The AFW systems in use generally consist of two motor driven pumps, one steam-turbine driven pump, and piping and valves. These components pump, carry and control water to the steam generators. See Figure 1 for a schematic representation of the AFW System, including relevant nomenclature.

STEP-BY-STEP PROCEDURE FOR AGING RISK ANALYSIS

The following steps refer to the flow diagram shown in Figure 2.

Step 1 - Obtain Component Time-Histories

The first step is to obtain the information required to develop time-histories for the systems/components to be analyzed. Possible sources of information include: maintenance records, material histories, operating records and plant process computer data. Comparison of data from numerous sources will aid in the development of the most reliable component time-histories. Although very little attention is given to this step in this paper, it should not be construed that the development is trivial or unimportant. To the contrary, the component time-histories are the backbone of the analysis and may be extremely difficult to develop. Poorly developed time-histories can result in either the false identification of aging where none is occurring or the false conclusion that aging is not occurring when it actually is. Of course, the latter case will result in the underestimation of risk. An overview for data base development which could be applied to the development of component time-histories was prepared by the Yankee Atomic Electric Company[1].

Step 2 - Define Relevant Component Failure Modes

Step two consists of the identification of the failure modes that will contribute to an increase in plant risk. These failures modes should be obtained from a plant-specific PRA. Caution should be taken not to ignore failure modes that were removed from consideration in a PRA at an early stage due to their low contribution to risk (e.g. removed from the cut sets by truncation). These failure modes may become more important, potentially even controlling, later in system life. A list of the seventeen failure modes obtained from a NUREG 1150 PRA study for a PWR[2] and adapted to the system from which the maintenance records were obtained is shown in Table 1. Adequate data to support development of component time-histories for the two testing and maintenance failure modes was not available from the maintenance records, therefore these two modes were not quantified even though they may be an important contributor to the age-dependent risk increase associated with the operation of the AFW system.

Step 3 - Define Failure Criteria

The determination of whether a particular record from the information gathered in step one describes the occurrence of one of the failure modes listed in step two is often subjective. This is because the information in the records was not designed for the development of failure tracking, therefore the information is imprecise as to the exact condition of the component. In order to reduce this subjectivity and to facilitate a more repeatable development of failure time-histories, two sets of failure criteria for each failure mode are developed.

The first set of criteria are developed for what is called a BROAD definition of failure. The criteria consist of a list of those conditions which are considered to possibly describe a failure, but which may only describe a problem which was fixed before it was actually necessary to remove the component from service. An example would be as follows:

Steam Driven Pumps - A failure record is considered to describe a BROAD failure if it states one of the following:

1. That conditions existed that led to a bearing repair or replacement,

2. That conditions existed that led to the repair of the trip/governor valve,

3. That conditions existed that led to the repair of the pump for some unspecified reason.

This last case is very broad, and is a catchall for those records that state that repairs have occurred, but that give no clue as to why the repairs took place. Records that are removed from consideration as failures by the broad definition include those due to preventive maintenance programs, design changes, functionally unimportant boundary leaks, gauge replacements, and minor deficiency repair.

The second set of criteria are developed for what is called a NARROW definition of failure. The criteria consist of a list of those conditions which are considered to describe the actual occurrence of a failure. These failures either resulted in an automatic loss of component function or the immediate manual removal of the component from service to avoid damage. An example would be as follows:

Steam Driven Pumps - A failure record is considered to describe a NARROW failure if it states one of the following:

1. That a pump trip occurred,
2. That a gross loss of lubrication occurred,
3. That erratic control by the trip/governor valve occurred.

The narrow failures are a subset of the broad failures. The use of the broad and narrow definitions of failure enables a risk quantification to be done using data describing failures which certainly took place, without the masking effect caused by information in which less confidence is placed. At the same time, the quantification of a combination of the actual and possible failures enables the identification of risk trends which should be further investigated to check their validity. The setting of these criteria is not simple and may involve some iteration with their application as described in step four.

Step 4 - Apply the Failure Criteria to the Component Time-Histories

The component time-histories are reviewed in step four to identify all potential and actual failures. Update of the failure criteria defined in step three is performed, as necessary, to incorporate knowledge gained by the in-depth review of the data.

Table 2 shows an example of the application of the failure criteria listed in step three to a portion of the Maintenance Records for the Turbine Driven Pumps. Only the descriptive fields that were useful in determining whether a failure had occurred are shown: "Problem Description" and "History Summary."

Step 5 - Construct Failure Timelines

It is useful to construct graphical representations of the data at this point, before continuing with any statistical analysis. This provides a "feel" for the data and some simple trends can be immediately identified. However, it is difficult to determine without statistical analysis of the data whether the apparent trends are statistically significant. An example of a failure timeline is shown in Figure 3.

Step 6 - Perform Statistical Analysis

The next step is to model the age-dependent behavior of the components for which time-histories have been developed and to estimate model parameters from the data. The model chosen to describe the data is of an exponential form which is referred to in this paper as the exponential failure rate.

$$\lambda(t) = \lambda_0 e^{\beta t}$$

Having chosen the model, statistical techniques are applied to make inference about the aging rate β, the initial failure rate λ_0, and the rate of failure $\lambda(t)$. The method follows work of Cox an Lewis[3]. Some of the details of the development of the equations are presented in a Technical Report on a survey of various data sources to develop failure rates[4]. The full details will be presented in two reports now in preparation[5,6]. In this paper, the general concepts are stated, but the specific equations are not presented.

The input for the broad and narrow definitions of failure are placed in an appropriate format for computer code manipulation and then the following assumptions are checked:

Similar components have a common aging rate and therefore can be pooled for analysis (β is the same for all members of the group),

The aging rate associated with a group of components is zero ($\beta = 0$),

Similar components, having a common aging rates, also have a common initial failure rate and therefore can be pooled for analysis (λ_0 is the same for all members of the group),

And finally, the aging model chosen (exponential) adequately describes the data.

Step 6A - Test Data Pooling Assumptions for Homogeneous Aging Behavior

The assumption that similar components have the same aging rate, β, is the first to be checked. The null hypothesis can be stated as: For a group of N components, $\beta_1 = \beta_2 = \ldots = \beta_N$. The test statistic is based on the difference between the maximum likelihood estimator of β for an individual component and the maximum likelihood estimator for the rest of the components taken as a group. The overall significance level is based on the Bonferroni inequality and rejected at 0.05 or less. If the pooling assumption is rejected, outliers are identified. A decision to delete an outlier should be based on an understanding of the physical process which resulted in the observed anomalous behavior.

A graphical presentation of the results of the evaluation is made to allow for a visual understanding of the test. The example graph in Figure 4 shows the maximum likelihood estimator for the aging rate β, and the associated 95% confidence interval for each component that indicated failure. Qualitative analysis can be made by checking the estimators and intervals to see if they overlap in a reasonable fashion. Also plotted for each component is the maximum likelihood estimator of the value of β for all the OTHER components taken as a group. The spread between the individual and group estimators is used to develop the statistic for checking the assumption of homogeneous value of β.

Figure 4 represents a case where the hypothesis was accepted. Visually, the graph demonstrates that the confidence intervals all overlap and in this case all individual estimates of β lie within the individual confidence intervals of all the other components.

Qualitatively, the pooling of the data for analysis appears acceptable. The quantitative test indicates a significance level of 1.00. This statistically supports the conclusion that the grouping is reasonable.

The results of this statistical test are shown in Tables 3 and 4 for each of the 14 groups of data developed from the AFW System Maintenance Records. Only one of the fourteen groups, the narrow Turbine Driven Pump fails to run, resulted in rejection of the constant failure rate hypothesis. In the absence of further data on the Turbine Driven Pump, the record was split for further analysis, thus a total of 15 groups of data were formed.

Step 6B - Test For Statistically Significant Aging

The next assumption checked is that the data were actually created by an age-independent process, i.e., the failure rate is constant and the aging rate is zero. The null hypothesis can be stated as: For a group of N components, $\beta_1 = \beta_2 = \ldots = \beta_N = 0$. The test statistic is applicable regardless of the form of the age-dependent failure rate and is a measure of the variation between the average of the failure times and the center of the observation period. If the significance level is less than 0.05, and therefore the hypothesis of constant failure rate is rejected, then the component shows statistically significant aging. The test is one-sided, testing $\beta = 0$ against the alternative $\beta > 0$.

In the application of this test to the 15 groups of data developed from the AFW System Maintenance Records, only four were found to show statistically significant aging. The results are displayed in Tables 3 and 4. It is interesting to note that if the first assumption had not been checked and therefore the turbine driven pumps had remained grouped, then the pump group would have demonstrated no aging. With the separation of the two pumps, based on the rejection of the homogeneous beta assumption, one of the pumps is found to be aging and the other not.

Step 6C - Test Data Pooling Assumptions for Homogeneity of λ_0

The adequacy of the assumption that the initial failure rate, λ_0, for similar components is equal is checked for all component groupings showing significant aging. The null hypothesis can be stated as: For a group of N components, $\lambda_{01} = \lambda_{02} = \ldots = \lambda_{0N}$. The test statistic is developed in an analogous fashion to that for the testing of homogeneity of β. The graphical presentation is also analogous and an example is not given. The hypothesis was accepted for the four component groupings considered to be aging as indicated in Tables 3 and 4.

Step 6D - Check the Exponential Aging Modeling Assumption

Most age-dependent failure rate models have one common feature: when the time becomes large, the models predict aphysically large failure rates. The exponential form used in this methodology is certainly prone to this problem. However, this is not serious if the data are adequately described over the time period of collection and if the results are not extrapolated far into the future. The problem of extrapolation is avoided by only predicting risk a few years past the date of data collection. The problem of adequate description of the data by the model is checked in this step by development of a statistic which measures the spread between the time when the various failures actually occurred and the time when they would be expected to occur based on the model and estimated parameters. The Kolmogorov-Smirnov test is used to test the hypothesis: The failure times were generated by a Poisson process with an exponential failure rate and the parameter values as estimated.

Once again, a graphical presentation is made to allow for qualitative understanding of the statistical test results. The presentation is known as a Quantile-Quantile (QQ) plot (Figure 5). Plotted on the X-axis are the actual failure occurrence times and plotted on the Y-axis are the calculated expected occurrence times. Since the axis scales are identical, the intersection of the first failure, the second failure, etc., should show no marked divergence from the 45 degree line if the model is adequate. If the overall plot shows a marked divergence from the 45 degree line, such as a large "S" shape so that the intersections are much lower in one half of the plot and much higher in another, then the exponential aging model would be considered inadequate to describe the data. A fairly good fit is shown in Figure 5. The results of the statistical test for the four groups of data considered to be aging indicated acceptance of the hypothesis that the exponential model adequately described the data.

Step 7 - Calculate $\lambda(t)$

For all sets of components that survive the screening of step six, the estimated value of $\lambda(t)$ and its associated confidence interval are calculated as a function of time. The maximum likelihood estimator of the failure rate is calculated at any desired time using the maximum likelihood estimators of aging rate and initial failure rate. Standard statistical analysis techniques are used to make joint inference to develop the confidence interval at each time.

Step 8 - Quantify the Age-Dependent Risk

The final step of the methodology is to calculate the risk incurred by the plant as a function of time, using the results from above as age-dependent basic-event input to a PRA. The methods for use of PRAs are somewhat plant specific and the details of the quantification are not presented here. The basic approach is to convert the $\lambda(t)$ and confidence interval for each component into the necessary parameters which describe the distribution for each associated basic event. This will be very simple for risk analysis tools which use failure rate and distribution as the basic event input. It is somewhat more complicated for risk analysis tools which use unreliability and unavailability for the basic event input, but methodology for conversion of distributions can be developed. Time-averaged failure rates are used for the remainder of the inputs, including those that were not evaluated for aging and those for which the evaluation was performed and for which statistically significant aging was not found.

The results for the single time dependent event for the narrow failure case and for the three age-dependent events for the broad failure case are shown in Figures 7 and 8, respectively. A NUREG 1150 PRA was used with necessary modifications to reflect the source of the component failure rate information. The resulting risk is represented as core damage frequency plotted as a function of time. The first time plotted is representative of the end of the data collection period and is the twelfth year of plant operation. The data is extrapolated to fifteen years, and while the risk at fifteen years is not expected to equal the value shown, the indicated trends are useful for making decisions. The base line in each figure represents the risk calculated at time zero, using the initial failure rate for the components which are showing time dependent aging and the time-averaged failure rates for the balance. The initial risk is slightly less in the broad failure case because the initial age-dependent failure rates are less than the time-averaged failure rates. This is as would be expected if the time averages are correct.

In the narrow case (Figure 6), the risk has not increased at the "present" time (year 12). The trend for the future indicates that the maintenance program continues to be successful with only a slight risk increase due to steam binding of the pumps. Based on this information, an engineer might recommend that no action be taken at present to change the plants maintenance procedures and that another risk calculation to check the steam binding trend and to look for developing trends be performed in a year.

In the broad failure case (Figure 7), the risk has tripled at the "present" time and the trends are for rapid increase in the near future. Once again a rather minor effect is seen at the end of the period for the steam binding failure mode, however, two new failure modes are seen in the broad case, and they have a noticeable effect on risk. The dominant mode is that of pump discharge check valves failing to shut. This failure, in combination with the failure of the associated pump results in the recirculation of all flow backwards through the idle pump, and therefore a complete failure of the system if no recovery action is taken by the operator. (Note that the risk values calculated DO NOT include recovery). The trend is for near term increases in this effect. The other failure mode seen is the failure of the Turbine Driven Pump to run. This mode has caused a doubling of the initial failure rate at the "present" time. The trend for this mode is fairly flat, indicating that the turbine-driven pump failure to run is so high that the unreliability is nearly one, i.e., the pump is sure to fail sometime during its mission. Note that this is not an artifact of the model, it is a reflection of the high unreliability of the pump at the "present" time.

Since the second plot of risk is based on a broad definition of failure, it is also one in which an engineer would have less confidence. As opposed to immediately taking action to adjust the maintenance and testing programs associated with the pump discharge check valves and the Turbine Driven Pump, the engineer might recommend a more thorough evaluation of the failure data for these two components to develop higher confidence in a set of data on which to repeat the statistical analysis. The results would then be combined with the age-dependent components identified by the narrow definition of failure, in this case the pump steam binding, and the risk recalculated. The engineer's search for more information might result in identification of only one or two failures out of the original ten potential failures being considered as actual, with the others defined as non-failures. The resulting analysis might well show no aging trend. On the other hand, the failures may be found to be a safety concern and action would then be warranted to arrest the trend. In this case, another analysis might be performed in six months to check the results of the actions taken to control the risk.

CONCLUSIONS

The following conclusions can be made based on the development and application of the methodology:

The methodology for the age-dependent quantification of risk provides current age-dependent risk and near-term trends that can be used to check the ability of plant maintenance and testing programs to control risk at an acceptable level. The results cannot be used to predict far future risk because of the great difficulty in accounting for possible human intervention and corrective action.

The data must be developed carefully to avoid inclusion of events that are not actually failures. Such inclusions may either mask actual risk trends of concern or identify trends that are not of concern.

The former is clearly a safety concern, while the latter may result in a safety concern due to the inappropriate use of limited resources. Additionally, the data must be developed carefully to avoid exclusion of events that might be failures. Such exclusion can result in the failure to identify trends. A narrow and broad set of failure time-histories may be developed to accomplish these two tasks simultaneously,

The assumptions made in pooling components and applying models must be statistically checked to avoid problems similar to those which arise from poor data development.

The methodology described provides features for both the careful development and statistical analysis of data used to quantify age-dependent risk.

REFERENCES

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3. D. R. Cox and P. A. W. Lewis, 1966, The Statistical Analysis of Series of Events, London: Chapman and Hall (US distributor: Halsted Press).

4. A. J. Wolford et al., 1989, A Survey of the Nuclear Plant Reliability Data System and Licensee Event Reports to Determine Linear Failure Rates, EGG-SSRE-8603.

5. A. J. Wolford et al., in preparation, Aging Risk Assessment Methodology: Demonstration Study on a PWR Auxiliary Feedwater System, NUREG/CR-5378.

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NOTICE

TABLE 1 AUXILIARY FEEDWATER SYSTEM COMPONENT FAILURE MODES, DESCRIPTIONS AND RELEVANT FIGURE 2 COMPONENT NUMBERS

Failure Mode	Description
AFW-ACT-FA-PMP*	No actuation signal to pump. * MDP-A,B
AFW-ACT-FA-*	No actuation signal to steam supply valve. * AOV-A,B
AFW-AOV-LF-*	Loss of flow through steam supply valve. * AOV-A,B
AFW-CKV-FT-CV*	Check valve fails to open. * 3" - CV-H,I,J 4" - CV-B,C 6" - CV-A,D,E,F,G Main Steam: 3" - CV-K,L,M
AFW-CKV-OO-CV*	Backflow through pump discharge check valve.* CV-A,B,C
AFW-MOV-PG-*	Motor operated valve plugged. * MOV-A,B,C,D,E,F
AFW-PMP-LK-STMBD-*	UNDETECTED, simultaneous leakage through one of the following combinations of check valves: At least one of CV-H,I,J PLUS Either CV-D & F or CV-E & G PLUS CV-A for *TDP or CB-B FOR *MDP-A CV-B or CV-C for *MDP-B.
AFW-PMP-FR-*	Pump fails to run. * TDP, MDP-A,B
AFW-PMP-FS-*	Pump fails to start. * TDP, MDP-A,B
AFW-PMP-TM-*	Pump unavailable due to testing or maintenance. * TDP, MDP-A,B
AFW-PSF-FC-XCONN	Flow diversion to opposite unit through motor operated valves. * MOV-G,H,I,J
AFW-PSF-LF-*	Faults in pipe segments. * Various pipe segments.
AFW-TNK-VF-CST	Insufficient water available from 110,000 gallon condensate storage tank.
AFW-XVM-PG-XV*	Manual valve plugged. * Various manual valves.
AFW-*-TM-*	Component unavailable due to testing or maintenance. * Any AFW component in testing or maintenance when it is required to be in service.
ACP-TAC-LP-BUS*	AC power not available. * 1A,1B
DCP-TAC-LP-BUS*	DC power not available. * 1A,1B

TABLE 2 EXAMPLE OF MAINTENANCE RECORDS BEFORE SCREENING

PROBLEM DESCRIPTION	HISTORY SUMMARY	FAILURE CLASSIFICATION
GROSS OIL-LOW DISCHARGE PRESSURE	RENEWED THRUST BEARING LININGS	NARROW
EXCESSIVE DISCHARGE PREE-PT15	REDUCED SPEED OF PUMP AT GOVERNOR	BROAD
BODY TO BONNET LEAK	RENEWED BONNET GASKET	------
GOV VALVE WILL NOT CONTROL PUMP SPEED	FIXED SATISFACTORY	NARROW
REFUEL PMS	DID PMS CHECKS	------
VARIOUS REPAIRS	REPAIRED AND TESTED GOV TRIP VALVE	BROAD
DRAIN, CLEAN, INSPECT SUMP REFILL	DRAINED OIL, CLEANED SUMP	------
SIGHT GLASS HAS OIL LEAK	TIGHTENED SIGHT GLASS	------
REPLACE GAUGE AND REPAIR LEAK	REPLACED GAUGE	------
OIL LEAK ON PUMP	REPAIRED PUMP AND HELD PM CHECK	BROAD
PMS AS PER MMP-P-FW-004	VOID	------
OUTBOARD PUMP BEARING THROWING OIL	RENEWED THRUST BEARING	BROAD
OIL SEAL PACKING LEAK	RENEWED THRUST SHOE	BROAD
OVERSPEED TRIP VALVE TRIPS	STRAIGHTENED LINKAGE	NARROW

TABLE 3 RESULTS OF STATISTICAL ANALYSIS FOR THE BROAD FAILURE CASES

FAILURE MODE	SIGNIFICANCE LEVEL FOR TESTING EQUALITY OF β[a]	SIGNIFICANCE LEVEL FOR TESTING $\beta = 0$[b]	SIGNIFICANCE LEVEL FOR TESTING EQUALITY OF λ_0[a]	CONCLUSION
AFW-PMP-FR-TDP	0.006	0.09[d]	----[e]	NOT HOMOGENEOUS
AFW-PMP-FR-TDP (unit 1 only)	N/A[c]	0.91	----[e]	NOT AGING, SINGLE COMPONENT
AFW-PMP-FR-TDP (unit 2 only)	N/A[c]	0.002	N/A[c]	AGING, SINGLE COMPONENT
AFW-PMP-FS-MDP	0.67	0.46	----[e]	NOT AGING, HOMOGENEOUS
AFW-PMP-FR-MDP	0.31	0.13	----[e]	NOT AGING, HOMOGENEOUS
AFW-MOV-PG	1.00	0.06	----[e]	NOT AGING, HOMOGENEOUS
AFW-MOV-FC	1.00	0.60	----[e]	NOT AGING, HOMOGENEOUS
AFW-PMP-STMBD	0.71	0.03	1.00	AGING, HOMOGENEOUS
AFW-CKV-OO	1.00	0.0001	0.66	AGING, HOMOGENEOUS

a. A value of 0.05 or less indicates strong evidence that the components do not have the same aging rate, β, or the same initial failure rate, λ_0.

b. A value of 0.05 or less indicates strong evidence that the components failures were not generated by a constant failure rate process.

c. Equality comparisons can not be made for a single component.

d. Without separation of components based on rejection of test for homogeneous β, the Turbine Driven Pumps would show no statistically significant aging trend.

e. Not checked, because aging was not statistically significant.

TABLE 4 RESULTS OF STATISTICAL ANALYSIS FOR THE NARROW FAILURE CASES

FAILURE MODE	SIGNIFICANCE LEVEL FOR TESTING EQUALITY OF β[a]	SIGNIFICANCE LEVEL FOR TESTING $\beta = 0$[b]	SIGNIFICANCE LEVEL FOR TESTING EQUALITY OF λ_0[a]	CONCLUSION
AFW-PMP-FR-TDP	0.13	0.80	----[c]	NOT AGING, HOMOGENEOUS
AFW-PMP-FS-MDP	0.11	0.10	----[c]	NOT AGING, HOMOGENEOUS
AFW-PMP-FR-MDP	0.69	0.30	----[c]	NOT AGING, HOMOGENEOUS
AFW-MOV-PG	1.00	0.23	----[c]	NOT AGING, HOMOGENEOUS
AFW-MOV-FC	0.32	0.68	----[c]	NOT AGING, HOMOGENEOUS
AFW-PMP-STMBD	0.71	0.03	1.00	AGING, HOMOGENEOUS
AFW-CKV-OO	----[d]	----	----[c]	NO DATA

a. A value of 0.05 or less indicates strong evidence that the components to not have the same aging rate, β, or the same initial failure rate, λ_0.

b. A value of 0.05 or less indicates strong evidence that the components failures were not generated by a constant failure rate process.

c. Not checked, because aging was not statistically significant.

d. No actual failures for this mode.

FIGURE 1 SCHEMATIC DIAGRAM OF A PRESSURIZED WATER REACTOR AUXILIARY FEEDWATER SYSTEM.

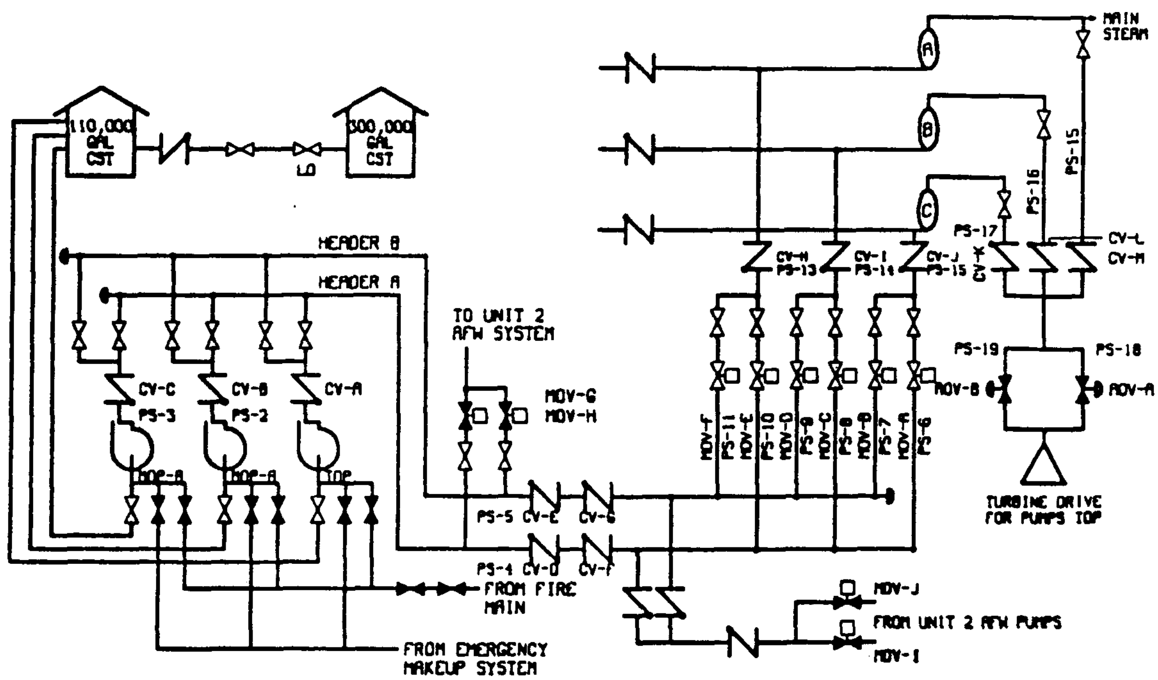


FIGURE 3 FAILURE TIMELINE FOR THE TURBINE DRIVEN PUMPS.

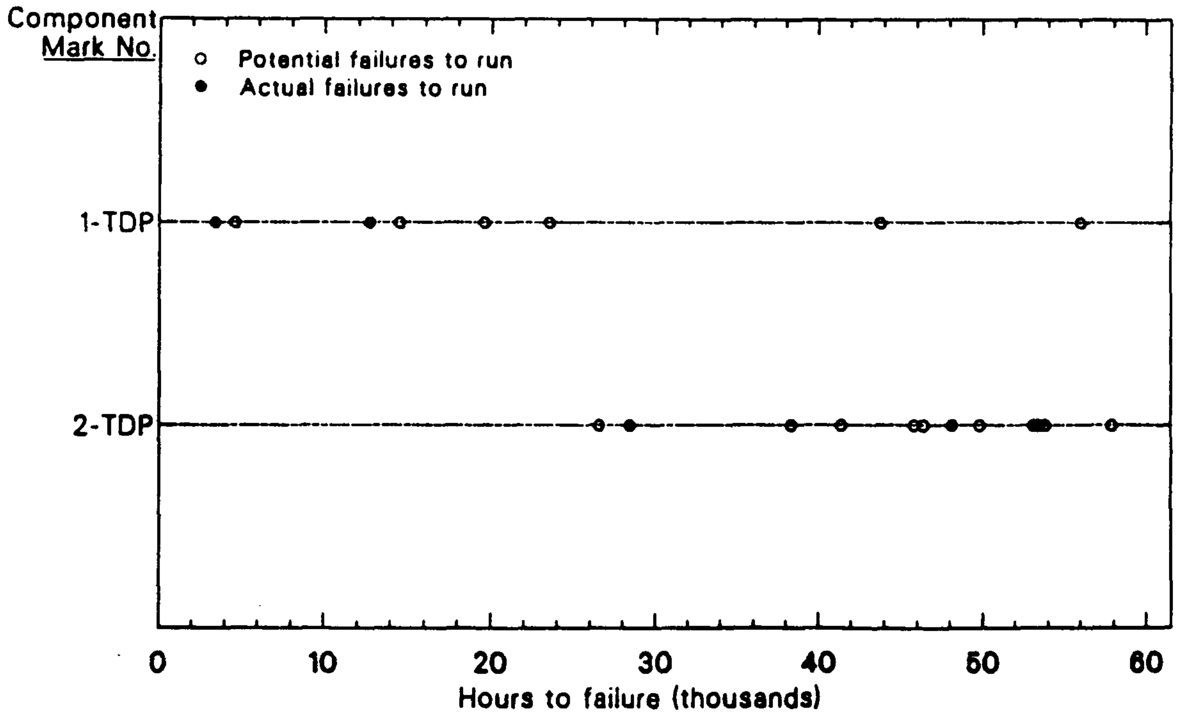


FIGURE 2 STEP-BY-STEP PROCEDURE FOR AGE-DEPENDENT RISK QUANTIFICATION.

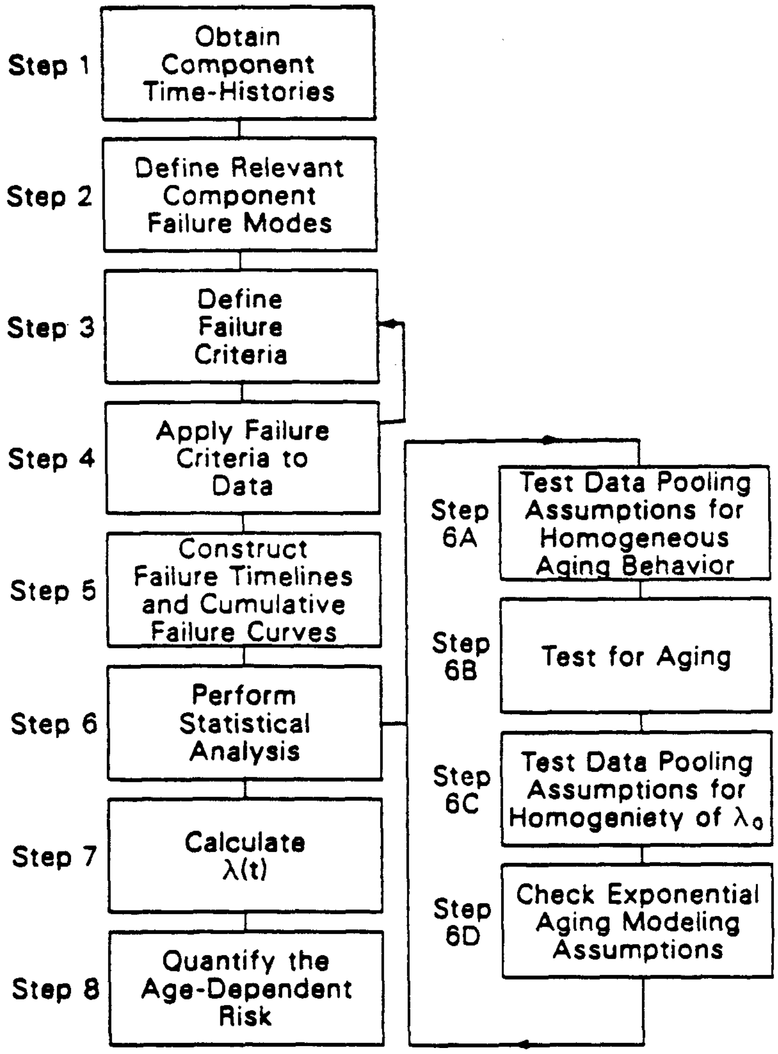
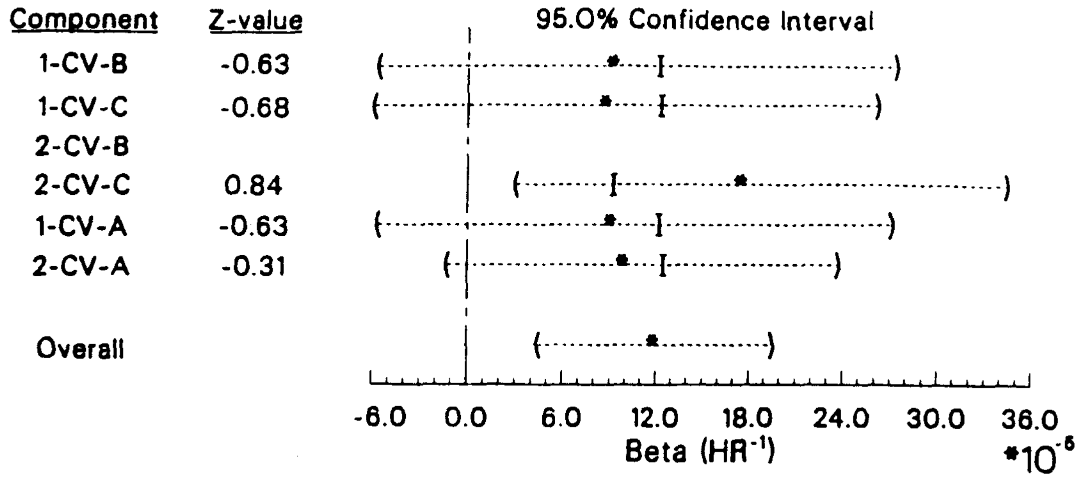


FIGURE 4 COMPONENT COMPARISONS FOR β FOR PUMP DISCHARGE CHECK VALVES. HYPOTHESIS OF SIMILAR β ACCEPTED: COMPONENT DATA CAN BE POOLED.



Significance level for testing equality of betas = 1.00

(- Lower bound
) - Upper bound
* - Maximum likelihood estimate for only the associated component
I - Maximum likelihood estimate for all but the associated component

FIGURE 5 QUANTILE-QUANTILE PLOT FOR THE TURBINE DRIVEN PUMP EXHIBITING STATISTICALLY SIGNIFICANT AGING.

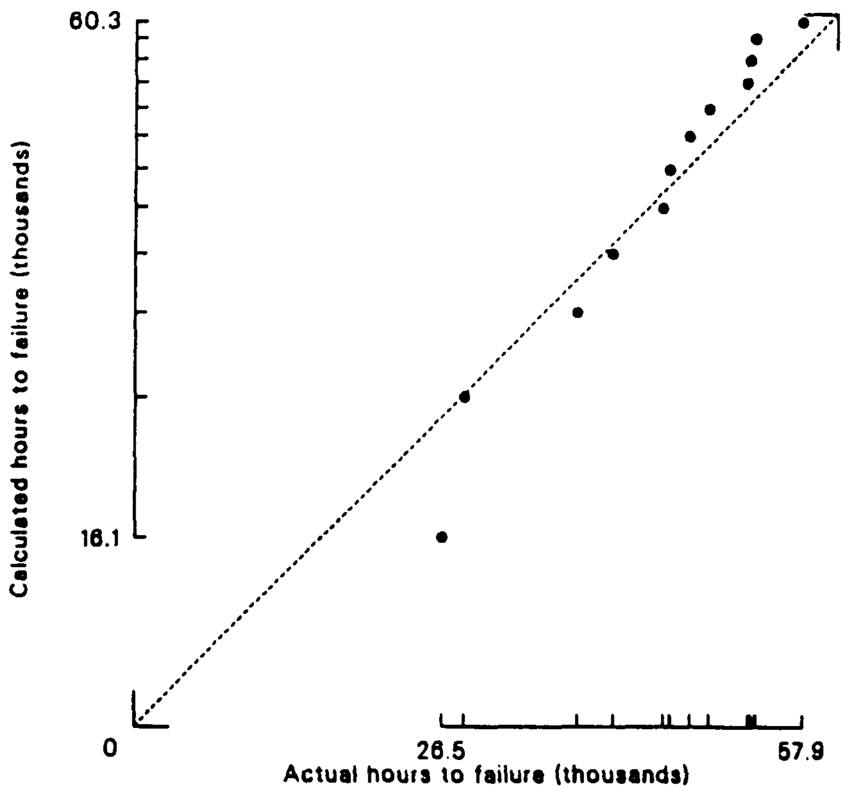


FIGURE 6 NEAR TERM PREDICTION: CORE DAMAGE FREQUENCY SHOWING CONTRIBUTION OF AGE-DEPENDENT EVENTS, NARROW DEFINITION OF FAILURE.

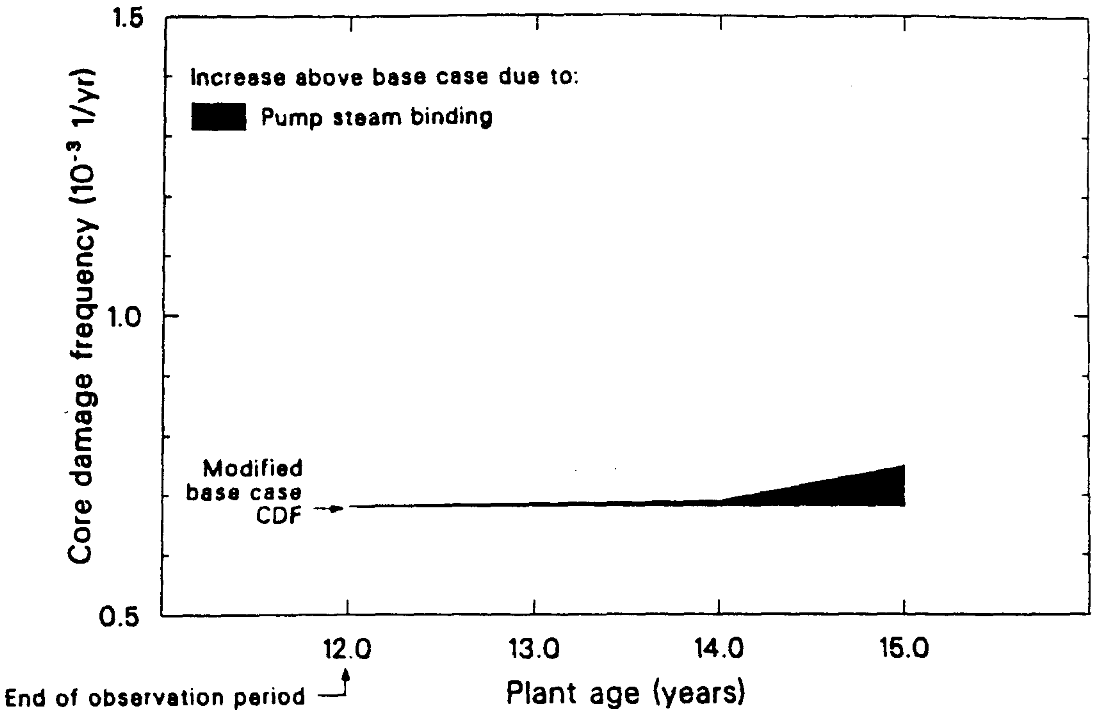
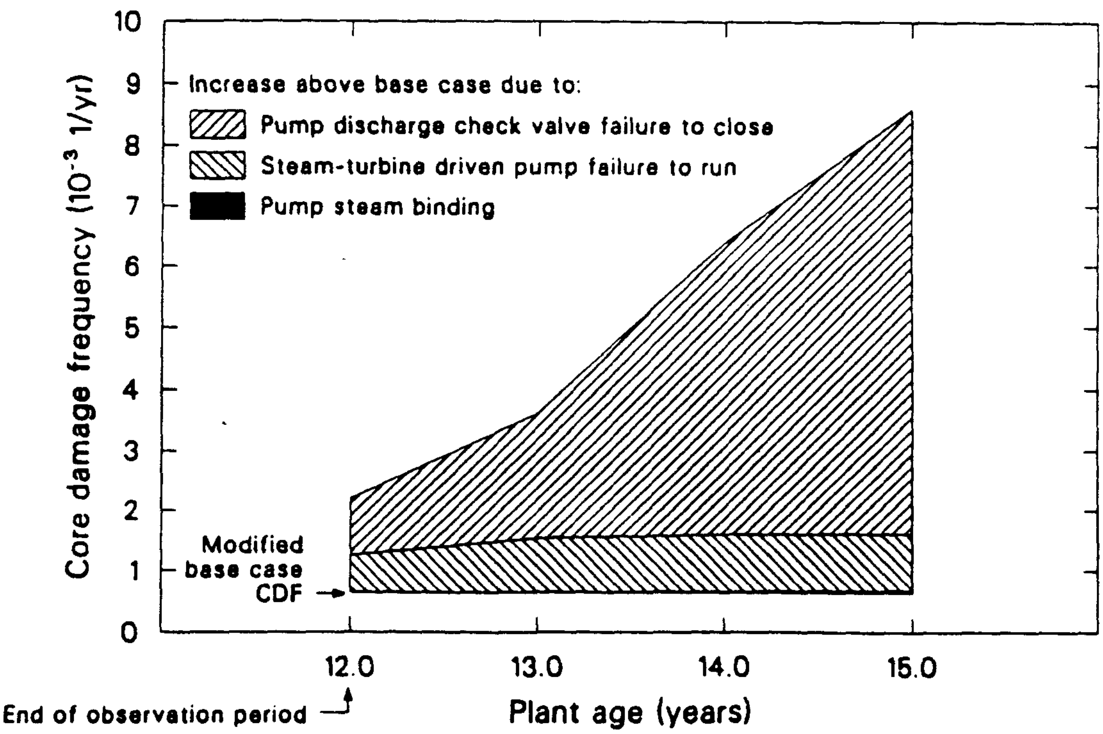


FIGURE 7 NEAR TERM PREDICTION: CORE DAMAGE FREQUENCY SHOWING CONTRIBUTION OF AGE-DEPENDENT EVENTS, BROAD DEFINITION OF FAILURE.



AGE-DEPENDENT RISK QUANTIFICATION USING STANDARD MAINTENANCE RECORDS. A.J. Wolford, C.L. Atwood and W.S. Roesener, Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, ID 83415. (Work suported by the U.S. Nuclear Regulatory Commission, Office of Research, Under DOE Contract No. DE-AC07-76ID01570).

A methodology for the analysis of standard maintenance records in order to detect and quantify changing failure rates is presented. The methodology is applied to the records for components from one system of a nuclear power plant and the results of the analysis are then used to quantify core damage frequencies and uncertainties. The first step of the methodology is to determine the times of failure occurrences from plant maintenance records. Next, inferences about the time dependent nature of the data are made following the methods of Cox and Lewis[1]. The specific aging model assumes a hazard function of the form $\lambda(t) = \exp(\alpha + \beta t)$ which we refer to as the exponential aging model. The data is first tested to see if a null hypothesis of no increasing failure rate should be rejected. If rejected, maximum likelihood approaches are employed for joint inference about α and β. Diagnostics are developed and used to confirm that component data pooling assumptions made appear to be correct. Constant equipment failure rate is employed when the Null is not rejected. Using the parameters and joint confidence region, the time-dependent hazard function is evaluated at various times. The time-dependent results for various components are used as basic event inputs to a probabilistic risk assessment model to determine the increase in core damage frequency as a function of time.

[1]Cox, D.R., and P.A.W. Lewis, 1966, The Statistical Analysis of Series of Events, London: Chapman and Hall (U.S. distributor: Halsted Press).