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Aging Assessment of Residual Heat Removal Systems in Boiling Water Reactors*

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ABSTRACT

The effects of aging on Residual Heat Removal systems in Boiling Water Reactors have been studied as part of the Nuclear Plant Aging Research program. The aging phenomena has been characterized by analyzing operating experience from various national data bases. In addition, actual plant data was obtained to supplement and validate the data base findings.

Time-dependent failure rates were calculated for several components to identify aging trends. A computer program was developed and implemented to model a typical RHR system and perform time-dependent Probabilistic Risk Assessment calculations. Using the time-dependent failure rates calculated from the data, the effects of aging on system unavailability and component importance were investigated.

INTRODUCTION

The Nuclear Plant Aging Research (NPAR) program was established by the Nuclear Regulatory Commission to address concerns related to aging effects on the safety and reliability of nuclear power plants. The goals of the program are to characterize aging and service wear effects and identify methods of detecting and mitigating them. Initial work under the NPAR program focused on specific components [1-8], whereas more recent work has addressed complete systems [9].

This paper presents preliminary technical results from the phase I evaluation of the effects of aging on Residual Heat Removal (RHR) systems in boiling water reactors. The goal of the phase I work is to characterize the aging phenomena by identifying predominant failure causes, modes and mechanisms, as well as time-dependent aging trends.

RHR SYSTEM DESIGN AND OPERATION

There are several different RHR system designs currently in use in the United States, however, the most common is the two loop design. Each loop has two pumps and one heat exchanger along with numerous valves and instrumentation (Figure 1).

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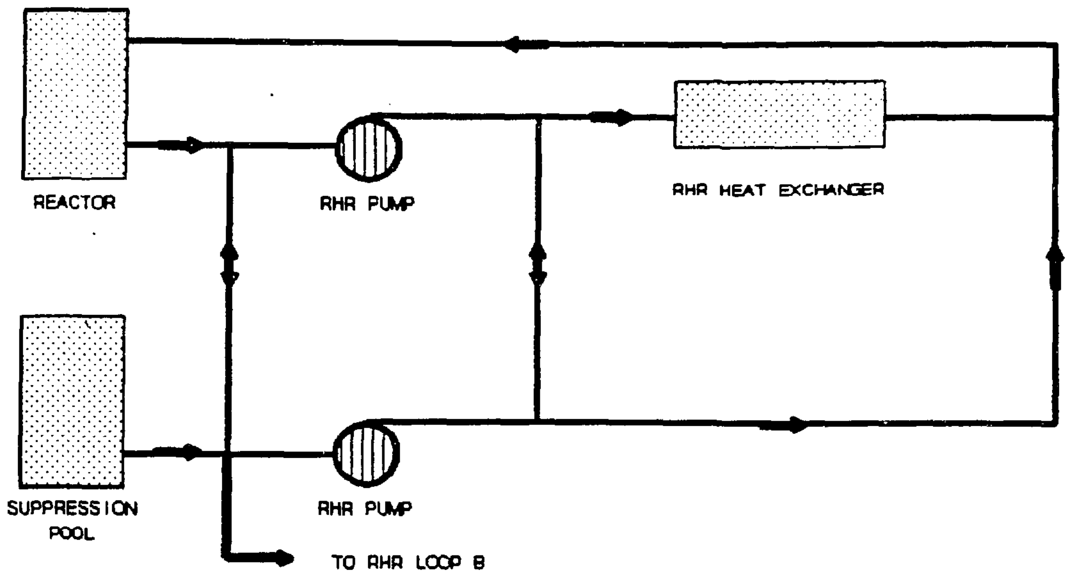

Figure 1: Typical RHR System Design

The RHR system can typically operate in several different modes, however, low pressure coolant injection (LPCI) and shutdown cooling (SDC) are the two most commonly aligned modes. This study focussed on these two modes.

In the LPCI mode, the RHR pumps take suction from the suppression pool and inject the coolant directly into the reactor bypassing the heat exchanger. This mode is automatically initiated following a loss of coolant accident (LOCA).

In the SDC mode, the RHR pumps take suction from the reactor recirculation loop, deliver the coolant to the heat exchanger where it is cooled, and then inject it back into the reactor. This mode is used during normal cool down of the reactor and is manually initiated.

AGING ANALYSIS

To evaluate the effects of aging on RHR system performance, past operating experience from various sources was obtained and reviewed. Data were obtained from national data bases, such as the Nuclear Plant Reliability Data System (NPRDS) and Licensee Event Reports (LER's). To mitigate the limitations of the data base information, each event was reviewed to assure consistency in aging determinations and interpretations of failure characteristics. In addition, actual plant data from an operating BWR were obtained and analyzed to supplement and validate the data base findings.

The NPAR definition of aging [10] was applied to each of the failures to determine if the failure was aging related. The fraction of failures that could be attributed to aging was then determined for each of the data sources. As shown in Figure 2 for the NPRDS data, large aging fractions were found indicating that aging degradation is present in RHR systems and is a significant contributor to failure.

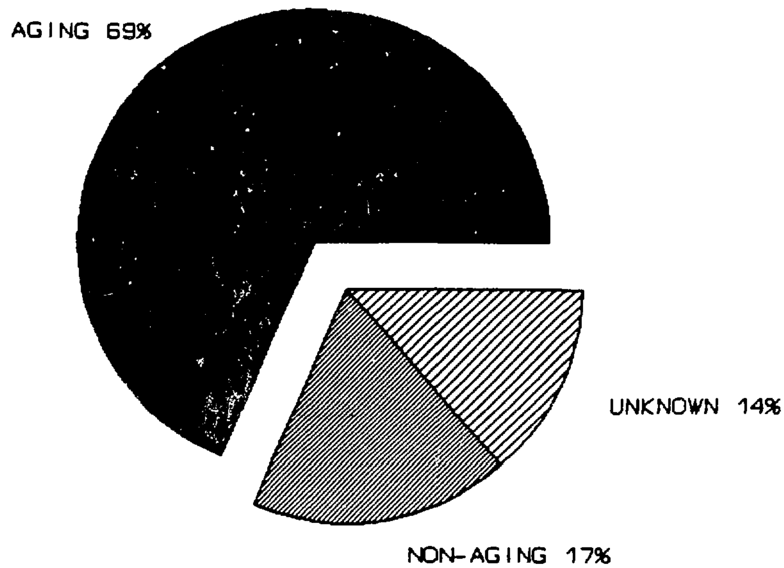

Figure 2 Fraction of Failures Related to Aging

The data were further sorted to identify the methods by which the failures are currently detected (Figure 3). It was found that tests and inspections detected the predominant number of failures (65%). However, approximately 27% of the failures were not detected until they resulted in some operational abnormality. This could include events such as the failure of a valve to transfer on demand or an instrument giving an incorrect indication. This finding shows that current test, inspection and maintenance practices do not detect all aging degradation before it results in failure.

To determine the effect of the failure at the system level, the data were categorized into four groups (Figure 4). Approximately half of the failures resulted in degraded system operation. This implies that the system could still perform its design function, however, the failure would eventually need attention or it would worsen and possibly result in loss of system function. Failures in this category included minor events, such as valve packing leaks, as well as relatively significant events,such as radiation leakage from heat exchangers. The data also showed that approximately 21% of the failures resulted in a loss of redundancy. This is significant since it increases the probability that the system could become unavailable which could adversely impact plant risk.

An important effect of RHR failures identified from the LER's is that they can result in radiological release (Figure 5). Although small in number, these failures are significant since each was aging related. The failures typically involved heat exchanger tube leakage caused by corrosion. Since corrosion is a time intensive aging mechanism, this type of failure can be expected to become more common as plants age if current methods cannot detect the degradation in a timely manner.

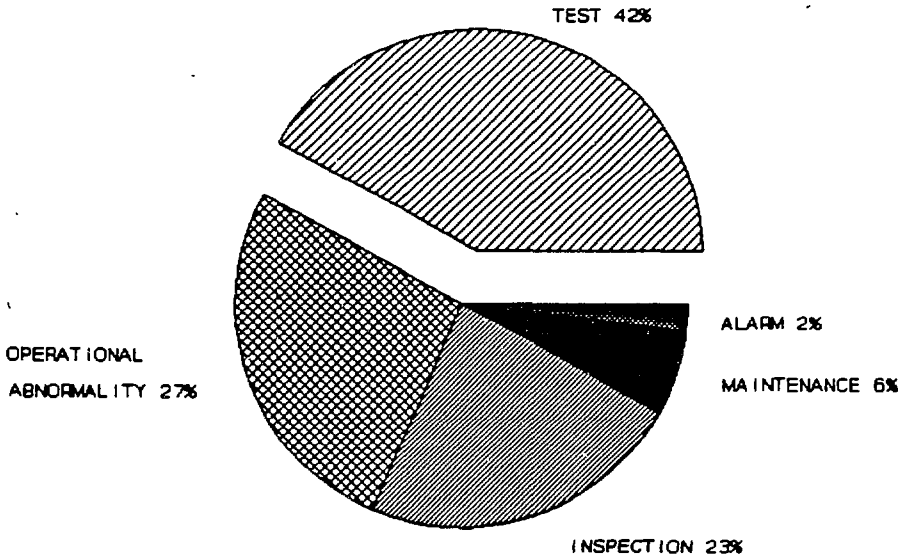

Figure 3: Failure Detection Methods

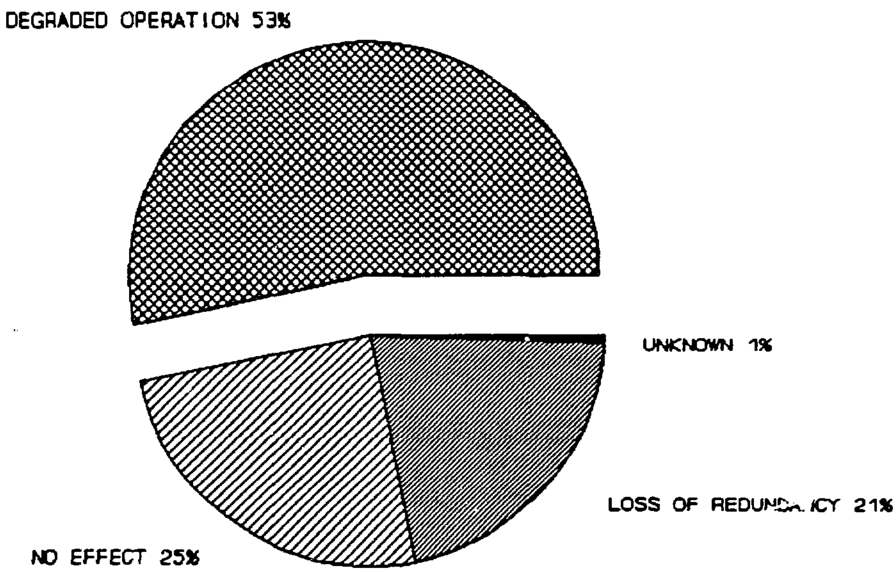

Figure 4: System Level Failure Effects

The predominant cause of failure was identified by categorizing the events into three classes; normal service, human error and other. Normal service included all causes related to degradation mechanisms the component is normally expected to be exposed to. This includes the typical aging mechanisms such as wear, corrosion, fatigue and calibration drift. The data were then sorted according to plant age to examine the time-dependent effects on cause of failure. As shown in Figure 6, the predominant cause of failure was found to be normal

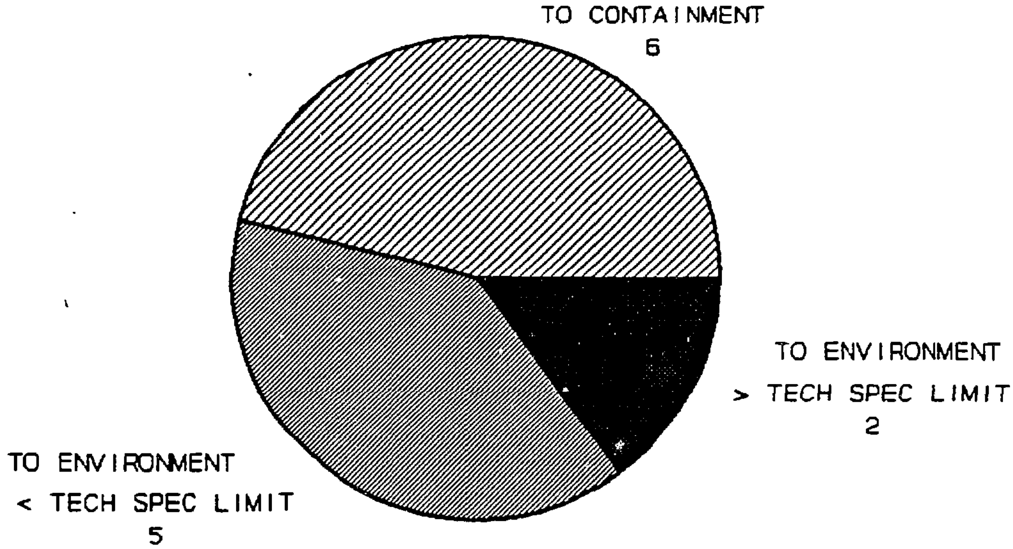

Figure 5: RHR Failures Resulting in Radiological Release

service for all plant ages. This is consistent with the large aging fraction discussed previously which indicates that aging degradation is a significant contributor to failures in the RHR system.

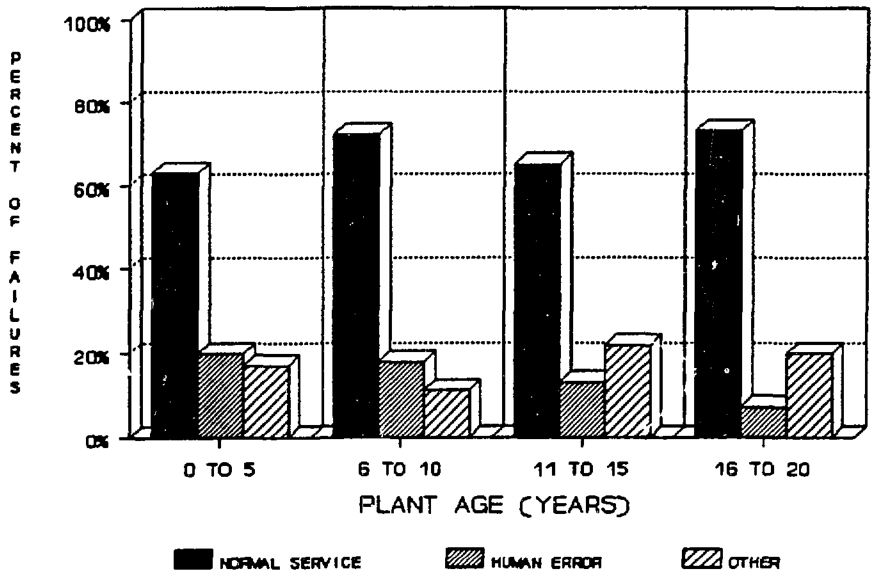

Figure 6: Failure Causes Versus Plant Age

Figure 6 also shows that the percentage of failures caused by normal service remains relatively constant with time. Therefore, no dramatic increases in failures with age are evident from past experience. This could be attributed to several factors including the predominant standby status of the RHR system which reduces exposure to operating stresses, as well as the relatively stringent test and inspection requirements on the system.

The predominant failure mechanisms were also identified from the data (Figure 7). Wear and calibration drift accounted for over half of the failures. Wear was typically associated with mechanical components, such as valves, pumps and heat exchangers, while calibration drift was typically associated with electrical components such as switches and sensors. It should be noted, however, that numerous other mechanisms are present in the RHR system which can lead to aging related failures. In order to detect all aging degradation, monitoring methods would have to be very diverse.

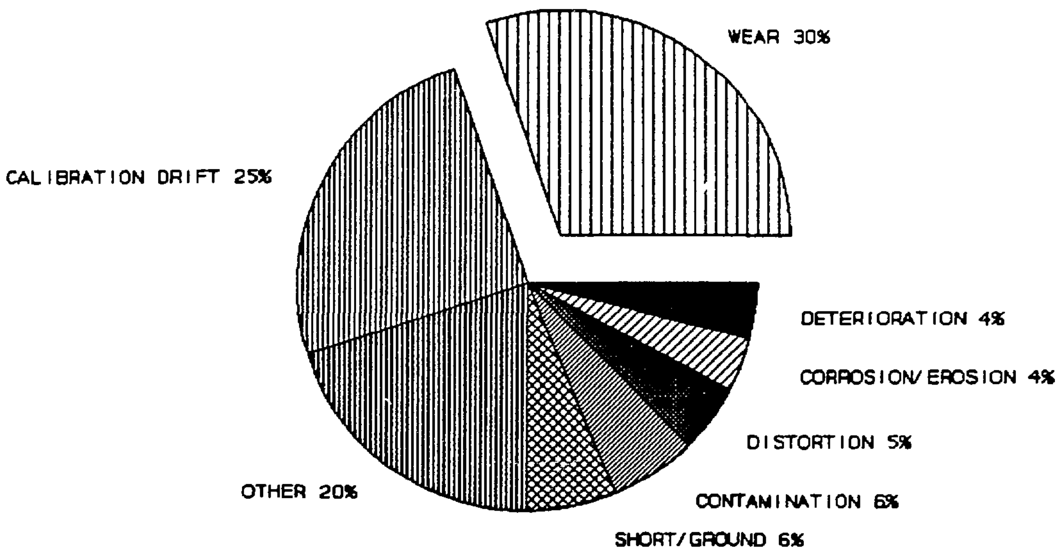

Figure 7: Failure Mechanisms

The data were further sorted to identify the components most frequently failed (Figure 8). Results showed that valves were the predominant component failing, followed by instrumentation/ controls and supports. These data are not normalized, therefore, population effects contribute to these results. However, it is noted that each of the components have a large fraction of failures which are aging related.

To identify the time-dependent effects of aging on component failures, the data were normalized to account for population and operating hours/demands. Time-dependent failure rates were then calculated for several of the RHR components. The calculations were performed by sorting the component failures by mode and plant age for individual plants. Linear regressions were then performed to obtain a failure rate curve for each plant. Results were then averaged over all plants to obtain generic failure rate curves. Upper and lower bounds were calculated using the standard error of the averages.

Figure 9 presents the time-dependent failure rate for motor operated valves (MOV's) failing to transfer. As indicated, the initial failure rate at age 0 is in good agreement with other commonly used sources, such as WASH-1400. However,

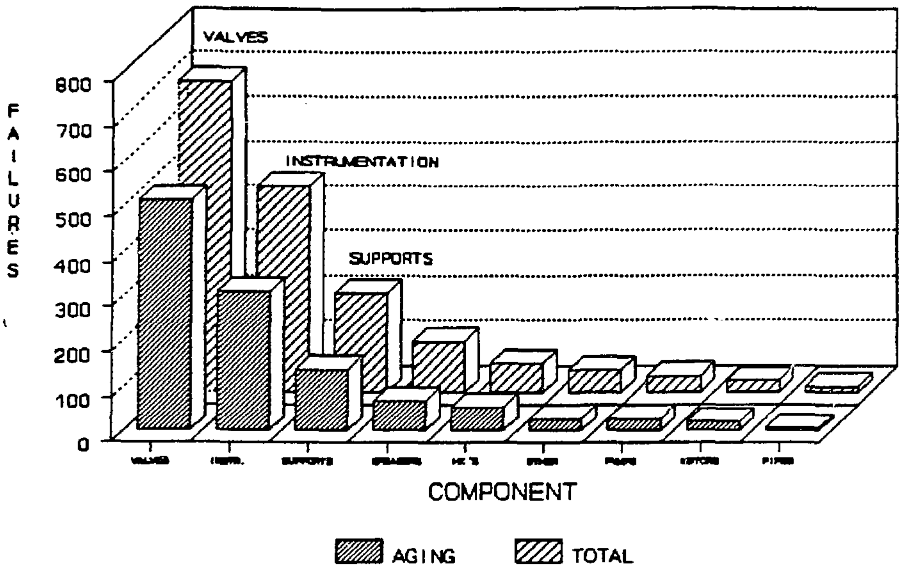

Figure 8: Failures Per Component

as component age increases the failure rate tends to increase also. For MOV's this increase was found to be 11% per year. In comparison with previous studies [9], in which failure rate increases as high as 20% to 30% per year were found, the increase found here for MOV's was judged to be moderate. Failure rate increases for other mechanical components were found to be moderate or low, including 8% and 17% per year for heat exchangers and pumps, respectively.

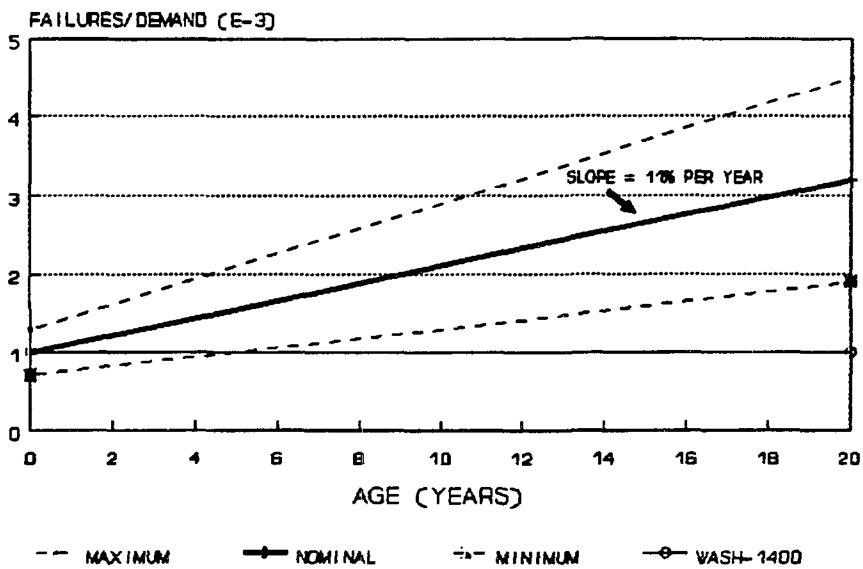

Figure 9: Time-Dependent MOV Failure Rate

Time-dependent failure rates were also generated for several electrical components. Figure 10 shows an example for level switch loss of function. As indicated, the failure rate did not show any increase with age for this component. Similar results were obtained for other electrical components with pressure and level sensors also showing no increase with age and pressure switches showing only a 3% increase per year.

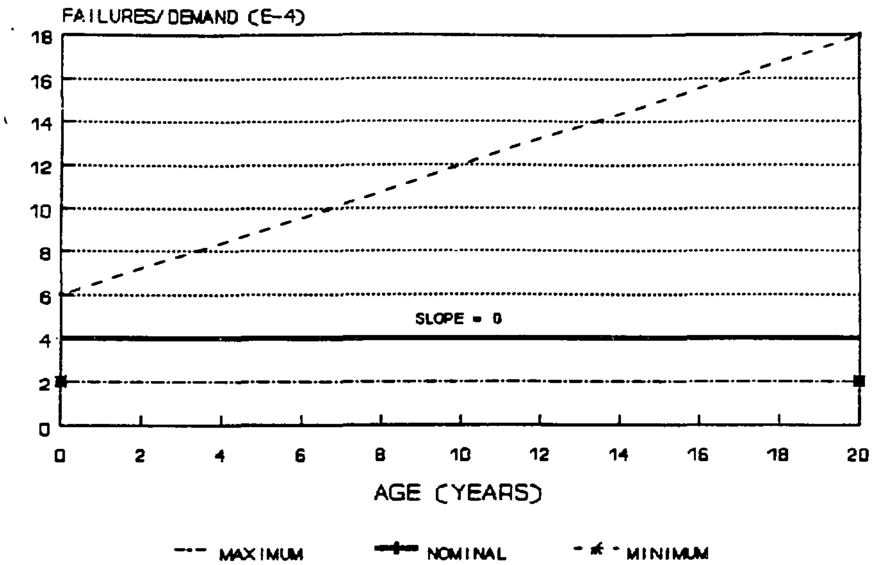

Figure 10: Time-Dependent Level Switch Failure Rate

To examine the effects of the increasing failure rates at the system level, a computer program was developed which performs time-dependent probabilistic risk assessment (PRA) calculations. The program (PRAAGE-1988) modeled the Peach Bottom RHR design in the LPCI mode and the SDC mode. Using the failure rates calculated from the data and extrapolating them, system unavailability projections were made over a 50 year period.

In Figure 11, the unavailability projection for the LPCI mode of RHR is presented. This projection accounts for aging of the two most important components contributing to system unavailability; MOV failure to transfer and pressure sensor loss of function. Failure rates used for all other contributors were the constant generic values originally found in the PRA. As shown, the LPCI unavailability was found to increase by a factor of approximately 2 over the 50 year time period. A similar projection was made for the SDC mode which resulted in an unavailability increase of approximately 4 times. The components aged for the SDC mode calculation were pumps, MOV's and pressure sensors, which were the leading contributors to system unavailability in this mode.

In a previous study [9], unavailability projections were made for the component cooling water (CCW) system, which is a continuously operating system. Comparing the results with the findings from this study (Figure 12) it is seen that the unavailability increase for the CCW system is significantly higher than for the RHR system. It must be noted that these results are based on analysis of only two specific systems, therefore generalized conclusions cannot be made.

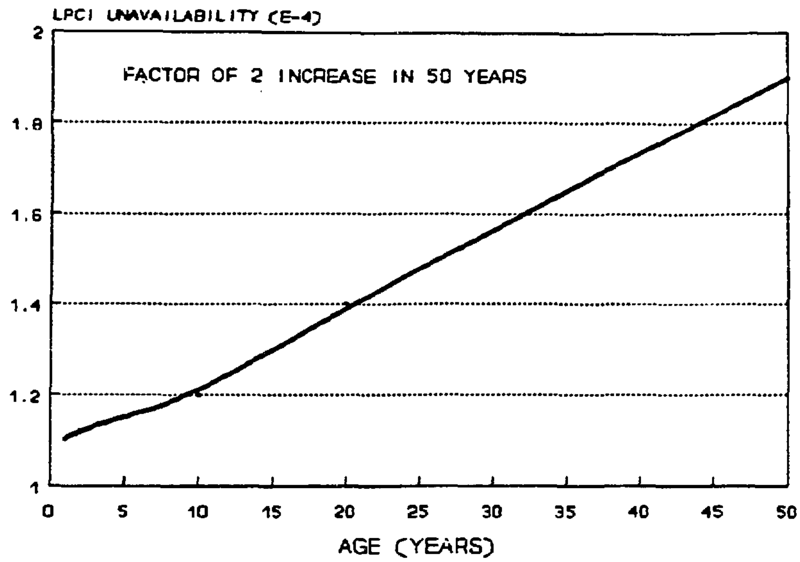

Figure 11: LPCI Unavailability Versus Age

However, the results shown here do indicate a potential trend for the unavailability of standby systems such as RHR to be less severely affected by aging then continuously operating systems such as CCW.

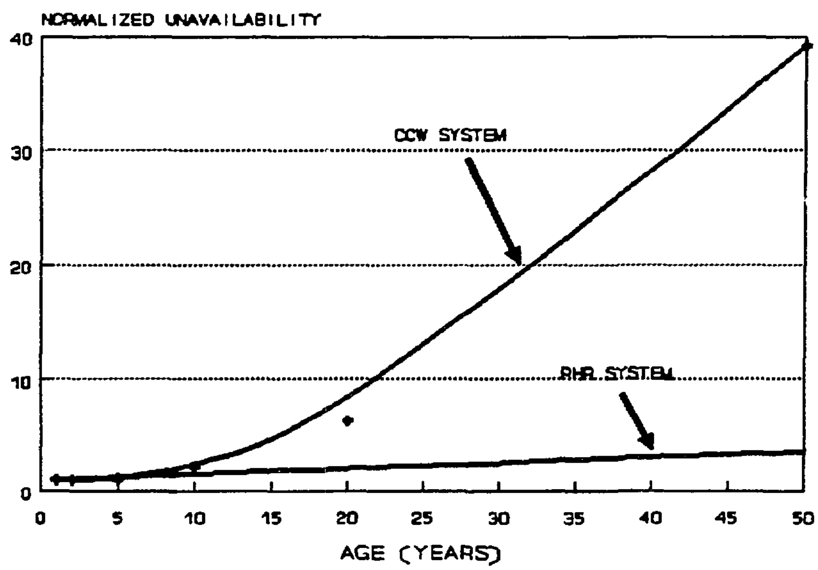

Figure 12: Normalized Unavailability Versus Age

The apparent mitigation of aging effects in the RHR system can be attributed to several factors. Since the system is predominantly maintained in standby status, exposure to operating stresses such as wear and erosion is reduced. Although these mechanisms are still present, they do not result in failures as rapidly as they would in a continuously operating system. This would result in a slower increase in failure rate with age for components in the standby system. In addition, since the RHR system is a safety related system, the test and inspection requirements are relatively stringent. This could be beneficial in that aging degradation may be detected before it results in a failure.

CONCLUSIONS

An analysis of past operating experience for RHR systems has shown that a significant number of failures are related to aging. The predominant cause of failure is normal service, which includes all operating and environmental stresses the system is normally expected to be exposed to. The predominant failure mechanisms are wear and calibration drift, which are associated with mechanical and electrical components, respectively. The components most frequently failed include valves and instrumentation/controls.

An evaluation of the time-dependent effects of aging on component failure rates and system unavailability has shown the following:

- Mechanical components show a low to moderate increase in failure rate with age. This may be attributable to their predominant standby status which reduces exposure to operating stresses such as wear and erosion. It may also be attributable to the relatively stringent test and inspection requirements placed on the RHR system.

- Electrical components such as switches and sensors show little or no increase in failure rate with age. This may be attributable to the relatively stringent test and inspection requirements placed on the RHR system. It may also be due to frequent replacement which is common with components such as these.

- Aging effect produce a moderate increase in the unavailability of the RHR system. Comparison with previous work has shown the potential for the unavailability of standby systems such as RHR to be less severely affected by aging than the unavailability of a continuously operating system.

Although the time-dependent aging effects found in this study have been judged to be moderate, it must be noted that this analysis was performed only at the system level. As part of the future phase II work, the results from this study will be used to analyze the effects of aging at the plant level. The impact of aging at the plant level will depend on many factors, however, it is possible that even a moderate increase in RHR unavailability can have a significant impact on plant risk. It is, therefore, important that this be addressed in the phase II work.

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