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Aging Assessment of Component Cooling Water Systems in Pressurized Water Reactors

Prepared by
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Prepared for
U.S. Nuclear Regulatory Commission

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Aging Assessment of Component Cooling Water Systems in Pressurized Water Reactors

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NUREG/CR-5052, "Operating Experience and Aging Assessment of Component Cooling Water Systems in Pressurized Water Reactors," July 1988.

ABSTRACT

A two-phase aging analysis of component cooling water (CCW) systems in pressurized water reactors (PWRs) was performed. In phase I, which was published separately as NUREG/CR-5052, the effects of aging on the CCW system were characterized, and the predominant failure modes, aging mechanisms, and components susceptible to aging degradation were identified. Failure rate trends were examined, and their effect on time-dependent system unavailability was investigated.

In phase II, which is the subject of this report, the methods used to manage aging degradation in the CCW system were studied. Information was collected and analyzed on inspection, surveillance, monitoring, and maintenance techniques from a survey of operating PWRs. The results are presented herein. Advanced techniques that may help detect and mitigate aging degradation also are included. A detailed examination of the materials of construction and their relationship to various aging mechanisms is discussed.

In addition, the various industry standards, codes, and regulatory requirements that govern the design, construction, and operation of the CCW system were investigated. Recommendations to better manage aging degradation in component cooling water system are discussed.

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EXECUTIVE SUMMARY

In the phase I aging analysis of component cooling water (CCW) systems, failure data from the nuclear plant reliability data system (NPRDS), licensee event reports (LERs), and actual plant data from an operating pressurized water reactor (PWR) were analyzed to characterize the effects of aging. The results showed that the CCW system is vulnerable to aging degradation. The majority of failures in the CCW system are related to aging, and the number of aging related failures increases with time. If this trend continues, component failure rates are likely to increase with time, and the availability of the system will decrease. The CCW system provides cooling water to several important loads throughout the plant under all plant operating conditions. Consequently, a decrease in CCW system availability could lead to increased plant risk. The phase I study provided an understanding of the effects of aging in the CCW system, and showed that these effects must be mitigated to ensure reliable system operation.

The goal of the phase II CCW aging analysis is to study methods that can be employed to better manage the effects of aging. These methods include ways to detect incipient aging degradation, before failures occur, as well as maintenance practices to mitigate the effects of aging. To achieve this goal, the research strategy for this study followed four separate paths; 1) an examination of current inspection, surveillance, monitoring, and maintenance (ISM&M) practices, 2) an investigation of the materials used in the construction of components, 3) a review of industry standards and codes related to inspection, testing, and maintenance requirements, and 4) a review of regulatory practices and how they can be used to evaluate the effectiveness of ISM&M programs for managing aging.

To review current ISM&M practices, a survey of operating PWRs and two site visits to operating PWRs were made to obtain information on the types of practices used, along with their frequency. The results showed that there are two categories of practices performed on a routine basis; basic practices that all plants perform, and supplemental practices that vary from plant to plant, depending on various factors. The basic practices are typically required by plant technical specifications or codes, and include such items as measuring pump head and vibration, or stroking motor operated valves. Additional discussion on these activities is presented in Section 2, and research results are summarized in Section 7.

The supplemental activities are selected by the plant based on manufacturers' recommendations or past plant experience, and typically are used to address specific plant operating conditions or past problems. These supplemental activities include such items as thermography examination of pumps to detect hot spots, and eddy current testing of heat exchanger tubes to detect cracks or flaws. While most plants may use these techniques when a problem is suspected, the survey shows that some plants use them regularly as part of their routine maintenance and monitoring program.

To aid in the evaluation of current ISM&M programs for managing aging, each of the basic and supplemental practices was correlated with the aging mechanisms they can detect or mitigate. The resulting charts, presented as Figures 7.1, 7.2, and 7.3, can be used by utilities to review their ISM&M practices. Current ISM&M programs are discussed in detail in Section 2.

In addition to the routine practices used in plants, several advanced practices were investigated, including ultrasonic testing, eddy current testing, remote field technique, internal rotary inspection system, vibration monitoring, and tracer technology. Each of these techniques can detect some form of aging degradation, including internal component leakage, material flaws, and wall loss. Section 6 gives a detailed discussion of these practices, and a summary is presented in Table 7.2.

The following findings were also obtained from the ISM&M review:

- In general, no specific actions are taken to address long term aging of the CCW components. For example, no routine measures are in place to monitor wall loss of heat exchanger shells, piping, pump casings, or valve bodies. Although the data do not indicate any failures related to wall loss in the CCW system, this is a potential concern for extended life operation. Over many years of operation, wall thinning may occur which could weaken these components.

- A standardized maintenance or monitoring program which requires all plants to perform the same actions would not be practical because of differences in plant designs, operating conditions, and environment. An optimum program should include the basic practices now performed by most plants, along with supplemental and advanced practices specifically chosen to address particular problems or weaknesses in the plant's ISM&M program. A discussion of recommended basic and supplemental practices is presented in Section 7.

In addition to ISM&M practices, the materials of construction were investigated. The results indicate that several different materials are used in the construction of various components, each of which is susceptible to certain types of aging degradation. In most cases, knowledge of the material used will help to identify the aging mechanisms that should be monitored for and protected against. Therefore, a maintenance and monitoring program should include the identification of materials used. Other findings from the review of component materials include the following:

- The majority of heat exchanger failures are caused by corrosion and wear of the tubes, which is directly related to the materials used and the operating environment. Because all tubes in the tube bundle typically are made of the same material and are exposed to the same environment, once tube failure begins, the number of failures can increase dramatically in a short time.

- There are several methods to extend the life of heat exchangers, including the use of cathodic protection, and protective coatings or liners. If the material selected for construction is incompatible with the operating conditions or environment, aging degradation will proceed rapidly. In these cases, the material should be replaced with one more suitable for the service conditions.

- A valve subcomponent that is extremely susceptible to aging is the packing. Several different materials are available for packing, however, installation can also be important. Using combinations of different materials can increase the life expectancy of the packing.

- Two other valve subcomponents that are susceptible to aging are the diaphragm and O-rings used in pneumatic valve operators. The materials most commonly used are neoprene and buna-N. These components should be inspected regularly and replaced periodically to prevent failures during operation. These materials degrade even while in storage, therefore, proper storage conditions should be maintained and shelf life tracked.

An additional area that can contribute to the proper management of aging involves the various industry codes, standards, and regulations that govern the design, inspection, testing, and maintenance of the CCW system. A review of these items resulted in the following findings:

- The design of the CCW system is governed by the General Design Criteria in the Code of Federal Regulations. Although the criteria address safe operation of the systems, there are no specific requirements addressing the issue of aging.

- Inservice inspection requirements for the CCW system are governed by ASME Section XI, and are included in the plant's technical specifications. The inspection requirements of Section XI are to pressure test the system and inspect for leakage periodically, and to visually inspect any snubbers in the system. Inspections to specifically address aging degradation are not required.

- Inservice testing requirements of the CCW system are governed by ASME Section XI, which references ASME Operation and Maintenance (O&M) standards. The testing requirements address pumps (ASME OM-6), valves (ASME OM-10) and snubbers (ASME OM-4). ASME standard OM-2 addresses performance testing of the CCW system as a whole, however, this standard is not a mandatory requirement. The OM-2 standard includes guidance on evaluating aging degradation which can be useful for evaluating the long-term effects of aging on system performance. It is recommended that this information be trended and used as an aging indicator.

- Additional testing requirements have been imposed by generic letters issued by the NRC in response to various problems detected during operation. Generic letter 89-10 requires licensees to implement a program for testing, inspecting and maintaining motor-operated valves (MOVs) in safety-related systems. Generic letter 89-13 requires licensees to establish a test program to verify the heat transfer capability of all safety-related heat exchangers cooled by service water.

- The General Design Criteria require that the CCW system be maintained throughout the life of the plant; however, there is no specific guidance on how to accomplish this. Codes or standards on system maintenance do not exist, although standards on good maintenance practices for various components are available.

Based on the findings of the phase 1 CCW system study, it was observed that the various codes and standards provide a means of detecting degradation caused by many aging mechanisms. However, they are not comprehensive enough to completely control all aging degradation. In order to effectively control aging, ISM&M programs should include a combination of basic practices, as required by codes and standards, along with supplemental practices chosen specifically to address any unique plant operating conditions or past problems.

Another important method of managing the effects of aging is to evaluate how effective a plant's practices are at detecting and mitigating aging degradation. To identify ways of doing this, current regulatory practices were reviewed. One practice was found to have the elements necessary for effectively assessing plant practices, namely the Safety System Functional Inspection (SSFI). These inspections are currently performed by the NRC to determine if safety systems can perform their design functions, if called upon. However, the structure of the SSFI also lends itself to obtaining information relevant in assessing aging management. This could be a useful tool for the NRC to use for evaluating how effectively a plant is managing aging degradation. Table 4.4 gives several additions to the SSFI format which would make it more suitable for this purpose. The types of information which can be obtained from an SSFI and used for aging management are demonstrated in the following examples, which were obtained from a review of previously performed SSFIs.

- One SSFI determined that CCW system design leakage may be underestimated in several plant designs. For instance, one plant did not design the makeup portion of the system as safety-related because zero leakage was expected. However, experience has shown that as valves, pumps, and heat exchangers age, leakage will increase. This aging process should have been considered in the system design.

- One SSFI determined that the expected ambient temperature in the CCW pump area during an accident was not accurately represented. A review indicated that the ventilation system would not be operable in a postulated accident, which would expose the CCW pump motors to higher temperatures than they had been designed and tested for. The long-term performance of CCW at this plant was essential for removing decay heat. The SSFI report indicated that the operating stresses which could affect operation of the CCW system had not been addressed adequately. The high temperature could impose aging mechanisms on the equipment, resulting in premature wear and failure. The equipment should have been designed and tested to operate under these conditions.

The results of the phase I and phase II aging studies show that the Component Cooling Water system is susceptible to aging degradation. As the system ages, the likelihood of failures increases, which can adversely affect the reliability of the system. However, the results of this phase II study show that there are measures that can be taken to monitor and mitigate the effects of aging. The following recommendations will help ensure that plants have the most effective maintenance and monitoring programs to manage aging of CCW systems.

- Personnel cognizant of the CCW system performance should understand the characteristics of aging degradation presented in the phase I study. This knowledge will provide them with insights into what should be monitored, and what aging mechanisms may be present in their particular system.

- Cognizant utility personnel should review past operating experience and failure data to determine if any aging trends are evident, such as increasing failure rates. This will help to identify the extent and magnitude of aging mechanisms present, along with any weaknesses in their maintenance program.

- Maintenance and monitoring programs should be reviewed in relation to the aging mechanisms identified for a particular CCW system. The review should ensure that effective techniques are in place to detect and/or correct any aging conditions. The ISM&M information presented in this phase II study can be used for this purpose.

- Consideration should be given to incorporating techniques to detect and monitor the effects of long-term aging, such as pipe wall thinning, and degradation of pump or valve bodies. Such degradation takes many years to manifest itself, and is a potential concern for extended life operation.

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1. INTRODUCTION

1.1 Background

The component cooling water (CCW) system is one of many systems that are vital for the safe operation of nuclear power plants. Many safety factors are incorporated into its design to ensure the system will perform its design function when needed. However, as plants age, the effects of accumulated wear and tear on the CCW components could degrade the safety factors, if the aging effects are not properly detected and mitigated. As plants age it becomes important to understand and control the effects of aging to maintain plant safety at its original design level. To address this concern, the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Engineering instituted the Nuclear Plant Aging Research Program (NPAR).

Work under the NPAR program has included various aging studies at the component and system level[1-8]. The studies are typically performed in two phases. The effects of aging are characterized in phase I, while the methods of detecting and mitigating aging effects are evaluated in phase II. The phase I CCW study is completed, and the results, which are summarized in the following section, are documented in Reference 9. The structure of the NPAR program is discussed in more detail in Reference 10.

The goal of the phase II study is to identify methods of better managing the effects of aging in CCW systems. To accomplish this goal, the approach taken was to identify and research several different areas related to aging detection and/or mitigation. The resulting tasks performed include an evaluation of current and advanced inspection, surveillance, monitoring and maintenance techniques, an analysis of the materials used in constructing components, the identification of existing regulatory practices that may be useful to assess a plant's aging management program, and an evaluation of how well industry standards address aging. This approach is summarized in Figure 1.1.

1.2 Summary of Phase I CCW Study

The goal of the Phase I CCW study was to identify and characterize the effects of aging in CCW systems. To achieve this goal, operating experience and failure data from various national data bases were reviewed and analyzed. Actual plant data also were obtained and analyzed to supplement and validate the database results. To make the study manageable, CCW systems in pressurized water reactors (PWRs) were focussed on.

Evaluation of the data shows that approximately 72% of the failures in CCW systems are related to aging. As defined in Reference 10, aging is the cumulative degradation that occurs with the passage of time. Aging degradation can be caused by material degradation mechanisms, such as erosion, corrosion, and embrittlement; by stressors imposed due to improper storage, operating environment, or external environment; by service wear; by excessive testing; or by improper installation, application, or maintenance. The dominant cause of CCW component failures is "normal service", while the major mechanism is "wear".

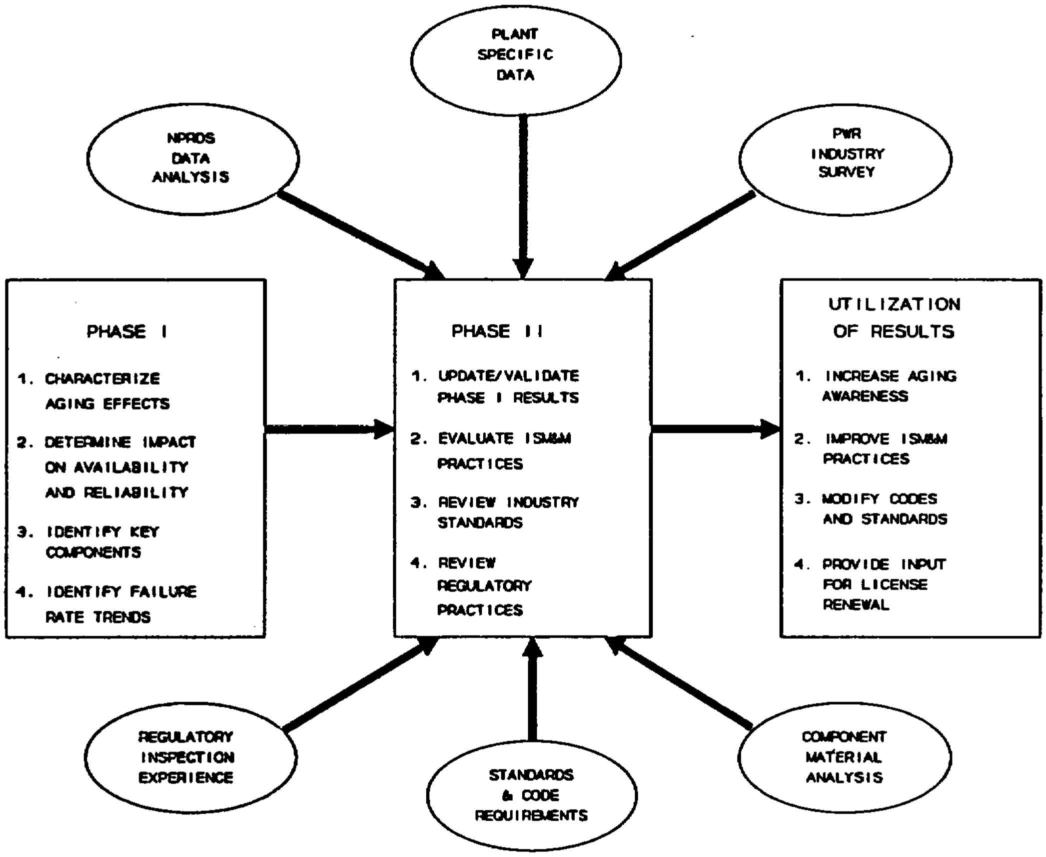

Figure 1.1 Phase II research approach

Examination of failure causes indicates that failures due to normal service increase with the system's age (Figure 1.2). Figure 1.2 also shows a decrease with age in failures caused by human error and other causes, which include failures of other components and/or systems, and failures for which the cause was unknown. These findings show that aging degradation occurring in CCW systems leads to failures, and that such failures increase with age.

The CCW components that fail most often are valves (including valve operators), followed by pumps, instrumentation, and heat exchangers (Figure 1.3). For all components, a large fraction of the failures are due to aging. Time-dependent component failure rates calculated from the data indicate an increasing trend with time; for example, in Figure 1.4 for CCW pumps. This increase is attributed to the accumulation of aging effects. To ensure proper system function and plant safety, these aging effects must be detected and mitigated in an incipient stage before the component fails.

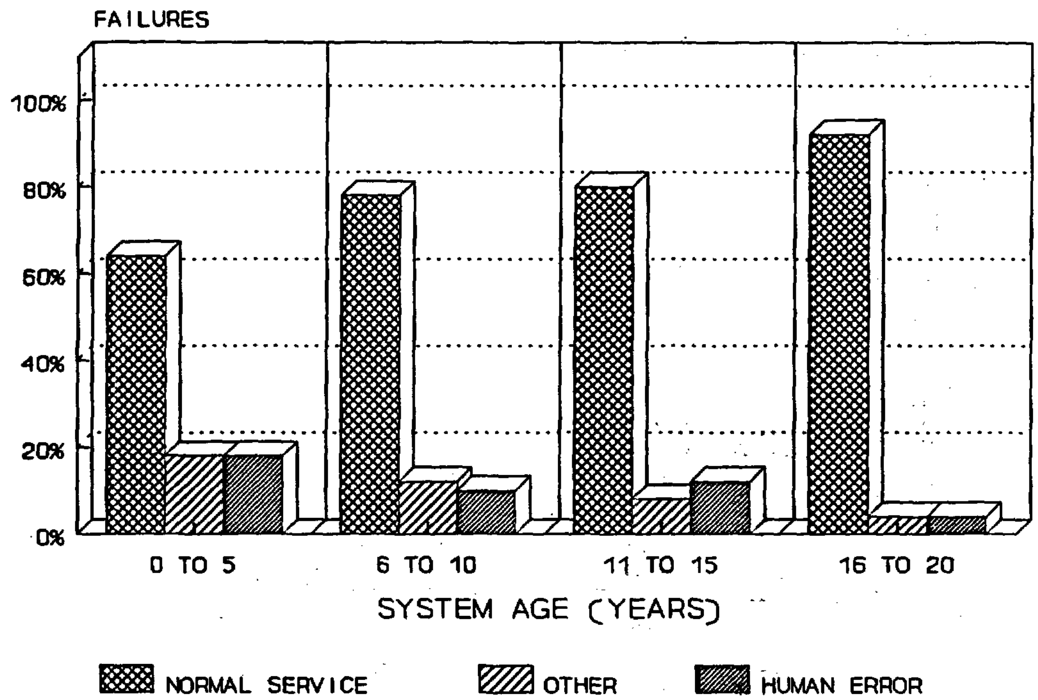

Figure 1.2 CCW failure causes versus system age

To investigate the effect of increasing failure rates on system performance, a typical CCW system was modeled to perform probabilistic risk assessment (PRA) calculations. Using time-dependent failure rates in the PRA analysis, two significant findings were obtained; 1) CCW system unavailability increases with time (Figure 1.5), and 2) the relative importance of the CCW components changes with time (Figure 1.6). From these findings it is clear that aging degradation must be controlled to maintain system unavailability at an acceptable level. It should be noted that this simplified analysis does not represent a quantitative evaluation of CCW system unavailability in general, and is presented here only to show the potential effects of increasing component failure rates.

Based on the phase I analysis, it is concluded that aging degradation in CCW systems is a concern which must be addressed to ensure acceptable system performance in later years. The effects of aging must be detected and mitigated through effective inspection, surveillance, monitoring (ISM), and maintenance. The identification of ISM and maintenance methods that are effective at detecting and mitigating aging effects is the focus of the phase II study discussed in this report.

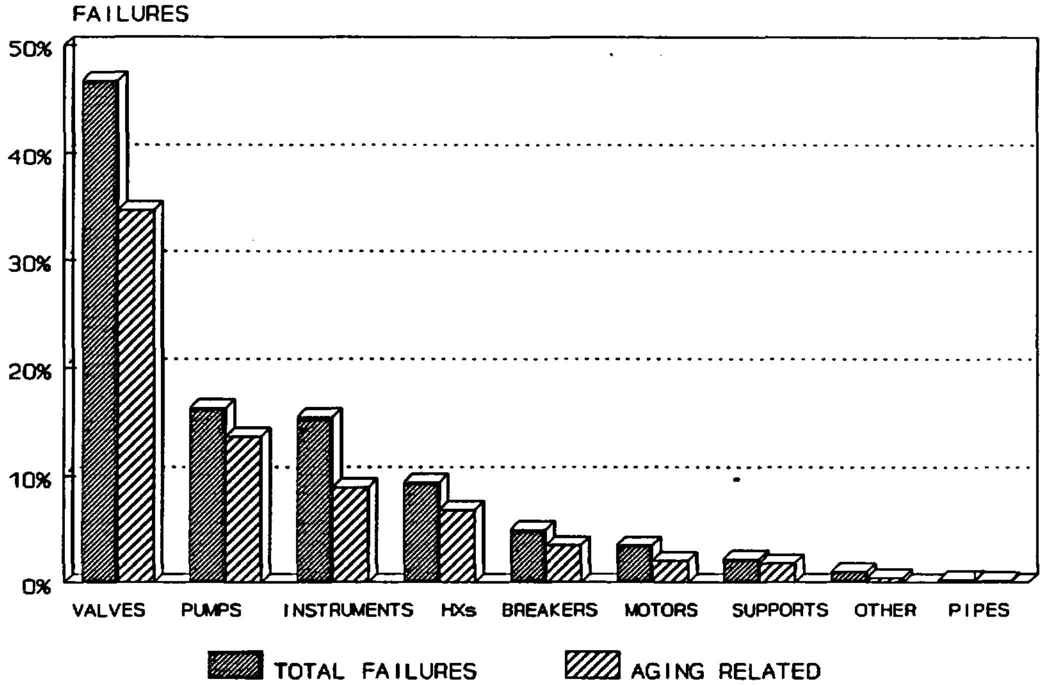

Figure 1.3 CCW component failures and aging fraction

1.3 Update of Phase I Data Analysis

The phase I aging analysis examined data on operating experience and failures from 1976 through 1987, and concluded that three of the main contributors to CCW system failures are valves, pumps, and heat exchangers (HXs). Since a significant period of time has elapsed since the phase I study was completed, the data were updated. The purpose of this update is to verify that the results of the previous work are still valid, and to determine if any new insights can be obtained from the new data. Accordingly, NPRDS records on CCW systems were obtained for January 1988 through May 1990. These data were reviewed and an analysis similar to that used in the phase I study was performed.

As was found in the phase I study, pumps and valves are still among the most frequent components to fail in the CCW system; consequently, they were focused on more closely in this data analysis. In addition, heat exchangers have a high potential for aging degradation in later years of operation, thus, they were also given increased attention.

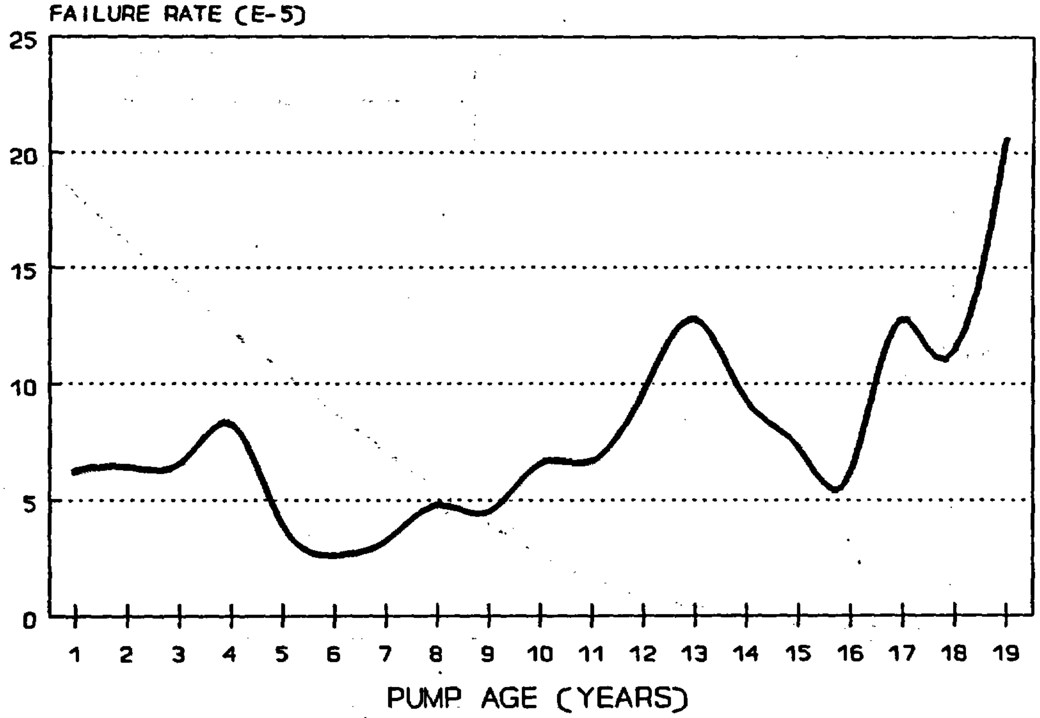

Figure 1.4 CCW pump failure rate versus age

1.3.1 Analysis of Heat Exchanger Data

Over the two-and-a-half years subsequent to January 1988, 75 entries on CCW heat exchangers were recorded in the NPRDS data-base. The problems addressed were predominantly related to tube leaks (56%) and plugged tubes (31%). A complete breakdown is shown in Figure 1.7.

Of the 24 PWRs reporting, eight plants contributed 49 of the 75 entries, with one plant accounting for 13 entries, all of which were related to plugging of the CCW heat exchangers. A relatively new plant (on-line in 1984) reported eight leaks within 15 months.

The data clearly indicate that tube leaks and plugging are fairly common problems in the industry. The safety significance of tube plugging is that if it is excessive, the component cooling water temperature will increase, which could lead to overheating of the safety-related equipment it supplies, or limiting the rate of decay heat removal. Tube leaks in the CCW heat exchanger increase the potential for releasing radiation to the environment through the open-loop service water system.

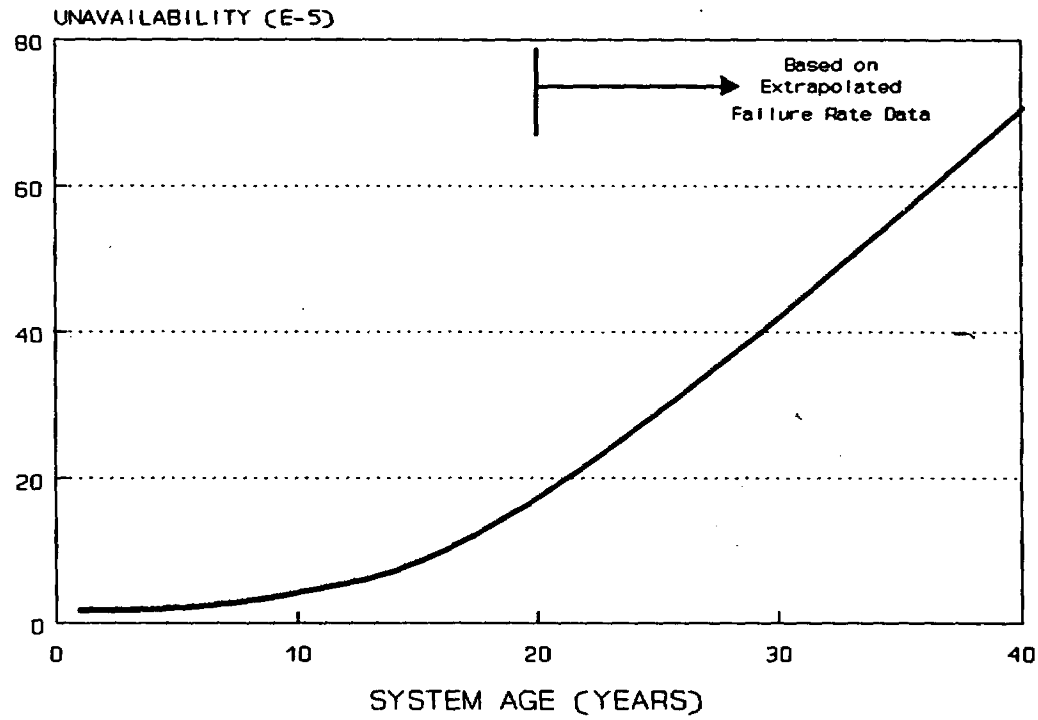

Figure 1.5 CCW system unavailability versus time

1.3.2 Analysis of Pump Data

The data reviewed for this update include 83 entries related to CCW pumps, reported by 44 plants. The problems addressed were dominated by failures of the mechanical seals (43%) and bearings (26%). The remaining failures were related to packings, gaskets, and other internal components. Each of the categories involving subcomponent wear is related to aging degradation. Figure 1.8 shows the complete breakdown.

These results are consistent with the findings from the phase I study. The need to detect pump degradation before a failure occurs is evident from the impact of pump failure on risk. The high percentage of seal and bearing failures, which can result in pump unavailability, show that maintenance and monitoring practices should be reviewed in these two areas.

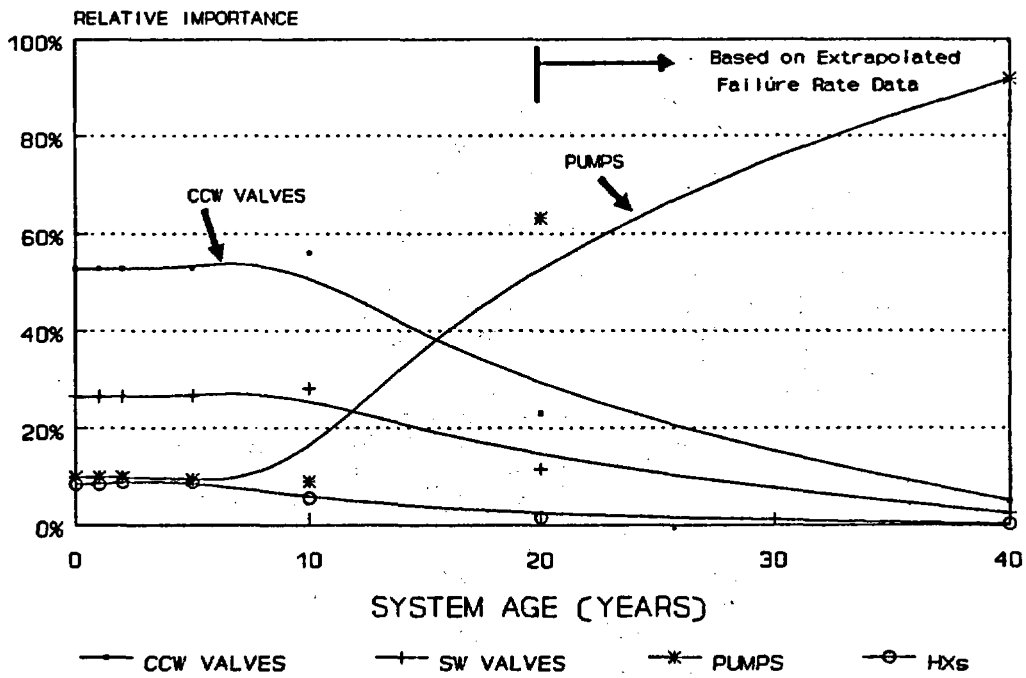

Figure 1.6 CCW component importances versus time

1.3.3 Analysis of Valve Data

There were 75 reports of failure of CCW control valves. Many of these failures were related to aging, and affected plant operation or safety-related equipment. Several reports noted that degradation had increased the stroke time of the containment isolation valves in the CCW system. Five events referred to failures of important CCW control valves to open or close, affecting the CCW supply to the reactor coolant pumps. One event described the wear out of seals and O-rings, which would have allowed accumulators to bleed down on a loss of instrument air. This would have caused the valve to close, making the decay heat removal cooler inoperable.

As discussed previously, most of the failures are related to aging, with many of them involving leakage. The predominant failure mechanism is wear and damage of internal components, which is consistent with the findings from phase I. These failures typically involve wear to valve plugs, seats, and discs, typically caused by erosion, corrosion or fatigue. Other valve failure mechanisms include the buildup of corrosion products or other debris on discs or seats, which causes the valve to stick or leak internally, and wear of the

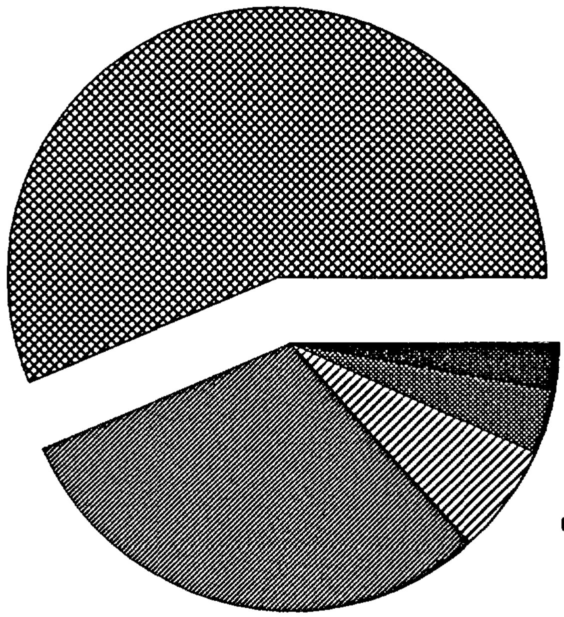

Figure 1.7 Heat exchanger failures (NPRDS 1/88 to 6/90)

packing, which causes the valve to leak externally. The various aging mechanisms are shown in Figure 1.9.

The control valves are typically composed of several important subcomponents. The data were further analyzed to determine which subcomponents contributed the most to failure of the valves. The results showed that the predominant number of problems with the control valve are due to the actuator. For air-operated valves, the root cause of the actuator problems was usually attributed to contamination of the instrument air supply by moisture or dirt. The subcomponents contributing to valve failures are shown in Figure 1.10. Table 1.1 gives the associated failure modes for each of the subcomponents.

The results of the update confirm that the phase I analysis is still valid: Pumps, valves, and heat exchangers remain important components in the CCW system that are susceptible to aging degradation. Therefore, the phase II study focuses on evaluating the inspection, monitoring, and maintenance practices for these components.

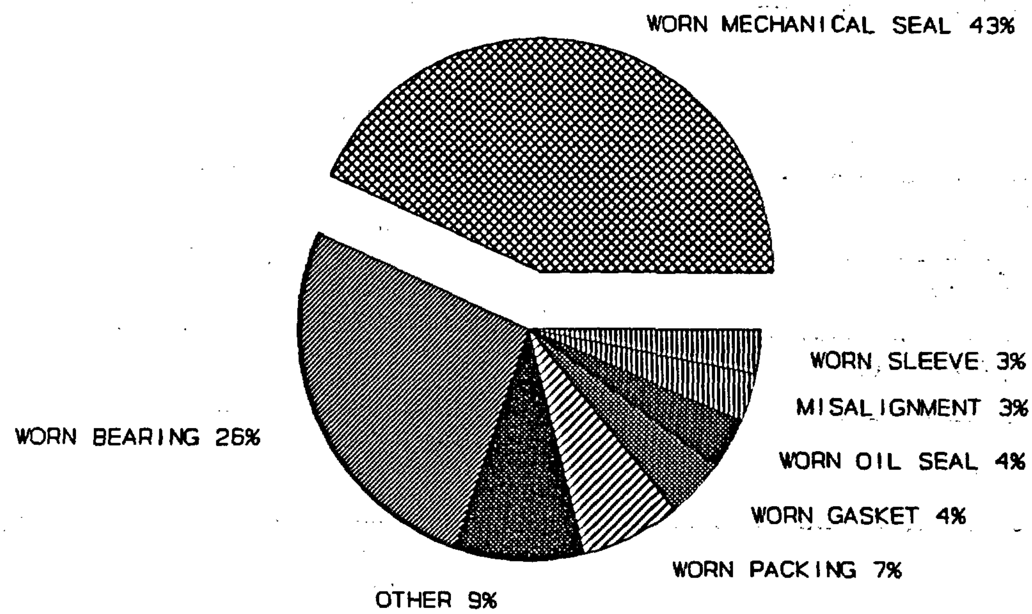

Figure 1.8 CCW pump failures (NPRDS 1/88 to 6/90)

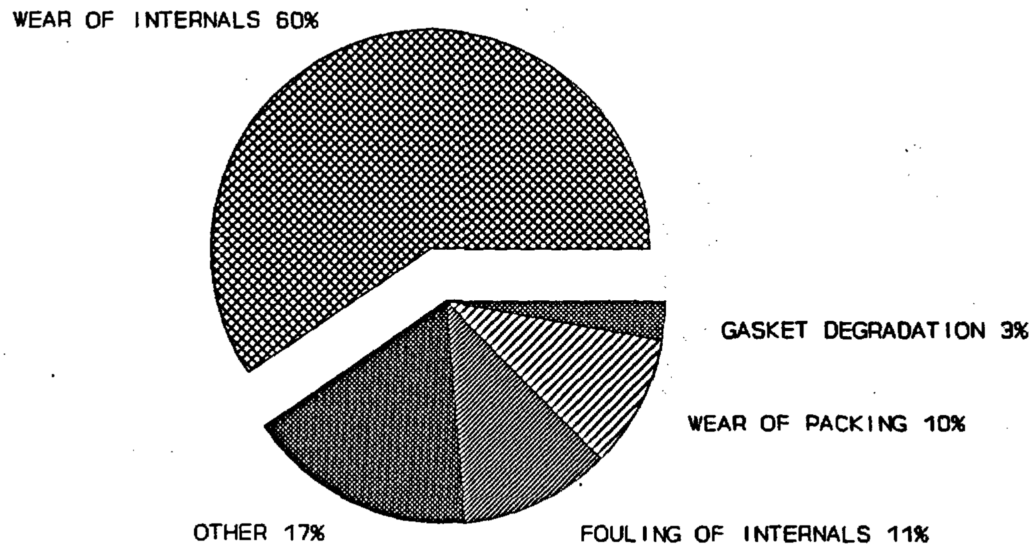

Figure 1.9 Valve failure mechanisms (NPRDS 1/88 to 6/90)

Table 1.1 Valve subcomponent failure modes

Subcomponent	Failure Mode
Diaphragm	- ruptured - worn - cracked - dilated/stretched - hardened
Regulator	- clogged - setpoint drift
Solenoid Operated Valve (electrical)	- shorted coil - open coil
Solenoid Operated Valve (mechanical)	- binding - sluggish
Actuator	- leakage - binding - stiffness
Valve Body	- packing leakage - gasket/seal leakage - wall thinning
Limit Switch	- out of adjustment - fused/degraded contacts

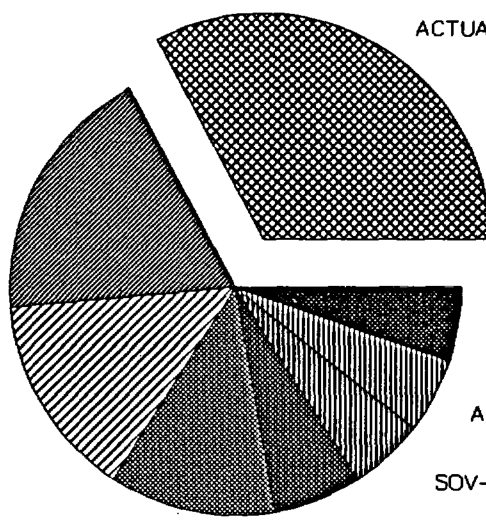

Figure 1.10 Valve subcomponent failures (NPRDS 1/88 to 6/90)

1.4 Objectives and Approach of Phase II Study

With an understanding of the aging effects obtained from the phase I work, the methods used to detect and mitigate aging degradation can be evaluated. The specific objectives of the phase II work are the following:

- Identify the inspection, surveillance, and monitoring methods currently used for CCW systems, and evaluate their effectiveness for detecting aging degradation.
- Identify the maintenance methods being used for CCW systems and evaluate their effectiveness at mitigating aging degradation.
- Recommend new methods or improvements to current methods to better detect and mitigate aging effects.
- Review and evaluate the materials used for component construction and their susceptibility to aging degradation.
- Review and evaluate NRC inspection programs and industry standards to ensure that aging is properly addressed.
- Identify aging concerns that are important for plant life extension.

To achieve these objectives, two operating PWRs were visited to collect information on their CCW systems. Engineers and maintenance personnel were interviewed, and copies of plant procedures were obtained to determine what practices are used to monitor and maintain the CCW system. When possible, failure records were also obtained to help evaluate these practices. In addition, a survey of other operating PWRs was performed to help identify current practices.

Various industry standards and NRC inspection plans were reviewed to identify areas where aging should be addressed, and where results from the NPAR CCW studies would be useful. Reviews were also performed of NRC bulletins and notices related to CCW systems, and NRC safety system functional inspections to supplement other results.

In the following section plant specific data is discussed, including the ISM&M practices currently in use and the failures typically experienced. Section 3 examines the various materials used to construct the components, and the effects of aging on them. Section 4 presents the findings from the review of the NRC safety system functional inspections, and section 5 presents findings from the review of regulations and industry standards. Section 6 discusses advanced detection and monitoring techniques that may be effective at detecting and mitigating aging degradation. Section 7 discusses how the results of this analysis can be used to better manage the effects of aging in CCW systems. Recommendations and conclusions are given in Section 8.

2. EVALUATION OF PLANT SPECIFIC DATA

To identify the inspection, surveillance, monitoring, and maintenance practices currently used for CCW systems, information was collected from several operating PWR nuclear power stations using a survey developed by BNL specifically for the NPAR program and performed by the Electric Power Research Institute (EPRI). In addition, BNL personnel visited two plants to collect data and interview the staff. This section discusses the findings obtained from the plant information.

2.1 Survey of PWRs

A questionnaire was distributed to various utilities requesting information on their CCW system. A total of 14 units responded, providing information on CCW testing, monitoring, and maintenance. Not all units completed all sections of the questionnaire; therefore, the number of units responding to a particular area was not always 14. In addition, the plants remained anonymous, therefore, the findings could not be correlated with system design, and discrepancies in the responses could not be investigated. However, the survey provides a good representation of current practices.

2.1.1 CCW Testing Practices

The BNL survey solicited information on testing of CCW components, including the test performed and its frequency. The responses covered pump testing, valve testing, and several miscellaneous tests performed by the utilities. In general, there are several basic tests for each component that all units perform. These are typically tests required by plant technical specifications or by the ASME code. In addition, there are also various other tests performed which provide supplemental information. These tests may be recommended by component manufacturers, or they may be desirable, based on the utility's past experience. The frequencies of the basic tests are consistent among utilities; however, the frequencies of the supplemental tests vary.

The results for pump testing show that virtually all units measure pump head and vibration, typically on a quarterly basis (Table 2.1). These are basic tests which are part of the ASME Section XI code requirements for pump testing. Although not all units reported that they perform them, testing pump suction pressure, pump flow rate, and bearing temperature are also basic tests which are required by ASME Section XI. Results from these basic tests give a general indication of the pumps condition and, if trended, could be useful as indicators of aging degradation. It should be noted that trending of all pump parameters may not be warranted or effective for controlling aging degradation. Each parameter should be evaluated at the component and plant level to determine if trending of it will be useful. It should also be noted that some units do not perform tests at the frequency required by code since relief may have been granted by the NRC due to special circumstances.

Several other tests performed by some of the units include vibration acceleration, and motor voltage and current tests. Two units stated that a "performance test" was done for the CCW pumps. Although no description was provided, it is expected that the performance test includes measurement of pump head and vibration, and is similar to what other units perform.

Results on valve testing indicate that most plants test MOV stroke time and check valve seat leakage. Stroke time testing of MOVs can be used as an indicator of aging degradation if the results are trended. Increasing stroke times would indicate increasing wear in subcomponents of the valve and valve operator. Check valve seat leakage measurements can only be used as an indicator if the actual leakage flow is measured. In some plants, check valve leakage is determined by observing whether a non-running pump upstream of the check valve rotates when there is flow on the downstream side of the valve. Since no measurements are taken, results from this type of test would not be trendable. Other tests which some of the units perform are measuring check valve flow, checking of remote position indicators, checking of relief valve set points, measuring isolation valve seat leakage, vacuum breaker stroking, MOV current measurements, and MOV signature analysis. These tests, along with their frequencies, are summarized in Table 2.2.

Table 2.1 Pump tests performed on CCW pumps

Test Performed	Test Frequency (Months)			
	1	3	12	18
1. Measure Vibration Amplitude*	1 unit	10 units	3 units	
2. Measure Pump Head*	3 units	10 units		
3. Measure Suction Pressure*	3 units	8 units		
4. Measure Flow Rate*	2 units	4 units		
5. Measure Bearing Temperature*		5 units		
6. Measure Lubricant Temperature		2 units	2 units	
7. Check Lubricant Level*		4 units		
8. Measure Vibration Acceleration				2 units
9. Measure Motor Voltage/Current	1 unit	1 unit		
10. Performance Test of the Pump		1 unit	1 unit	

*Tests required by ASME Section XI

Table 2.2 Valve tests performed on CCW valves

Test Performed	Test Frequency (Months)							
	3	12	18	24	36	54	60	120
1. Measure MOV Stroke Time*	10 units							
2. Check Valve Leakage*	5 units		4 units					
3. Measure Check Valve Flow*	5 units							
4. Check Remote Position Indicator*			1 unit	2 units	1 unit			
5. Check Relief Valve Setpoint*						2 units	3 units	1 unit
6. Measure Valve Seat Leakage*	1 unit							
7. MOV Signature Analysis			1 unit					
8. MOV Current, Insulation Resistance, Timing Check		1 unit						
9. Vacuum Breaker Stroke	1 unit							

*Tests required by ASME Section XI or Generic Letter 89-04.

Other tests performed on the CCW systems include hydrostatic tests, system logic response tests, and system leakage tests. The hydrostatic tests and system leakage tests are an ASME code requirement, and must be performed every 10 years and three to four years, respectively. The system logic response tests include slave relay tests and automatic actuation of components. Although these tests are good indicators of system integrity and should be continued, they do not provide the type of information that would be useful for trending as an aging indicator. The units performing these tests and their frequency are summarized in Table 2.3.

2.1.2 CCW Inspection and Monitoring Practices

The BNL survey specifically asked for information on inspecting and monitoring CCW pumps, valves, heat exchangers, and electrical components. The information requested included parameters which are monitored/inspected monthly, as well as parameters which are monitored daily, typically using shift logs.

Table 2.3 Miscellaneous CCW system tests

Test Performed	Test Frequency (Months)						
	1	3	12	18	24	40	120
1. Hydrostatic Test							7 units*
2. Slave Relay Test	2 units	3 units					
3. Auto Component Actuation			1 unit	7 units			
4. System Leakage Test		1 unit				1 unit	
5. Protective Relay Test				3 units	1 unit		
6. HX Performance Test				1 unit			
7. Motor Winding Phase/ Polarization Index				2 units			

* 2 other units did not specify frequency

In general, the inspection/monitoring (IM) practices vary from plant to plant. Unlike the testing practices, the survey does not indicate a basic set of IM practices which all units perform. Aside from the daily, routine readings taken during shift watches, most units do not perform any additional inspection or monitoring activities on the CCW system. The few additional IM activities that were reported are not performed by all plants. This could be due to the existence of plant specific problems with a particular component, which necessitate giving it additional attention. The IM practices for CCW pumps, valves, heat exchangers, and electrical components are shown in Tables 2.4 through 2.7, respectively.

Table 2.4 CCW pump inspection/monitoring practices

Inspection/Monitoring Practice	Frequency (Months)		
	1	3	12
1. Check lube oil level	1 unit	1 unit	
2. Check lube oil temperature	1 unit	1 unit	
3. Mechanical seal inspection			2 units

Table 2.5 CCW valve inspection/monitoring practices

Inspection/Monitoring Practice	Frequency (Months)			
	3	18	48	120
1. Check valve inservice inspection	4 units	2 units	1 unit	
2. AOV disassembly inspection		1 unit		1 unit
3. MOV disassembly inspection				1 unit

Table 2.6 CCW heat exchanger inspection/monitoring practices

Inspection/Monitoring Practice	Frequency (Months)		
	12	18	Unspecified
1. External visual inspection			1 unit
2. Open/internal visual inspection	1 unit		
3. Eddy current tubes		1 unit	

Table 2.7 CCW electrical component inspection/monitoring practices

Inspection/Monitoring Practice	Inspection/Monitoring Frequency (Months)							
	3	6	12	18	40	48	60	120
1. Check lube oil level		1 unit						
2. Motor insulation resistance check			3 units	2 units				
3. Motor inspection						1 unit	2 units	
4. Motor space heater check			1 unit	2 units				
5. Monitor stator current			1 unit					
6. Thermoscan							1 unit	
7. Motor disassembly/inspection								1 unit
8. Motor vibration measurement	2 units							
9. EQ inspections					2 units			

All plants have shift watches during which operators walk down the plant, visually inspect the various systems and components, and take various readings from local gauges on the equipment, and from control room gauges. Operating equipment is observed to ensure that there are no unusual noises or operating conditions. These routine observations are typically recorded on a daily log sheet. Twelve units responded to this portion of the survey which identified the most common CCW parameters monitored daily. The results show that a number of different parameters are monitored; however, not all plants monitor all of them. For example, of the 12 units responding to this part of the survey, 5 units monitor CCW pump discharge pressure, while 7 do not. Results for additional parameters are shown in Figure 2.1.

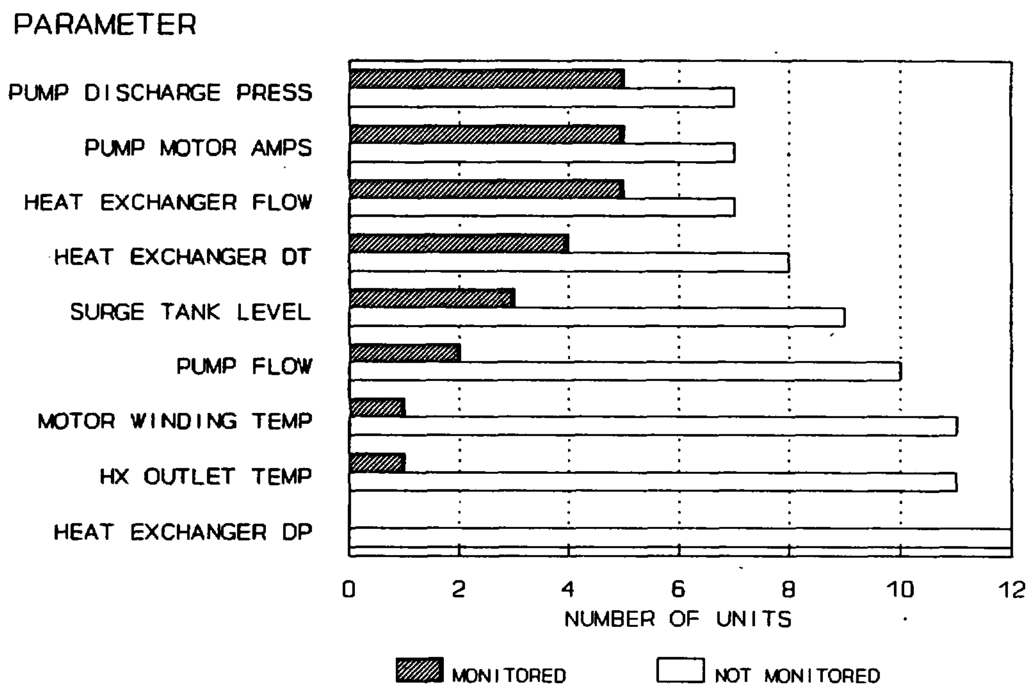

Figure 2.1 Routine CCW parameters monitored

Of the two units monitoring pump flow, one unit reported monitoring it once per hour by computer, while the second unit reported monitoring it once per shift. Although no units monitor heat exchanger pressure drop, two units reported they would monitor it if fouling was suspected. Three units monitor surge tank level once per shift. The unit monitoring heat exchanger outlet temperature reported doing it once every four hours. For heat exchanger delta temperature, one unit monitors it every hour by computer, while three units monitor it once per shift. Monitoring frequencies were not supplied for the other parameters.

2.1.3 CCW Preventive Maintenance Practices

In addition to test and inspection practices, the BNL survey requested information on preventive maintenance (PM) practices currently used by the utilities. The survey addressed five specific types of components; pumps, valves, heat exchangers, electrical components, and instrumentation/controls. Twelve units responded to this portion of the survey.

Ten units do some PM on their pumps, while two units do none, The PM performed includes oil changes, lubrication, alignment, and gasket replacement (Table 2.8). Three units reported doing an overhaul or disassembly inspection as part of their PM practices.

Table 2.8 CCW pump preventive maintenance practices

PM Performed	Frequency (Months)							
	6	12	18	36	48	60	84	90
1. Lube oil system PM	2 units	2 units	2 units					
2. Bearing oil change	1 unit	1 unit						
3. Coupling lubrication		1 unit				1 unit		
4. Coupling alignment				1 unit				
5. Replace Gaskets (EQ)							1 unit	
6. Disassembly inspection					1 unit	1 unit		1 unit

The number of units performing PM for valves varied with the type of valve. Out of ten units responding, 8 reported doing PM on MOVs, while 7 reported doing PM on AOVs. Only 5 said PM was performed on manual valves, and only 3 units reported doing PM on check valves. These differences can be partially attributed to the different valve types, since MOVs and AOVs include valve operators which add to the complexity of the valve and necessitate that they be given more attention. The PM activities include cleaning, lubricating, and replacement of some parts; these are listed in Table 2.9, along with their frequency (note: some units responded with only a yes or no and did not list specific activities).

Table 2.9 CCW valve preventive maintenance practices

Preventive Maintenance Practice	Frequency (Months)							
	3	12	18	36	40	43	48	60
1. MOV: Circuit Breaker Maintenance	1 unit	2 units						
2. MOV: Operator Maintenance		2 units	1 unit	2 units				
3. MOV: Operator EQ Maintenance			2 units		2 units			
4. MOV: Packing Replacement				1 unit				
5. MOV: Motor Replacement								1 unit
6. MOV: Parts Replacement					1 unit			
7. AOV: Lubrication		1 unit						
8. AOV: Packing Replacement							1 unit	
9. AOV: Diaphragm Replacement								1 unit
10. AOV: Parts Replacement						3 units		
11. MAN: Clean/Lube Stem	1 unit	2 units						

PM activities on electrical components include cleaning of air filters and lubrication of bearings. Several units reported doing maintenance on circuit breakers, however, they did not specify what was included. For instrumentation and controls, the maintenance actions reported were all calibrations. Tables 2.10 and 2.11 list the PM activities for electrical components and instrumentation/controls, respectively.

Table 2.10 CCW electrical component preventive maintenance actions

PM Performed	Frequency (Months)			
	6	12	18	24
1. Clean Air Filters	1 unit			
2. Lubricate Bearings	1 unit	1 unit	1 unit	
3. Switchgear Circuit Brkr Maintenance		2 units	2 units	
4. Pump Circuit Breaker Maintenance		1 unit		1 unit

In addition to maintenance, several operational activities are used to mitigate excessive wear on a particular component. All of the 12 units responding to this portion of the survey reported that they rotate their CCW pumps to balance the operating time on each of them. This prevents any one pump from wearing excessivley. However, a disadvantage of pump rotation is that if all pumps wear at the same rate, there is the potential that all will fail at the same time, although the probability is very small. Along with pump rotation, 5 units rotate the use of the CCW heat exchangers. Another practice used by all units is chemical treatment of the CCW water with chromates, hydrazine, or nitrite borate to mitigate corrosion. Table 2.12 summarizes the operational activities used and their frequency.

As part of the BNL survey, the units were asked whether they had a reliability or trend analysis program in place. Ten of the 12 units responding said they did. Four of the ten units reported that they did not have a formal program in place; however, they evaluate NPRDS, ISI/IST, and PM data. Two units reported that they trend valve stroke times, pump head, pump vibration, and bearing temperature. One unit reported trending pump flow, pump head, pump vibration, and motor current. Two units only trend pump vibration.

2.1.4 Summary of Findings

The BNL survey shows that there are various basic inspection, monitoring, and maintenance actions that all units use to mitigate failures. These include monitoring pump head and vibration, stroking valves, and performing system walkdowns (see also Section 7). Some basic actions are required by technical specifications or are code requirements. In addition, there are several other supplemental plant specific activities. These may be done because of the past experience of plant personnel, the plant's operating environment, or they may be the result of a component's performance history. The frequency at which some activities are performed also varies from plant to plant. Therefore, there is probably no one set of generic test, inspection, and maintenance activities that will satisfy the requirements of all plants. The optimum program for any particular plant should be a combination of activities selected based on specific plant conditions.

Table 2.11 CCW instrumentation/control preventive maintenance actions

PM/Calibrations Performed	Frequency (Months)							
	12	18	24	36	48	60	96	120
1. Panel meter				2 units				
2. Surge tank level	1 unit	6 units	1 unit		2 units			
3. Flow indicators	1 unit	6 units	1 unit		2 units			
4. HX flow loops	1 unit		1 unit	2 units				
5. Header press switch	1 unit			2 units	2 units		1 unit	
6. RCP return flow	1 unit		1 unit	2 units				
7. RCP thermal barrier temp.	1 unit		1 unit	2 units				
8. Temp. indicators & alarms	1 unit		1 unit	2 units	2 units			
9. Cont. spray pump seal flow	1 unit							
10. Pump suction press			1 unit	2 units				
11. Pump discharge press	1 unit	6 units					1 unit	
12. Hx outlet temp.	1 unit		1 unit					
13. RCP oil cooler flow				2 units				
14. Motor stator temp.								2 units
15. Motor bearing temp.								2 units
16. Pump bearing temp.								2 units
17. RHR Hx flow alarms				2 units				
18. RTD probe					1 unit			
19. Clean limit switch contacts						1 unit		

Table 2.12 CCW operational activities to mitigate degradation

Operational Activity	Frequency (Weeks)				
	1	2 to 3	4	12	As Required
1. Rotate pumps	4 units	1 unit	3 units	2 units	2 units
2. Rotate heat exchangers	1 unit		2 units		2 units
3. Chemical injection					12 units

2.2 Plant A Data Evaluation

In addition to the survey, interviews were held and data were collected at two operating PWR plants. Plant A has two nuclear units operating at the same site. Each unit is approximately 17 years old and has its own CCW system. The following subsections discuss the system's design, and plant monitoring and maintenance practices.

2.2.1 Plant A CCW System Design

The CCW system at plant A consists of two redundant, safety-related loops and various loops for cooling non-safety-related components (Figure 2.2). The cooling loops are supplied by 3 CCW pumps and 3 CCW heat exchangers, each of which can supply either or both of the safety-related cooling loops. The CCW system is cooled by the service water system, which uses brackish salt water.

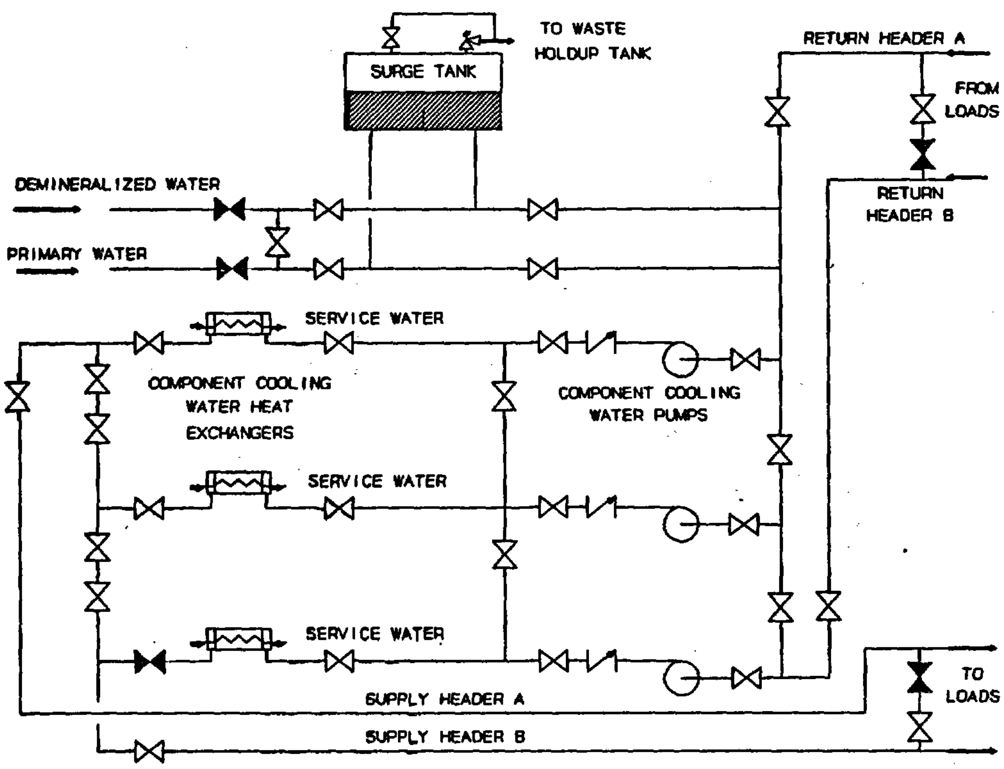

Figure 2.2 Plant A CCW system design

The system is of the closed loop design, with fluid continuously circulating. The three pumps are each 100% capacity, and the three heat exchangers are each 50% capacity. During normal full power operation, two pumps and two heat exchangers will accommodate the heat removal loads. The system also includes a surge tank, and various manual valves, check valves, relief valves, air operated valves (AOVs) and motor operated valves (MOVs).

The CCW system is considered an engineered safeguard system since it is vital during recovery from an accident. Therefore, it consists of two independent Seismic Category I loops (Header A and Header B), each of which serves a single train of identical engineered safety feature (ESF) components. The redundant loops assure cooling to at least one train of safety-related components (i.e., residual heat removal pumps, containment spray pumps, RHR heat exchangers, etc.). There are also various non-ESF equipment supplied by the A and B headers through the appropriate valving.

Tie headers are located at the suction and discharge of the CCW pumps and at the discharge of the CCW heat exchangers. These tie headers allow any pump or any heat exchanger to supply either or both headers. Normally, the system is aligned to the B header.

2.2.2 Plant A Inspection, Surveillance, and Monitoring Practices

The inspection, surveillance, and monitoring (ISM) practices used at plant A include actions which are performed periodically, on a weekly or monthly basis, as well as actions which are performed on a daily basis, as part of the shift watch. The daily practices include system walkdowns to check for visual or audible abnormalities in operating equipment, and to monitor operating parameters. No formal procedures are used and findings are recorded on log sheets. The parameters monitored are summarized in Table 2.13.

Table 2.13 CCW parameters monitored daily for plant A

Parameter	Frequency
1. CCW flow to/from loads	4 to 24 hours
2. CCW temp. to loads	4 to 24 hours
3. CCW surge tank level	4 hours
4. CCW pump discharge pressure	4 hours
5. CCW Hx outlet flow	8 hours
6. Check for unusual noise	4 hours
7. Check for unusual leakage	4 hours

The practices performed periodically include tests and inspections which require formal procedures, and are done to satisfy plant technical specifications or code requirements. However, some periodic activities are performed as a result of past plant experience or equipment history.

CCW pump activities at plant A are performed under two procedures; an inservice test procedure and a general inspection procedure. The test procedure is performed quarterly to satisfy ASME section XI pump testing requirements; it includes measurement of pump head, vibration, bearing temperature, seal leakage, and motor amps. All parameters are trended using the test results. The general inspection procedure, performed monthly, includes checks for excessive or unusual noise, a lube oil analysis, inspection of the seals for leakage, and inspections for corrosion and erosion on the pump externals. Disassembly inspections and non-destructive examination (NDE) techniques are not performed routinely. CCW pump activities are summarized in Table 2.14.

Table 2.14 Plant A CCW pump ISM practices

ISM Practice	Frequency	Trending
1. Check lube oil level	Daily	No
2. Perform lube oil analysis	Monthly	No
3. Inspect for external corrosion/erosion	Monthly	No
4. Measure vibration	Quarterly	Yes
5. Measure differential pressure	Quarterly	Yes
6. Measure bearing temperature	Quarterly	Yes
7. Measure seal leakage	Quarterly	No
8. Measure motor amperage	Quarterly	No
9. Perform thermography exam	Quarterly	Yes
10. Inspect for casing/shaft cracks	At Overhaul	No
11. Inspect for shaft warpage	At Overhaul	No
12. Inspect impeller/seals/internals	At Overhaul	No

ISM practices for the CCW valves are performed when preventive maintenance is needed. During the system walkdowns, the valves are visually inspected for gross leakage and the valve's position (open/closed) is checked; however, no other actions are performed. When PM is performed on the valves, which typically occurs during cold shutdown or refueling outages, the valves are disassembled and thoroughly inspected for wear, corrosion, erosion, pitting, distortion, and any other degradation. Any part found to be unacceptable is replaced. The parts are then cleaned and lubricated, if applicable, and the valve is reassembled, typically with new gaskets. Depending on the type of valve, other checks and inspections are made. For example, on MOVs, the limit and torque switches are inspected, cleaned, lubricated, and calibrated. A complete listing of valve ISM practices is presented in Table 2.15.

CCW heat exchanger performance is monitored by visual inspections to detect erosion, corrosion, and leakage, as well as by eddy current tests to determine if there is excessive thinning of the tube wall, or if there are any cracks in the tubes or shell. Tube fouling is determined, based on heat balances using inlet and outlet temperatures and flow rates. The amount of fouling is correlated with the service water temperature required to meet the cooling load, and curves are plotted for use by the operators. The actual temperature of the service water, which is used to cool the CCW heat exchangers, is monitored and compared to these fouling curves. When the actual service water temperature exceeds the required service water temperature, the heat exchangers are cleaned and new gaskets are typically installed. Table 2.16 lists the heat exchanger ISM practices.

Table 2.15 Plant A CCW valve ISM&M practice

Valve Type	ISM&M Practice	Frequency
All	Visually inspect for gross leakage	Daily
MOVs	Disassembly inspection and overhaul - Clean/inspect parts for wear/corrosion/erosion - Lubricate moving parts - Replace degraded parts as needed - Check electrical connections for tightness - Inspect, clean electrical contacts/controls - Inspect wiring for cracks/brittleness/abrasions - Check lube oil for water/dirt/foreign material - Adjust torque/limit switch settings - Measure motor current - Measure stroke time - Verify position indicator functioning - Install new gaskets	18 Months
	MOVATS testing - Measure stem thrust - Measure motor current - Check operator alignment - Perform signature analysis - Check stem play	5 Years or after Overhaul
AOVs	Disassembly inspection and overhaul - Clean/inspect parts for wear/corrosion/erosion - Replace degraded parts as needed - Lubricate moving parts - Adjust limit switches - Clean air filter - Clean and calibrate pressure regulator - Adjust actuator spring tension - Bench test the actuator	18 Months
Manual	Inspection and Lubrication - Clean studs/nuts/stem/reach rod - Inspect parts for wear/corrosion/pitting/scaling - Inspect packing for leaks - Inspect handwheel for cracks/loose nuts - Inspect bonnet/body for cracks/corrosion/leaks - Inspect reach rods for binding/distortion - Lubricate moving parts	6 Months
	Stroke Valve Open/Closed	18 Months
Relief	Bench test	5 years

Table 2.16 Plant A CCW heat exchanger ISM practices

ISM Practice	Frequency
Visually inspect for gross leakage	Daily
Monitor heat exchanger flow	Daily
Monitor cooling water temperature at load	Daily
Measure shell/tube thickness	18 Months
Check for shell/tube cracks	18 Months
Inspect for corrosion/erosion	18 Months

2.2.3 Plant A Preventive Maintenance Practices

The maintenance practices are all performed using formal procedures. Each component has at least one procedure specifically written to address preventive maintenance, and is typically performed quarterly. The maintenance actions are based on manufacturer's recommendations and past operating experience.

During every refueling outage, one of the CCW pumps is overhauled. Of the three pumps, the one selected for overhaul is based on the number of outstanding maintenance work requests (MWRs) on the pumps, as well as the time since the last overhaul. As part of the overhaul, the pump is disassembled and thoroughly inspected for signs of wear, erosion, corrosion, and degradation, and any parts showing abnormal degradation are reworked or replaced. All moving parts within the pump are lubricated, and a lube oil analysis is performed. A lube oil analysis is also performed monthly by a separate procedure, and the lube oil is changed when warranted. Table 2.17 summarizes the CCW pump preventive maintenance practices.

Table 2.17 Plant A CCW pump preventive maintenance practices

PM Practice	Frequency
Change lube oil	As Needed
Replace gaskets	As Needed
Replace seals	As Needed
Replace bearings	As Needed
Rework impeller	As Needed
Replace wear rings	As Needed
Retorque bolts	Overhaul*
Lubricate moving parts	Overhaul*
Check for casing/shaft cracks	Overhaul*
Check for shaft warpage	Overhaul*
Realign pump and motor	Overhaul*

* At least 1 pump is overhauled every refueling outage.

As part of this study, the plant maintenance practices and the manufacturer's recommended maintenance practices were compared. According to the manufacturer's literature, maintenance on this type of pump should include changing the bearing oil periodically, lubricating all couplings, and overhauling the unit when performance drops off. Disassembling the pump for inspection is not recommended unless there is evidence of internal problems. When the pump is overhauled, the inside waterways of the casing should be cleaned and painted to resist rust and erosion. An overhaul also should include an inspection of wear rings for excessive wear, an examination of the shaft for rust, pits or distortion, and an examination of the bearings for wear, cracks, or scratches. A comparison with the plant practices indicates that all manufacturer's recommendations are addressed, with the exception of painting the casing waterways. This item should be considered as an addition to current plant practices, since it would help to mitigate long term corrosion and erosion of the casing, which is not currently addressed. Disadvantages of this practice which should also be considered are peeling of the paint, which could clog downstream equipment, and the additional maintenance required to repaint the surfaces periodically.

Valve maintenance is also performed during overhaul for MOVs and AOVs, which are overhauled every 18 months during refueling outage. Manual valves are inspected and lubricated every 6 months, as specified in the manufacturer's recommendations, and overhauled when necessary. No other maintenance is recommended by the manufacturer for manual valves. During overhaul of MOVs and AOVs, the valve and operator are disassembled and inspected for excessive wear, erosion, or corrosion. Any parts found to be excessively degraded are reworked or replaced. Following the overhaul of MOVs, MOVATS testing is also performed to measure operator thrust, as well as stroke time, torque and limit switch settings, and motor current signature during operation. The results from the MOVATS tests are recorded and trended. Table 2.15 includes the CCW valve maintenance practices.

The only preventive maintenance performed on the CCW heat exchangers is to clean the tubes when fouling has become unacceptable. This is determined using fouling curves developed from past operating data, and by comparing the heat transfer characteristics to the temperature of the service water available. A formal procedure is used for the tube cleaning, which includes replacing head gaskets and retorquing bolts. At every refueling outage, a full eddy current test of all tubes is performed to determine if any cracking or wall thinning is present. Any tubes that are cracked or have their wall thickness reduced by more than 60% are plugged. A summary of heat exchanger maintenance practices is presented in Table 2.18.

Table 2.18 Plant A CCW heat exchanger preventive maintenance practices

PM Practice	Frequency
Clean tubes	As Needed
Replace gaskets	As Needed
Plug crack/thinned tubes	As Needed
Retorque bolts	As Needed

2.2.4 Plant A Corrective Maintenance Events

To understand the effectiveness of the IS&M and PM practices currently used at Plant A, an analysis was made of the corrective maintenance (CM) events needed for CCW system components. Plant records covering two years from 1988 to 1990 were obtained, and reviewed to identify any problem areas not addressed by current practices. The data included 254 CM events from both units at the plant site, each of which has its own CCW system.

The majority of CM events are related to valves (47%), followed closely by instrumentation and controls (44%), as shown in Figure 2.3. Pumps (8%), and heat exchangers (1%) account for a very small percentage of the CM events. Since these results are not normalized to account for the numbers of components, the relatively large percentage of CM events for valves and I&C can be attributed to the large number of these components found in the plant. These results are typical of those found in the previous Phase I study, and show where the predominant CM effort is expended. As indicated in Figure 2.3, the majority of the CM events are related to aging of the components.

A closer examination of the valve CM events, which totaled 119, shows that by far the type of valve most commonly requiring CM is the manual valve (70%), as shown in Figure 2.4. This is followed by the air operated valve, the motor operated valve, the relief valve, the check valve, and the solenoid operated valve. Again, these results are not normalized, therefore, population effects contribute to the relative percentages. The fact that manual valves require the most CM does not, by itself, mean that current ISM and PM practices for this component are inadequate.

Since manual valves account for most of the CM activities (83 events), the data were examined to identify their failure modes. The predominant failure mode was found to be packing leaks (30%), followed by binding of the valve (20%), failure of the operating chain or reachrod (12%), and broken or missing handwheels (11%), as shown in Figure 2.5. The packing leaks are typically detected by visual inspection, however, there was one incident where the packing blew out of the valve completely, resulting in a relatively large leak. The leak was detected by observing that the surge tank required an excessive amount

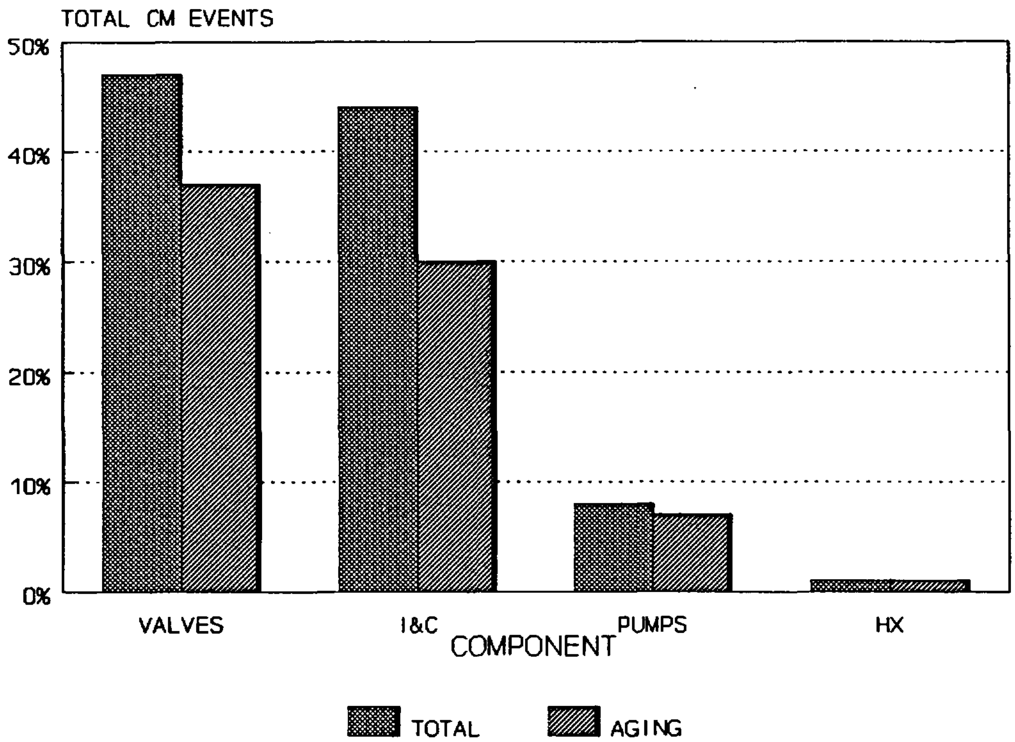

Figure 2.3 Plant A corrective maintenance events

of makeup water. CM events attributed to binding had several causes, including packing that was adjusted too tightly, gear box problems, and malfunction of the operator.

The 27 CM events for air operated valves (AOVs) and motor operated valves (MOVs) were also reviewed to identify failure modes (Figure 2.6). As for the manual valves, the predominant failure mode was packing leaks (19%), along with seat leakage (19%), excessive stroke time (19%), and failure to open or close (19%). Again, the packing leaks are typically detected by visual observation and usually require readjustment or replacement of the packing. The seat leakage problems were typically associated with the AOVs, and were due to incorrect stroking of the valve, which prevented it from fully closing. This was usually corrected by readjusting the stroke settings.

From the analysis of the valve data, one area that might benefit from increased attention is valve packing inspections. Consideration should be given to replacing the packing, or, as a minimum, readjusting it regularly to mitigate the number of leaks experienced. It should be noted that occasional CCW valve packing leaks are a relatively minor problem, which can usually be dealt with without shutting down the plant. However, if the root cause of the failure is not corrected, the packing failures may become more frequent as the component

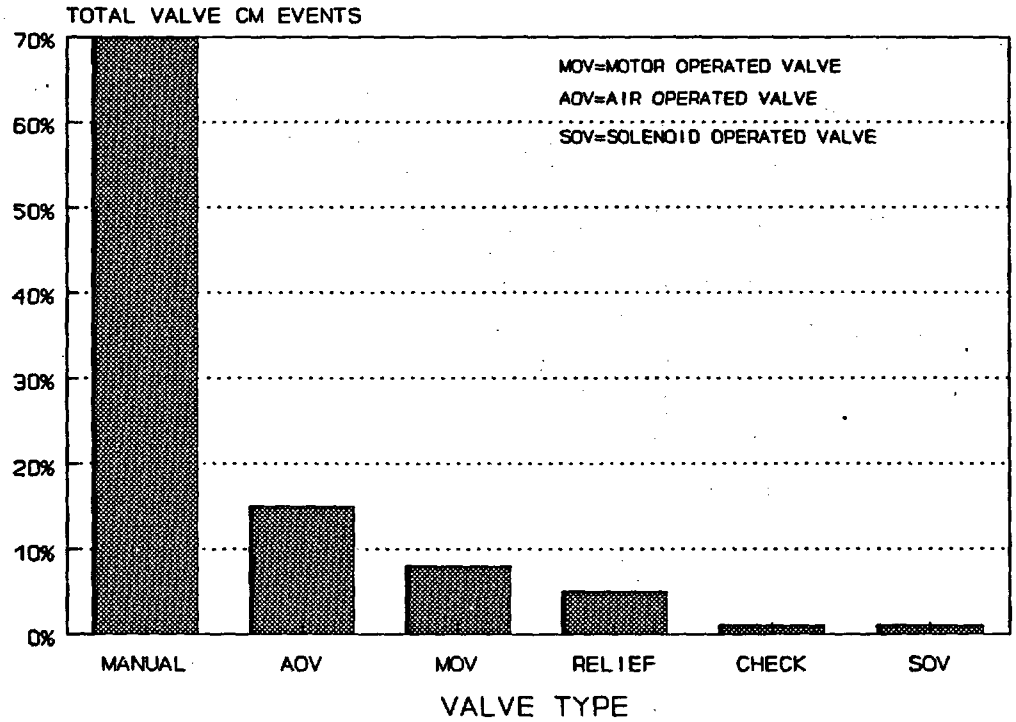

Figure 2.4 Plant A valve types requiring CM

ages. Therefore, in addition to checking the packing, the structural subcomponents interacting with the packing should also be examined for signs of long term aging. This includes the stuffing box, packing gland, and valve stem. Long term aging effects such as distortion, pitting, scoring, or cracking can result in premature failure of the packing. This type of degradation may take many years to manifest and become a serious problem; therefore, techniques to detect it may not be included in the periodic inspections. Since it could cause increasing failure rates, it is important that it be considered.

The plant data were also analyzed to identify the types of I&C components receiving CM. As shown in Figure 2.7, of the 111 CM events, indicators (73%) were by far the predominant I&C component receiving CM, while controllers (16%) and transmitters (11%) contributed only a small part of the I&C CM activities. The most common failure mode was incorrect reading (50%), followed by broken face glass (20%), bent or broken indicator (12%), and leaky fittings (5%), as shown in Figure 2.8. Indicator failures giving an incorrect reading typically involved the instrument reading no flow with flow in the line, or reading a flow with the system shutdown. Failures involving incorrect reading can be aging related; however, failures involving breaking of the face glass or bending of the indicators are not.

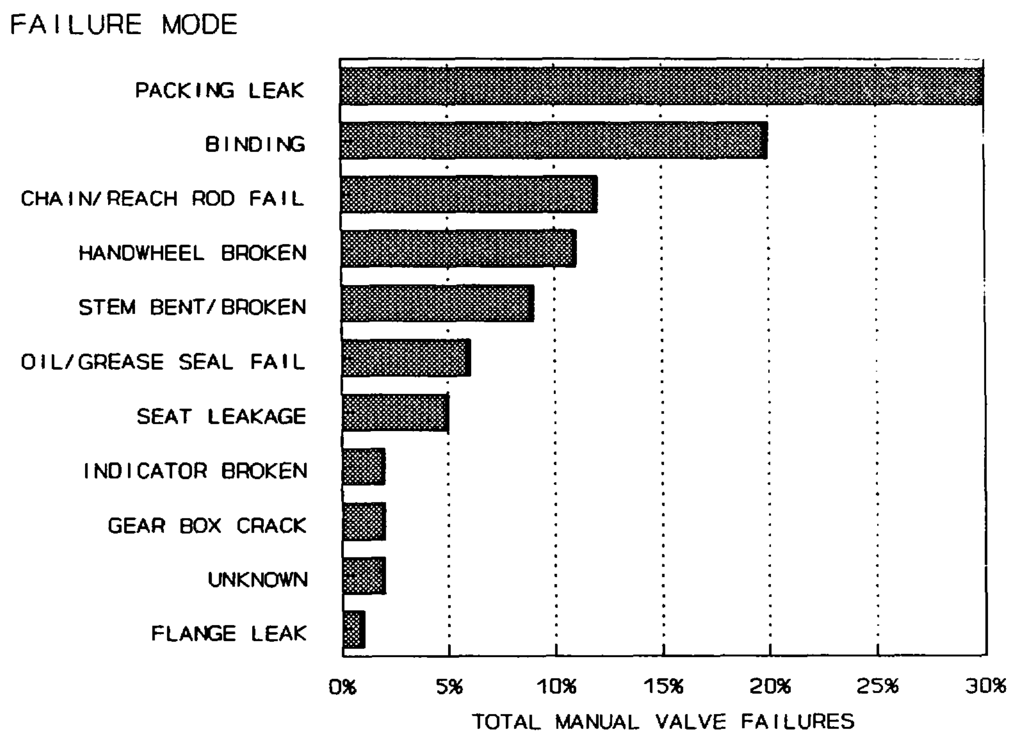

Figure 2.5 Plant A manual valve failure modes

Relatively few pump CMs were found in the two years of data reviewed (20 events). However, the pumps are a very important component for CCW system reliability (Figure 1.6), therefore, effective pump ISM and PM practices are critical. The pump failure modes identified from the data showed that 45% of the pump CMs were due to leakage of the water seals (Figure 2.9), followed by leakage of the oil seals (35%), breakage or leakage from the constant level oiler (15%), and loosening of the slinger ring (5%). The failures related to leakage of the water and oil seals were all detected by visual observation. A thorough inspection of the seals is made every time the pumps are overhauled, during refueling outages when at least one pump is overhauled. Since not all pumps are overhauled during refueling, some of the pump seals may not be given a thorough inspection for several years. This contributes to the fact that seal degradation is usually not detected until failure occurs.

With the redundancy built into the system design, occasional pump seal leaks do not seriously impact CCW system availability or reliability. They are typically handled without shutting down the plant, although a limiting condition for operation (LCO) state may be entered. However, the cause of the seal failures may be due to undetected aging degradation of structures internal to

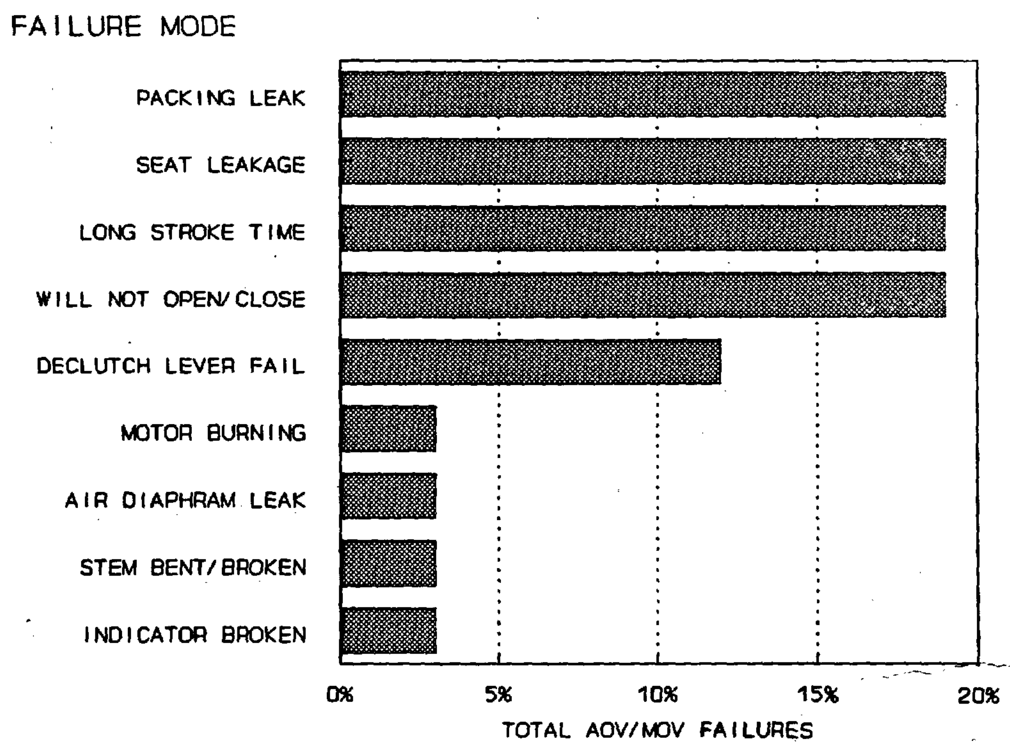

Figure 2.6 Plant A AOV and MOV failure modes

the pump casing, such as support structures or mounting surfaces. Over the years, clearances can change or parts can become distorted, resulting in increased wear on the seals. If the frequency of seal failure increases, it may decrease system availability and reliability. Therefore, it is important to trend the nature and frequency of component failures with time. Although the failed subcomponent has been replaced, the underlying cause of the failure may not have been corrected.

The corrective maintenance data are also useful for evaluating the effectiveness of preventive maintenance practices. One method of doing this is to construct time-lines representing the PM/CM history of a particular component. By comparing the relative frequency of PM events with the resulting CM events, the strengths and weaknesses of the various PM activities can be determined. This was done on a trial basis for two years (June 1988 to June 1990) for three of the components from plant A; a manual valve, a motor operated valve, and a pump.

The manual valve selected for the time-line analysis is a CCW isolation valve from a non-regenerative heat exchanger. The data show that for the time period examined, no preventive maintenance was performed on this valve (Figure 2.10).

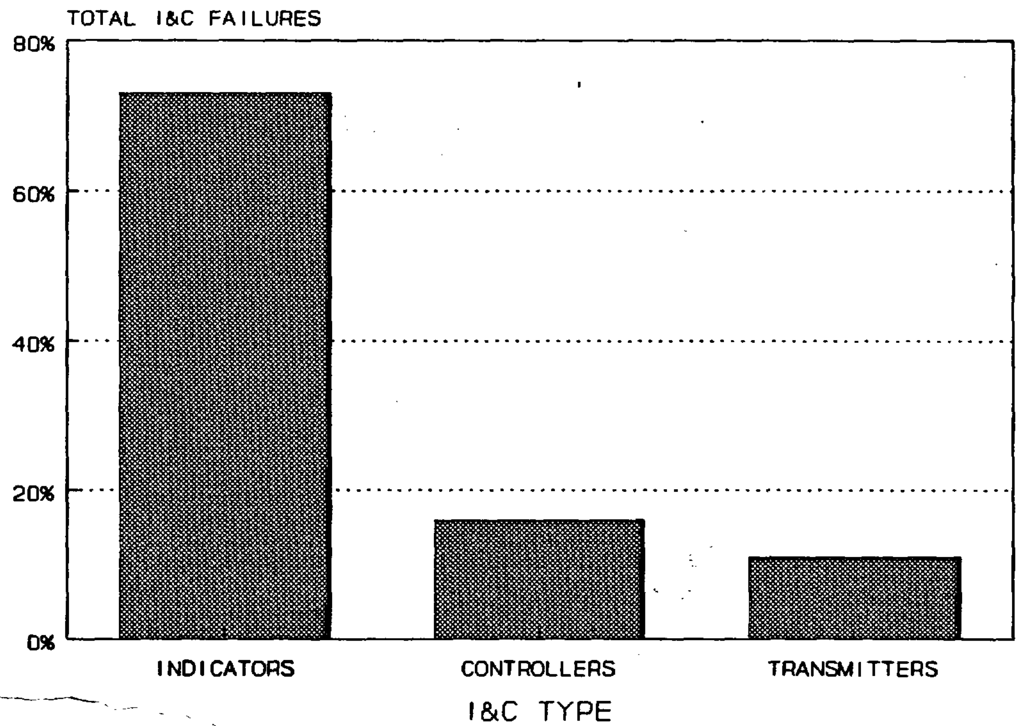

Figure 2.7 Plant A I&C components requiring CM

This is in contrast to the plant's practice of inspecting and lubricating manual valves every 6 months, as stated previously. It is possible that the PM actions were performed but never recorded, however, the time span includes at least four scheduled inspections, and none are shown in the data. The data for other manual valves show that these inspections are typically recorded. It is also possible that certain manual valves are not considered important enough to warrant periodic maintenance, and this particular valve may be in that category, or this valve may be in a high radiation area and ALARA concerns prevent regular preventive maintenance.

There were three instances of packing leaks in this manual valve in 1989, approximately 2 months apart (Figure 2.10). The first two instances were detected visually, and the valve packing was adjusted. In the third instance, the packing was blown out of the valve resulting in a relatively large leak. This caused the surge tank level to drop and makeup water to be added to the system. These two indicators were used to detect the third leak. After this occurrence the valve was rebuilt.

Analysis of this valve history indicates that the valve packing problem should have received more attention. It is possible that the packing was

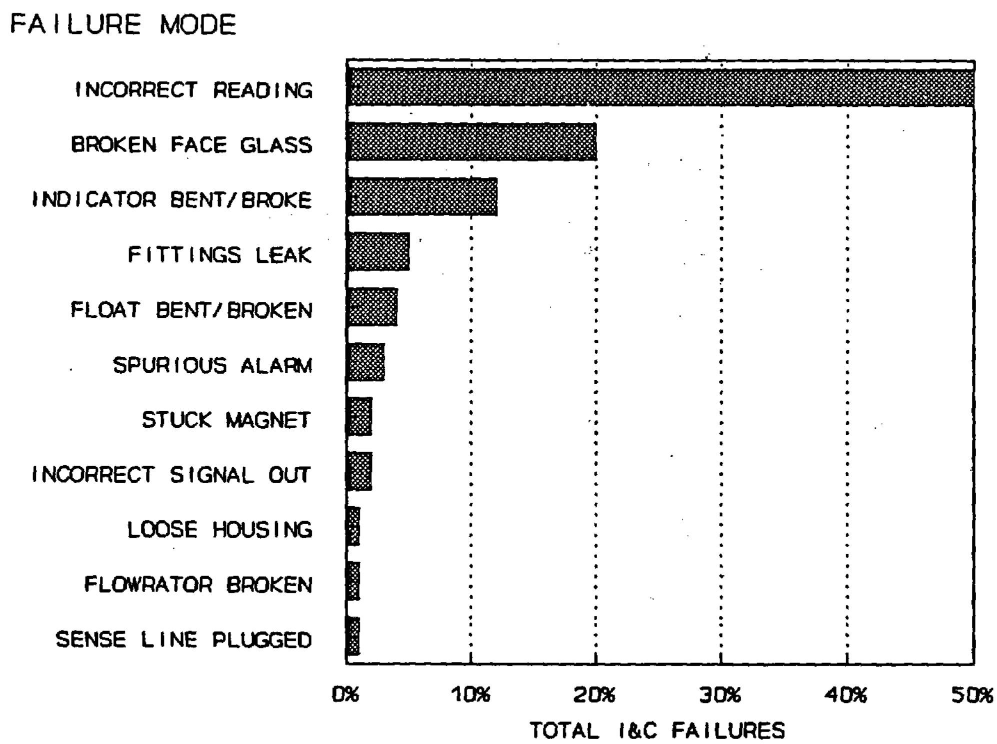

Figure 2.8 Plant A I&C component failure modes

installed or adjusted improperly, or the wrong packing was used. It is also possible that the packing had reached the end of its useful life. In cases such as this, where repeated failures occur, a root cause evaluation should be performed. Although the failures of this valve did not have a major impact on the system, a similar failure of a more critically located valve might adversely affect the system's availability.

A similar time-line history was generated for a motor operated valve (Figure 2.11). The valve is a CCW isolation valve at the outlet of an RHR heat exchanger. There were three incidents of packing leaks for this valve; one occurring two months after an EQ inspection of the valve in 1988. Following each repair, a post maintenance test was performed to check motor current and verify proper operation. Since MOVs are a more complicated component than manual valves, it is expected that they would fail more often. This was found to be the case in the Phase I CCW study[9]. The fact that this plant does not have a higher failure rate for the MOVs suggests that their maintenance and monitoring practices are effectively detecting and mitigating aging degradation before it results in failure. Aside from the packing leaks, no serious failures of the valve were experienced.

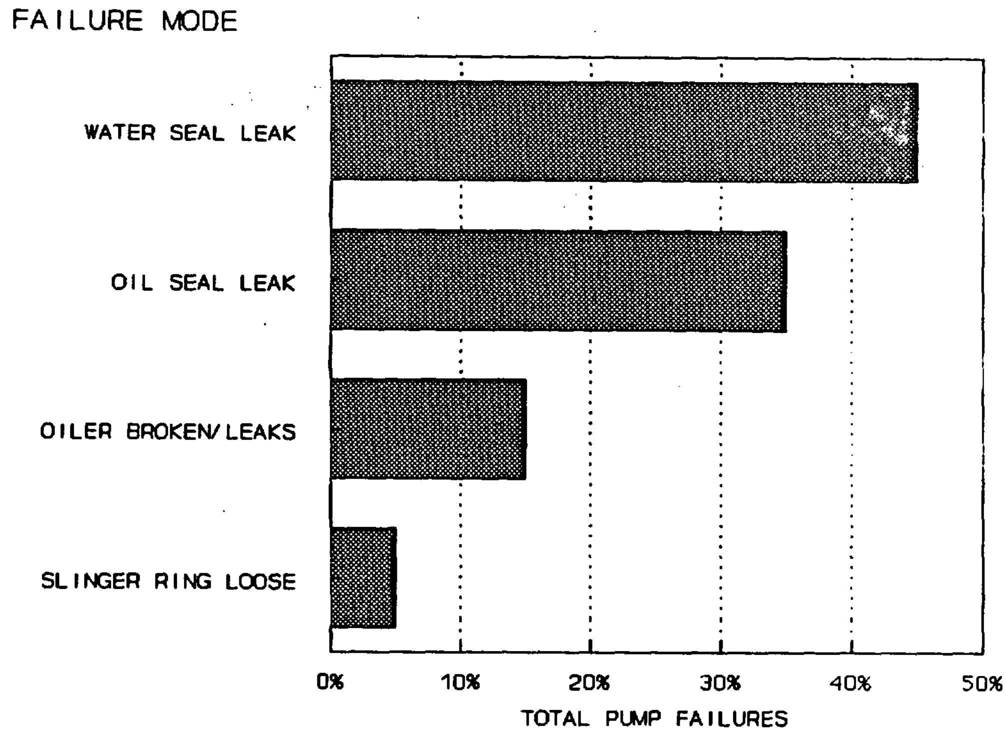

Figure 2.9 Plant A pump failure modes

The last component analyzed using the time-line history method was one of the CCW pumps (Figure 2.12). The pump history shows that quarterly inspections and bearing oil changes were performed regularly. The only failures were a water seal leak and a bearing oiler leak. The pump uses a gravity-fed, constant level oiler to lubricate the bearings. From the previous discussion on plant ISM practices, the quarterly pump inspection includes measurement of seal leakage; however, the results are not trended (Table 2.14). The time-line history shows that seal failure occurred approximately two months after the quarterly inspection, suggesting that the inspection may not have effectively determined the extent of seal degradation. One improvement might be to trend the results of the leakage measurements. An increasing amount of leakage could indicate increasing degradation. In addition, a more thorough inspection of the seal subcomponents may be required. Since this may require some disassembly of the pump, it should only be performed if some other indication of a seal problem is apparent.

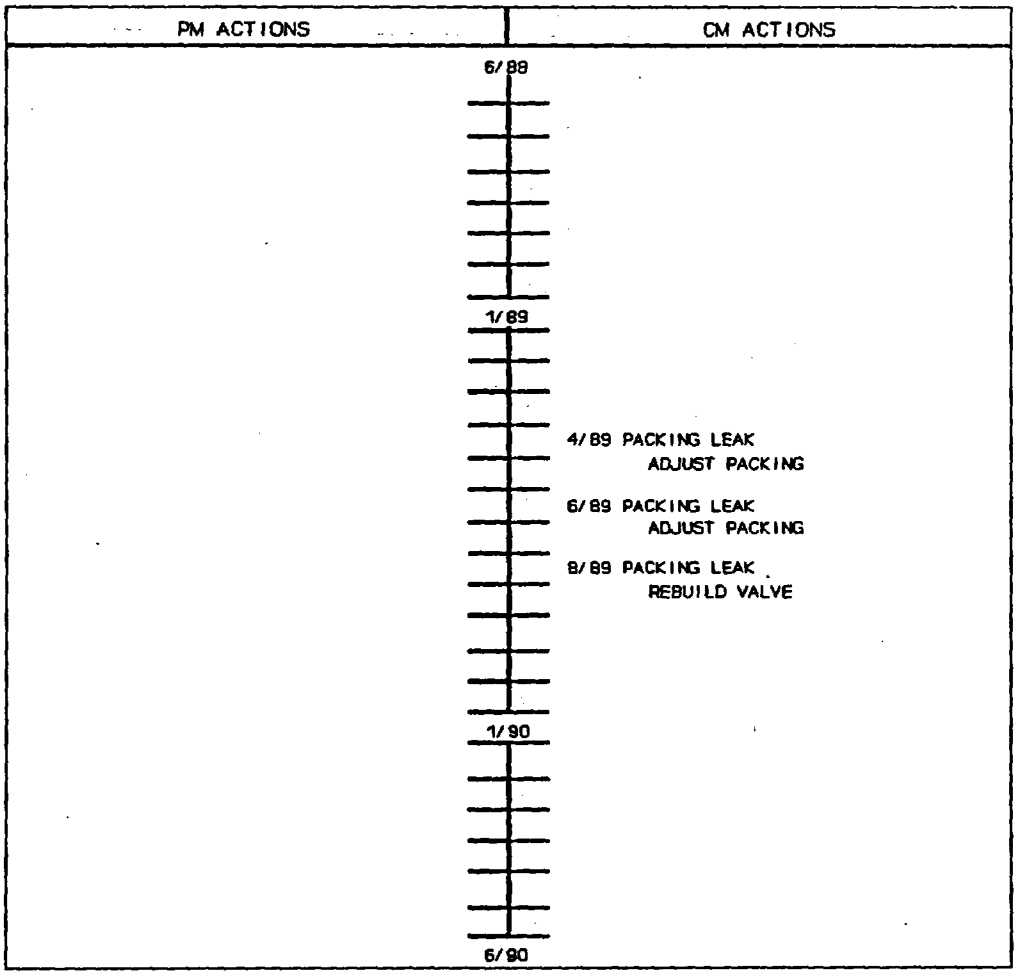

Figure 2.10 Plant A manual valve time-line history

2.2.5 Summary of Plant A Findings

Examination of the corrective maintenance data for plant A indicates that their inspection, surveillance, monitoring, and maintenance practices are effective at detecting and mitigating gross forms of aging degradation. This conclusion is based on the fact that for the two years of data examined, the only component failures occurring involved seal or packing leaks which did not result in loss of component function and were relatively easy to repair. There were no serious failures involving complete loss of the component or loss of system function. This analysis is limited, however, because only two years of data were available for analysis. The effectiveness of current practices at

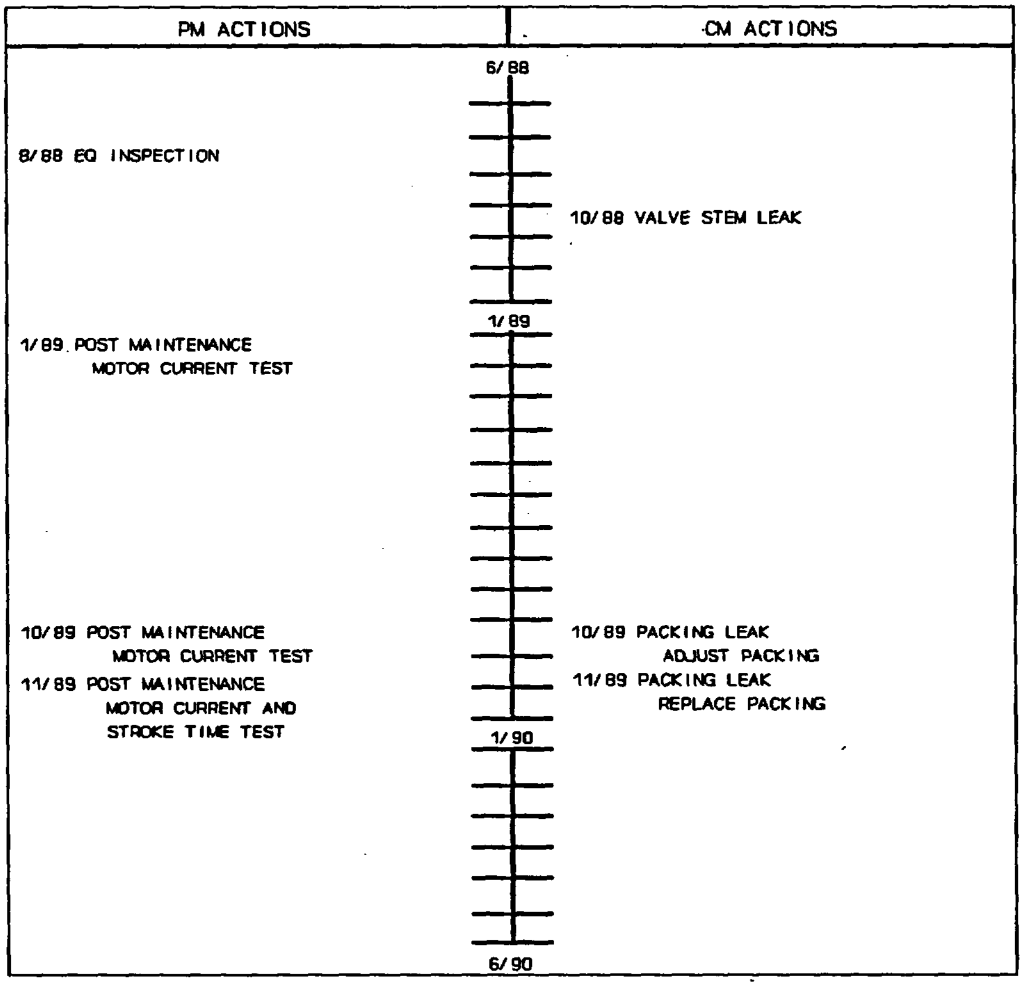

Figure 2.11 Plant A MOV time-line history

managing aging mechanisms that require a longer time period to manifest can not be evaluated. For example, corrosion or erosion of a pump casing may require twenty years or more to result in a detectable failure. If techniques are not in place to measure casing wall thickness periodically, no evidence will ever exist that current practices are not effectively controlling this aging-related failure mechanism until a failure occurs. Therefore, although current practices appear to be managing the most common aging-related failure mechanisms, attention needs to be given to detecting the less obvious mechanisms which require a longer time period to result in failure.

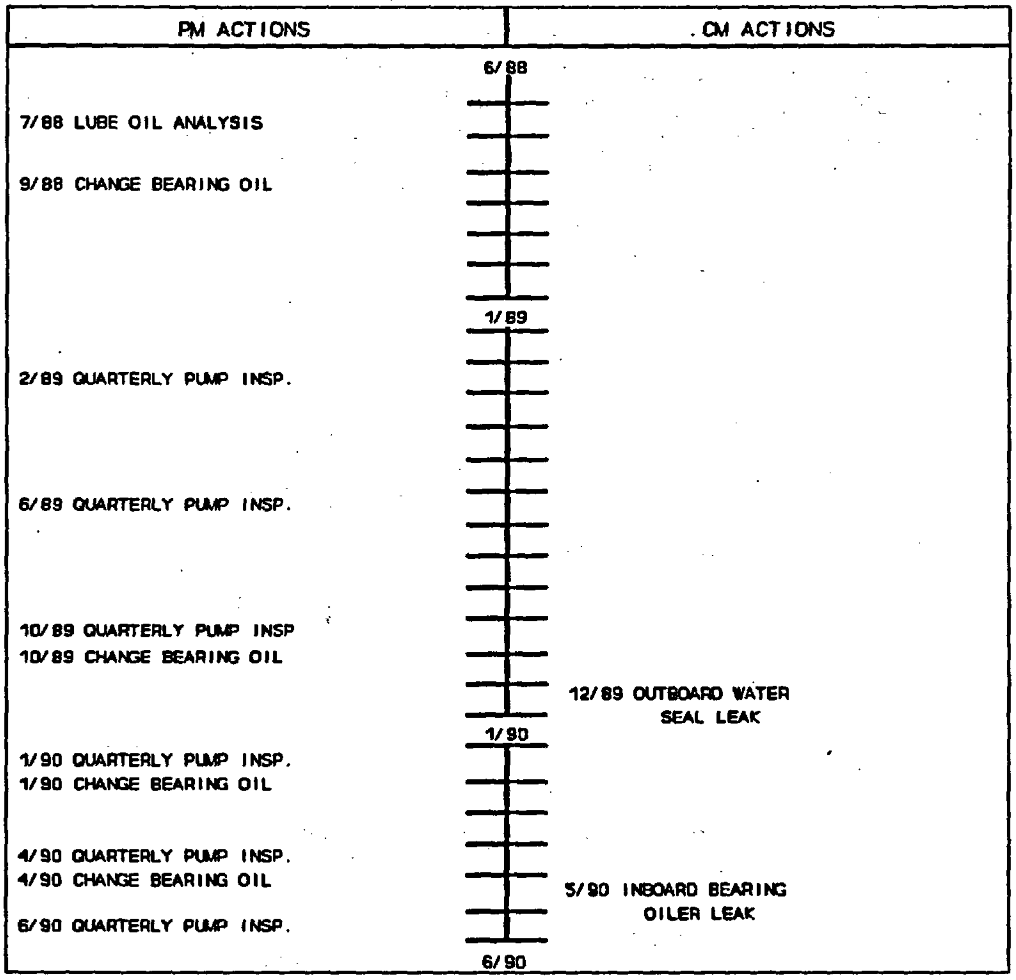

Figure 2.12 Plant A CCW pump time-line history

2.3 Plant B Data Evaluation

The second plant visited to collect CCW information also is approximately 17 years old but has one reactor unit on site. As for plant A, information was collected on CCW system ISM&M practices and a list of corrective maintenance events was obtained for the past several years for plant B. This section will discuss the analysis of that information.

2.3.1 Plant B CCW System Design

The plant B CCW system design includes three pumps, two heat exchangers, and one surge tank (Figure 2.13). The pumps are of the horizontal, centrifugal type with a capacity of 3600 gpm, an operating pressure of 150 psig, and a design temperature of 200°F. The pumps are driven by 250 HP motors and are equipped with mechanical seals. The heat exchangers are tube and shell type, and are cooled by service water from a nearby river on the tube side.

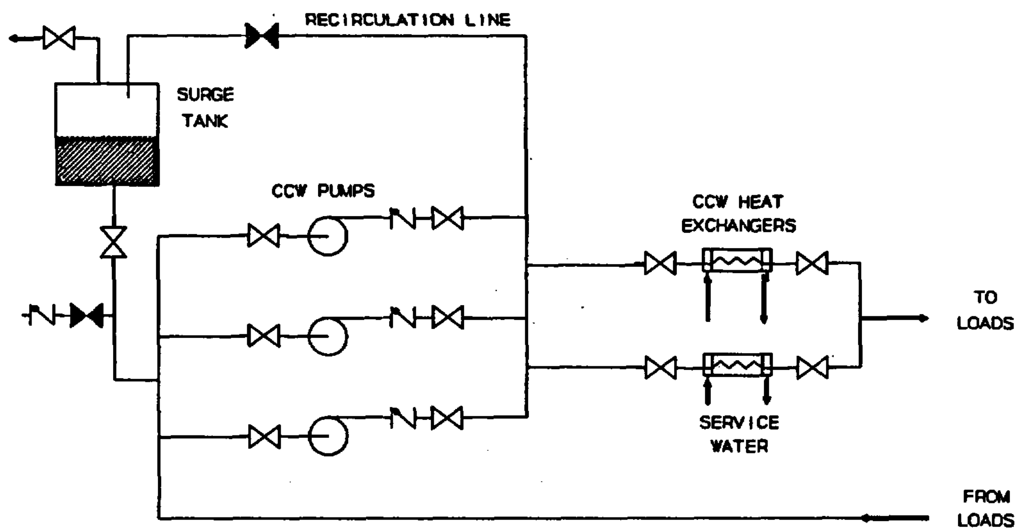

Figure 2.13 Plant B CCW system design

During normal powered operation, two pumps and two heat exchangers are required to be in service. The pumps discharge into a common 20 inch header. From the header, the flow is directed to the shell side of the heat exchangers through two separate 14 inch tributary headers. The heat exchanger outlets are headered together in a 20 inch supply line which directs cooling flow to the various plant loads.

The surge tank accommodates expansion, contraction, and in-leakage of water, as well as providing a reserve supply of cooling water in the event of a system leak. The surge tank is normally vented to the atmosphere. In the event of a radiation leak into the CCW system, the vent valve closes automatically. The working fluid in the CCW system is purified water treated with potassium chromate as a corrosion inhibitor.

2.3.2 Plant B Inspection, Surveillance, and Monitoring Practices

The format of the ISM practices used at plant B is similar to that used at plant A in that some practices are performed daily, while others are performed quarterly or yearly. The daily activities include system walkdowns to check for visual or audible abnormalities in operating equipment, and to monitor various operating parameters. Formal procedures are not required and findings are recorded on log sheets. The CCW operating parameters monitored daily are shown in Table 2.19.

Table 2.19 CCW parameters monitored daily for plant B

Parameter	Frequency
1. CCW flow to/from loads	4 hours
2. CCW temperature to loads	4 hours
3. CCW surge tank level	4 hours
4. CCW pump suction temperature	4 hours
5. CCW HX outlet flow	4 hours
6. Check for unusual noise	4 hours
7. Check for unusual leakage	4 hours

The ISM practices performed periodically are typically required to satisfy plant technical specifications or code requirements. Formal procedures are required to perform them. CCW pump practices include a quarterly test which measures pump head, vibration, and bearing temperature to satisfy ASME code requirements. In addition, pump seal leakage is measured quarterly. The lube oil level is checked daily during the system walkdown, and every 6 months a lube oil analysis is performed. If there is evidence of deterioration or contamination, the lube oil is changed. Every two years the pump is disassembled and thoroughly inspected for internal corrosion and erosion. In addition, the impeller, seals, and bearings are examined for signs of wear. The casing and shaft are visually inspected for cracks. However, non-destructive examination (NDE) techniques, such as dye-penetrant or eddy current testing, are not used to detect hidden flaws. A dial indicator is used to measure shaft warpage, and wear ring clearances are measured. Any parts showing unacceptable degradation are replaced or refurbished. The pump ISM practices are summarized in Table 2.20.

The ISM practices for CCW valves also are similar to those at plant A, however, the frequencies are different. As at plant A, all valves are visually inspected daily during system walkdowns to check for gross leakage. For the MOVs, a stroke time test is performed every cold shutdown. Disassembly inspections are not performed unless there is evidence of a problem with the valve. MOVATS testing is being instituted, and will be performed every 5 years or after an overhaul. The AOVs are stroke tested quarterly. As for the MOVs, disassembly inspections are not made unless there is a problem with the valve. For the manual valves, there are no scheduled actions. This is in contrast to plant A, which strokes and lubricates the manual valves every 6 months. The CCW relief valves are bench tested every 5 years. The ISM actions for CCW valves at plant B are summarized in Table 2.21.

Table 2.20 Plant B CCW pump ISM practices

ISM Practice	Frequency	Trended
1. Check lube oil level	Daily	No
2. Measure vibration	Quarterly	Yes
3. Measure differential pressure	Quarterly	Yes
4. Measure bearing temperature	Quarterly	Yes
5. Measure seal leakage	Quarterly	No
6. Perform lube oil analysis	6 months	No
7. Inspect for corrosion/erosion	2 years	No
8. Inspect impeller/seals/internals for wear	2 years	No
9. Check rotor torque	2 years	No
10. Inspect for casing/shaft cracks	2 years	No
11. Inspect for shaft warpage	2 years	No
12. Inspect bearings/shaft sleeves for wear	2 years	No
13. Measure wear ring clearance	2 years	No

ISM practices for the CCW heat exchangers at plant B are limited to daily observations of heat exchanger flow and temperature at the loads. These parameters are used as indicators of heat exchanger performance. Plans are being made to institute inspections for tube leakage and tube fouling. Table 2.22 lists the heat exchanger ISM practices for plant B.

2.3.3 Plant B Preventive Maintenance Practices

The preventive maintenance (PM) practices are performed using formal procedures; however, many of the PM actions are only performed on an as-needed basis. Therefore, for these components, certain PM actions are not performed unless there is some indication that the component requires attention. For example, seals are not replaced unless there is some indication that the existing seal is degraded to an unacceptable level. This is similar to the practice at plant A for some PM; however, plant A schedules more overhauls based on operating time, without requiring a degraded condition as a prerequisite.

Pump PM practices include lube oil changes and lubrication of motor bearings and pump couplings. The remaining pump PM actions are performed only if pump performance degrades. In this case, the pump may be disassembled and inspected to determine and correct the cause, or it may be overhauled completely. The pump PM actions for plant B are summarized in Table 2.23.

Table 2.21 Plant B CCW valve ISM&M practice

Valve Type	ISM&M Practice	Frequency
ALL	Visually inspect for gross leakage	Daily
MOVS	Stroke time test Disassembly inspection and overhaul - clean/inspect parts for wear/corrosion/erosion - lubricate moving parts - replace degraded parts as needed - check electrical connections for tightness - inspect, clean electrical contacts/controls - inspection torque/limit switches for cracks/breaks - inspect wiring for cracks/brittleness/abrasions - check lube oil for water/dirt/foreign material - adjust torque/limit switch settings - measure motor current - measure stroke time - verify position indicator functioning - install new gaskets MOVATS Testing - measure stem thrust - measure motor current - check operator alignment - perform signature analysis - check stem play	Cold Shutdown As needed 5 years or after overhaul*
AOVs	Stroke Time Test Disassembly inspection and overhaul - clean/inspect parts for wear/corrosion/erosion - replace degraded parts as needed - lubricate moving parts - adjust limit switches - clean air filter - clean and calibrate pressure regulator - adjust actuator spring tension - bench test the actuator	Quarterly As needed
Manual	No planned actions	
Relief	Bench Test	5 years

*Currently planned

Table 2.22 Plant B CCW heat exchanger ISM practices

ISM Practice	Frequency
Visually inspect for gross leakage	Daily
Monitor heat exchanger flow	Daily
Inspect for tube leakage	Planned
Monitor cooling water temp. at load	Daily
Check for tube fouling	Planned

The PM actions for the CCW valves are also limited to cases where there is evidence of degraded performance. If a valve is operating properly, the only attention it receives is the ISM actions discussed previously. When a valve requires overhaul, it is common to replace the packing, gaskets, and seals, and to lubricate all moving parts. On MOVs and AOVs, the torque or limit switches may also be replaced, and the operator and valve are realigned. These PM actions are shown in Table 2.24.

There are no scheduled PM activities for the CCW heat exchangers. When performance degrades to an unacceptable level, as indicated by the outlet cooling water temperature, the tubes are cleaned and checked for leaks. If the heat exchangers are disassembled for inspection and cleaning, new gaskets are typically installed and the head bolts are retorqued upon reassembly. The heat exchanger PM activities for plant B are summarized in Table 2.25.

Table 2.23 Plant B CCW pump PM activities

PM Practice	Frequency
Change lube oil	6 months
Lubricate motor bearings	6 months
Lubricate pump couplings	12 months
Replace gaskets	As needed
Replace seals	As needed
Replace bearings	As needed
Rework impeller	As needed
Replace wear rings	As needed
Retorque bolts	As needed
Replace shaft/shaft sleeves	As needed

Table 2.24 Plant B CCW valve PM actions

PM Practice	Frequency
Replace packing	As needed
Replace Gaskets/Seals	As needed
Replace torque/limit switches	As needed
Realign operator	As needed
Lubricate moving parts	As needed
Retorque bolts	As needed

Table 2.25 Plant B CCW heat exchanger PM activities

PM Practice	Frequency
Clean tubes	As needed
Replace gaskets	As needed
Plug cracked/thinned tubes	As needed
Retorque bolts	As needed

2.3.4 Plant B Corrective Maintenance Activities

The corrective maintenance events for the CCW system of plant B were analyzed to determine the effectiveness of the plant's monitoring and maintenance programs. Plant records covering three years from July 1986 to June 1989 were reviewed, and a total of 72 CM events were recorded. The results were sorted and tabulated to identify problem areas.

The data analysis identified the components most frequently requiring CM. As shown in Figure 2.14, valves required the most CM (58%), followed by instrumentation and controls (24%). This is consistent with the findings from plant A and, again, is attributable to population effects. Pumps (15%) also contributed a significant number of CMs, while heat exchangers (1%) and piping (1%) accounted for a very small portion.

Examination of the valve CMs (42 events) shows that manual valves account for the majority reported (48%), followed by air-operated valves (33%) and motor-operated valves (12%), as shown in Figure 2.15. Check valves (5%) and solenoid valves (1%) accounted for a very small portion of the valve CMs. These findings are also consistent with those for plant A. Since the population of manual valves in the CCW system is much higher than that of other valve types, these findings are understandable. They do not, by themselves, indicate that manual valve maintenance and monitoring practices are ineffective.

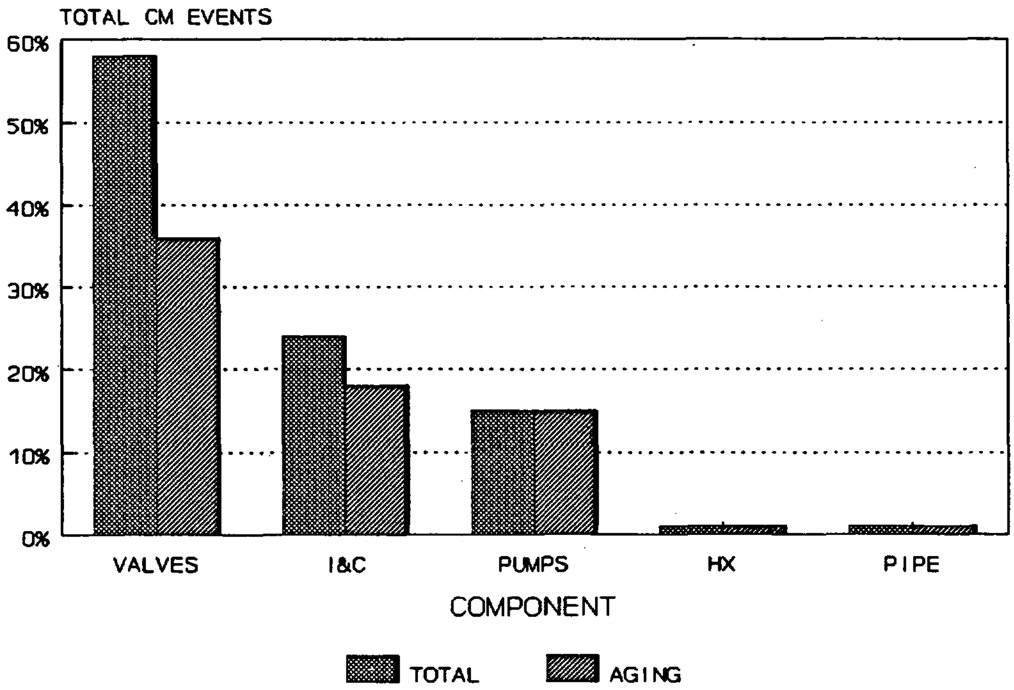

Figure 2.14 Plant B corrective maintenance events

To better understand the reasons for the manual valve CMs (20 events), the data were sorted to identify the failure modes. As shown in Figure 2.16, the most common failure mode for the manual valves was a broken or missing handwheel (35%). This type of failure is clearly not related to aging of the valve, and is in contrast to the most common failure mode for plant A's manual valves, which was packing leaks. The second most common failure mode was broken stems, which also is not aging related. The most common aging related failure mode was packing leaks, however, they accounted for only 15% of the manual valve CMs. Therefore, plant B has fewer failures of manual valves caused by aging degradation than plant A. This could be attributable to better maintenance and monitoring, less severe operational environments, better materials of construction, or a combination of these factors. It should be noted that the low percentage of packing leaks in plant B could be due to unreported adjustments of packing nuts. This could not be determined from the information available.

The failure modes for MOVs and AOVs were also identified from the data (19 events), the most common being failure of the limit switches (37%), followed by failure to open or close (16%), as shown in Figure 2.17. No failures due to packing leaks were reported during the three-year period examined, which is in

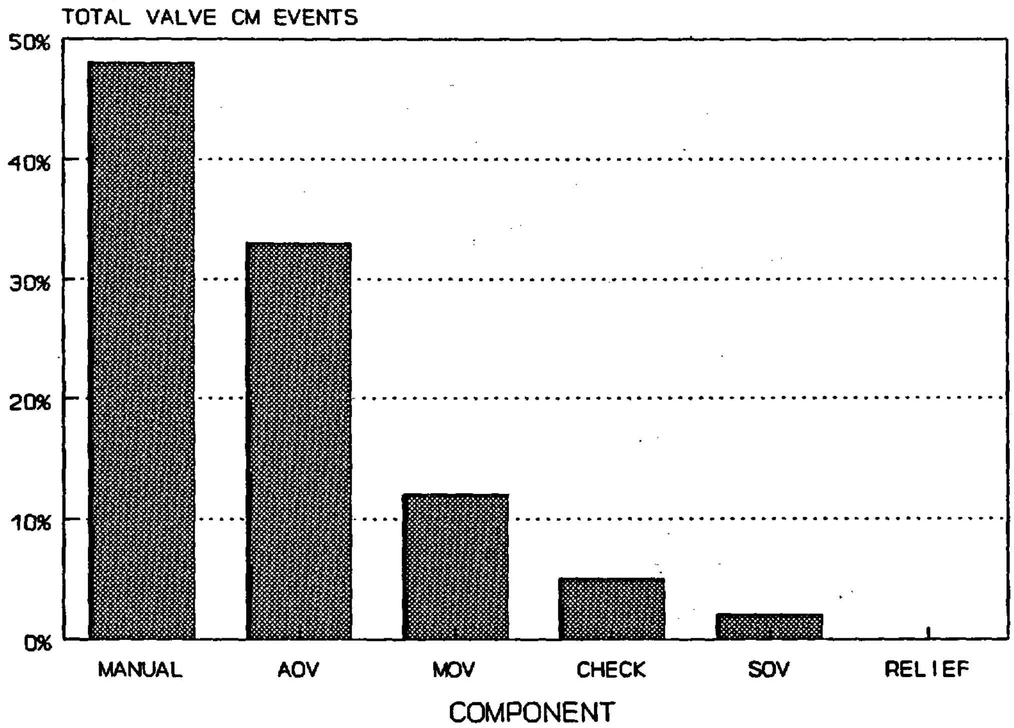

Figure 2.15 Plant B valve types requiring CM

contrast to the failure modes for plant A, where packing leaks were the predominant failure mode for MOVs and AOVs. This difference is not attributable to any special ISM&M techniques for valve packing, since none is used at plant B.

The component category ranking second in CM frequency is instrumentation and controls (17 events). In that category, temperature and flow controllers accounted for the predominant number of CMs (Figure 2.18), followed by indicators (24%), and transmitters (18%). These results differ from those of plant A where indicators accounted for 73% of the I&C CM events. For plant B, the most common I&C failure mode is incorrect reading (41%), followed by fitting leaks (23%), as shown in Figure 2.19. Again, no special ISM&M techniques are used at plant B which would account for this.

As for plant A, few pump failures were found for plant B (11 events). However, since the CCW pumps are an important component for system availability, the failure modes were identified. The most common pump failure modes were leakage of the water and oil seals, and leakage of the gaskets (Figure 2.20). These are typical pump failure modes and are consistent with the findings from plant A.

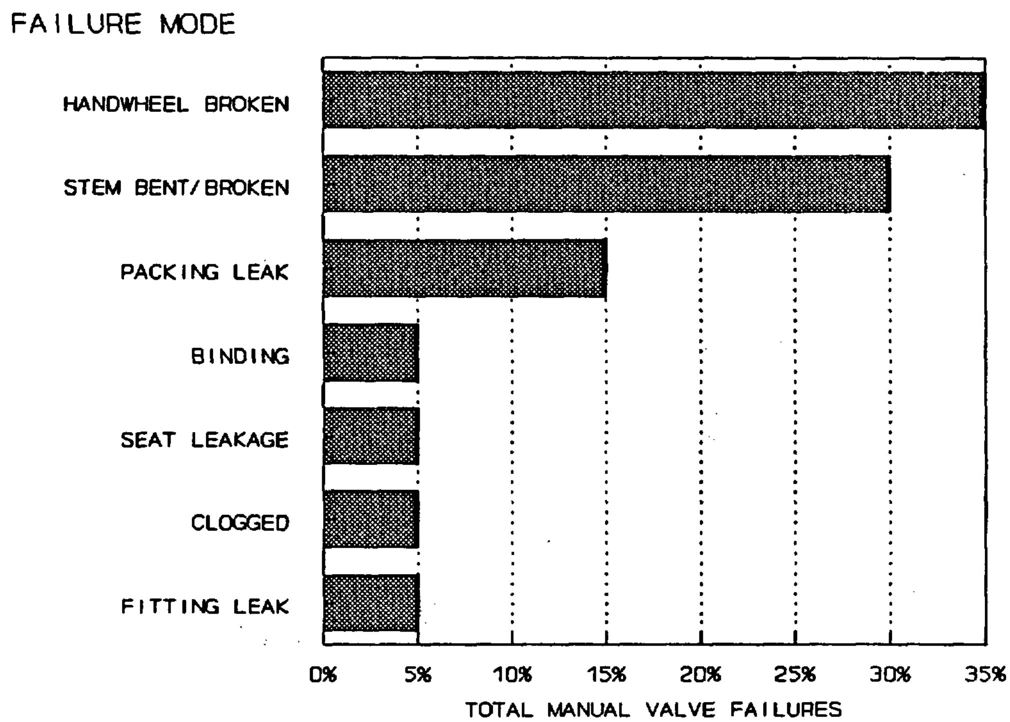

Figure 2.16 Plant B manual valve failure modes

2.3.5 Summary of Plant B Findings

The maintenance and monitoring practices at plants A and B are very similar, with the exception of the performance frequencies. At plant B, many of the maintenance actions are not scheduled periodically, but are performed only on an as-needed basis. For example, the CCW pumps are overhauled only if their performance degrades to an unacceptable level. At plant A, however, at least one CCW pump is overhauled every refueling outage, whether its performance is unacceptable or not.

As was found for plant A, the monitoring and maintenance practices for plant B do not include practices to address long-term aging. For example, there is no mechanism to measure and trend pipe wall thicknesses nor valve/pump casing thicknesses. Over many years, corrosion and erosion could reduce wall thicknesses in critical locations to unacceptable levels. Unless there are specific techniques to monitor such long-term aging effects, they may never be manifested until they result in a catastrophic component failure. This common weakness in the maintenance and monitoring programs at both plants should be addressed, particularly if extending the operating life of the plant is being considered.

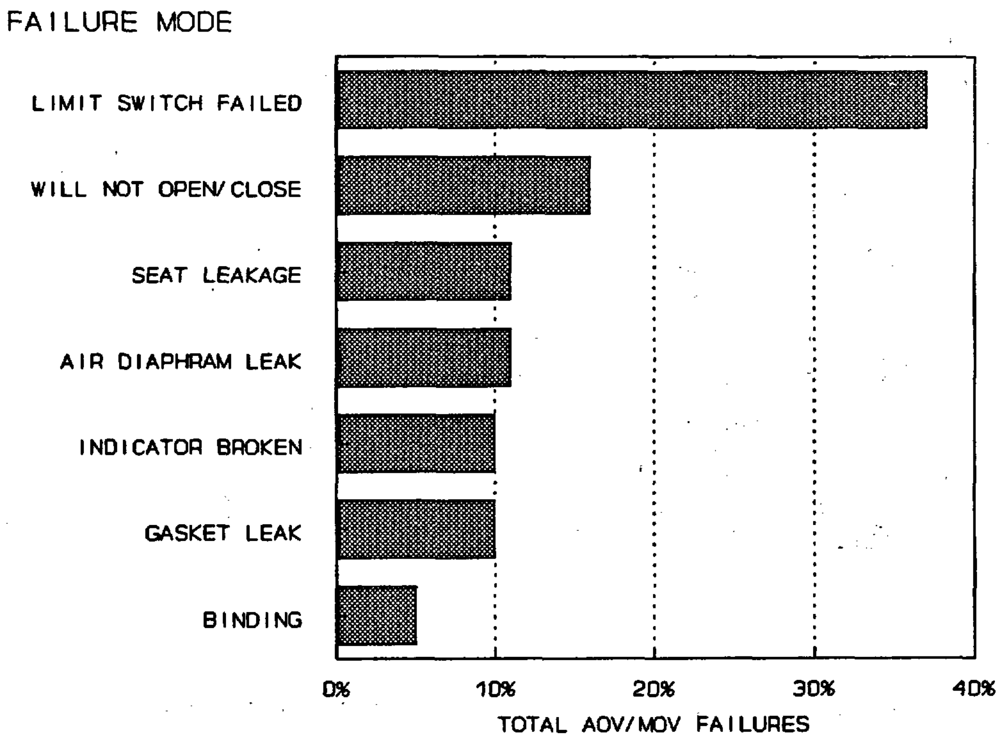

Figure 2.17 Plant B AOV and MOV failure modes

In discussing the data analysis for the survey, as well as for plants A and B, recommendations have been made for increased maintenance in some areas. For example, some of the data indicated that increased adjustment or replacement of valve packing might be beneficial. In each case, it is assumed that the maintenance would be performed correctly. However, it should be noted that there is some probability that maintenance could be performed incorrectly and lead to a failure that may not have occurred. This should be considered when increasing maintenance frequencies.

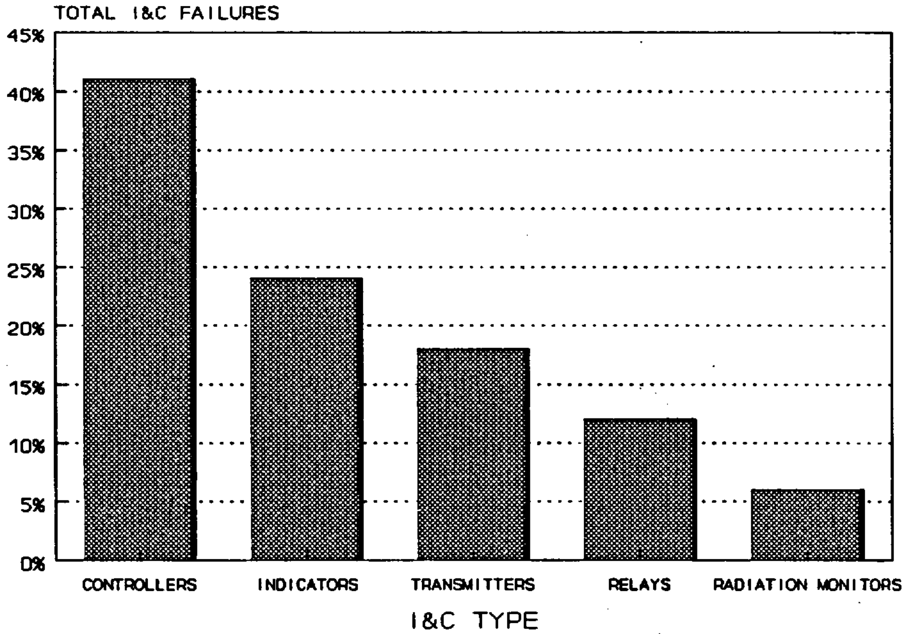

Figure 2.18 Plant B I&C components requiring CM

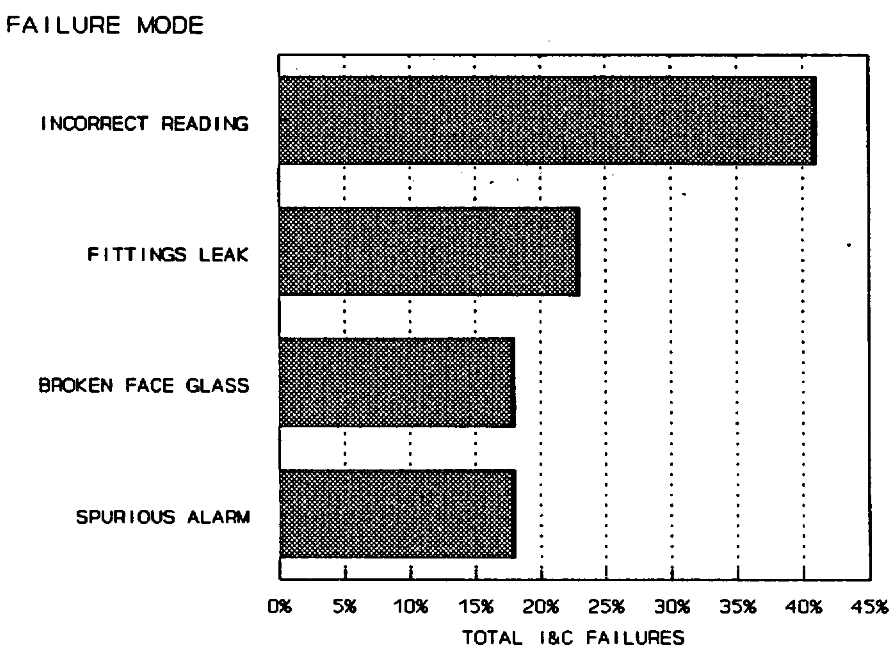

Figure 2.19 Plant B I&C component failure modes

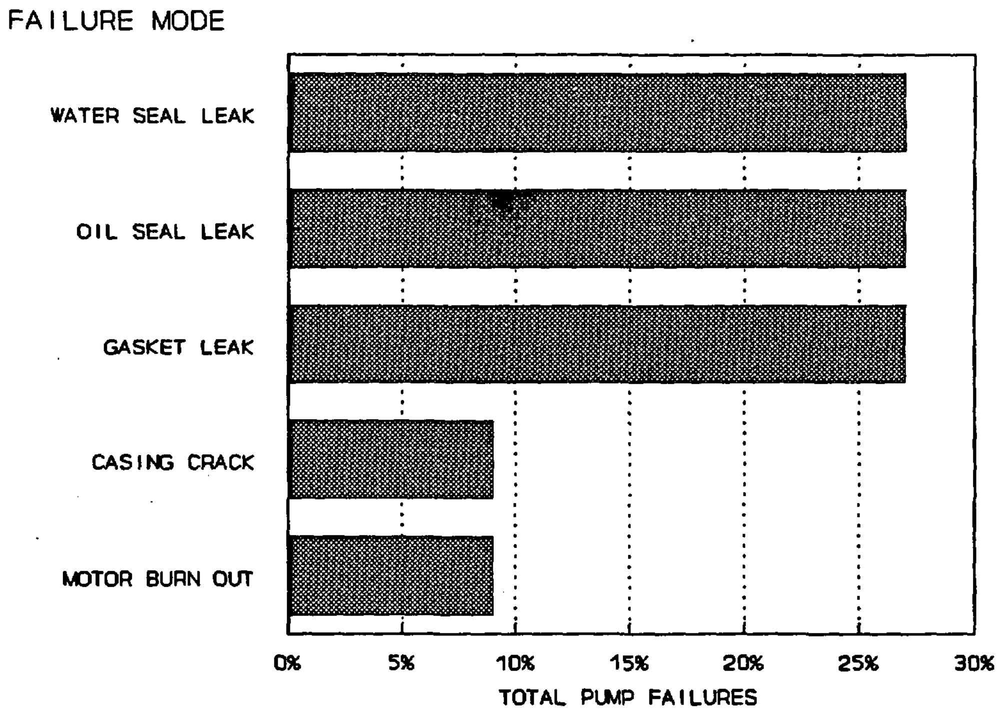

Figure 2.20 Plant B pump failure modes

3. EVALUATION OF COMPONENT MATERIALS

The materials used to construct the various components in the CCW system influence the type and degree of aging degradation. For example, some materials may be less susceptible to corrosion in a particular environment; therefore, their use could help mitigate failures due to corrosion. An understanding of the various materials used can also help determine the extent and frequency of inspections and maintenance actions required. Since material selection plays such an important role in managing aging, this subject was reviewed for the major components in the CCW system. Information was obtained from the data and literature reported by utilities, as well as from various manufacturers and vendors.

3.1 Heat Exchangers

Heat exchangers are one of the primary components in the CCW system, and are prone to aging degradation. In this section, the materials used to construct the heat exchangers for the CCW system are presented, and their susceptibility to aging degradation is discussed.

3.1.1 Description

Most CCW heat exchangers in use are of the horizontal shell and tube type with straight tubes (Figure 3.1). The major parts of the heat exchanger are the shell, the channel/bonnet heads, the tube bundle, the tubesheet, and the baffles. Although designs vary greatly among plants, the specifications for a typical horizontal shell and tube CCW heat exchanger are as follows:[11]

Number of Tubes:	3,389 straight tubes
Shell Diameter:	68 in
Overall Length:	75 ft
Tube Diameter:	0.75 in
Tube Thickness:	18 BWG AVG
Tube Length:	64 ft
Tubeside Design Velocity:	3 ft/sec

CCW flow is typically on the shell side of the heat exchanger, while service water flow is on the tube side. This arrangement facilitates cleaning out any debris introduced by the service water, which is usually seawater, brackish water, or fresh water from a river or lake. The material used for the shell is usually carbon steel, while the tube material varies, depending on the service conditions. Table 3.1 shows the typical shell and straight tube heat exchanger design conditions for the three main PWR vendors.[12]

3.1.2 Heat Exchanger Materials

Materials of construction are primarily chosen based on expected service conditions, which include low susceptibility to corrosion and erosion, good weldability, and high thermal conductivity. For tube bundles and tube sheets, which are exposed to the harsh environment of service water, the most common materials are the admiralty metals, brass, bronze, and copper-nickel (Figure 3.2). Each material is briefly discussed in the following paragraphs.

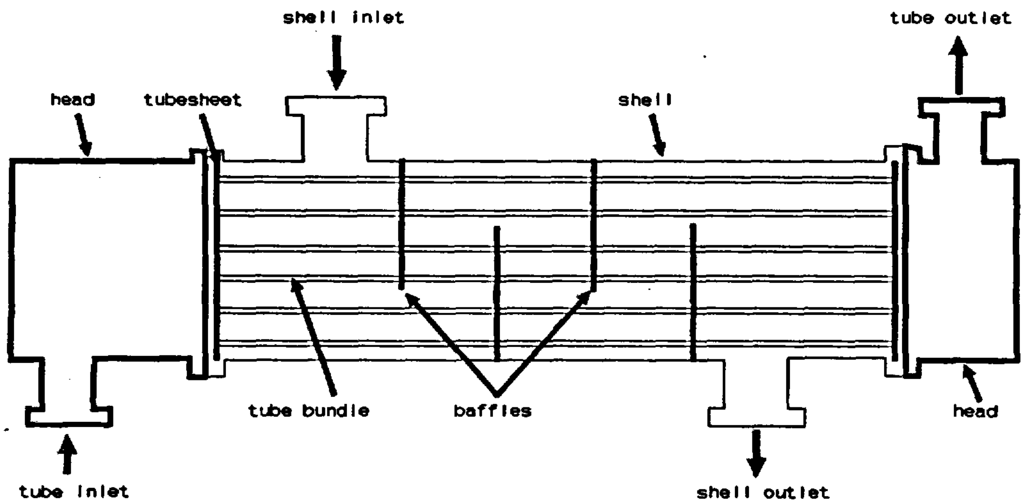

Figure 3.1 Typical shell and tube heat exchanger

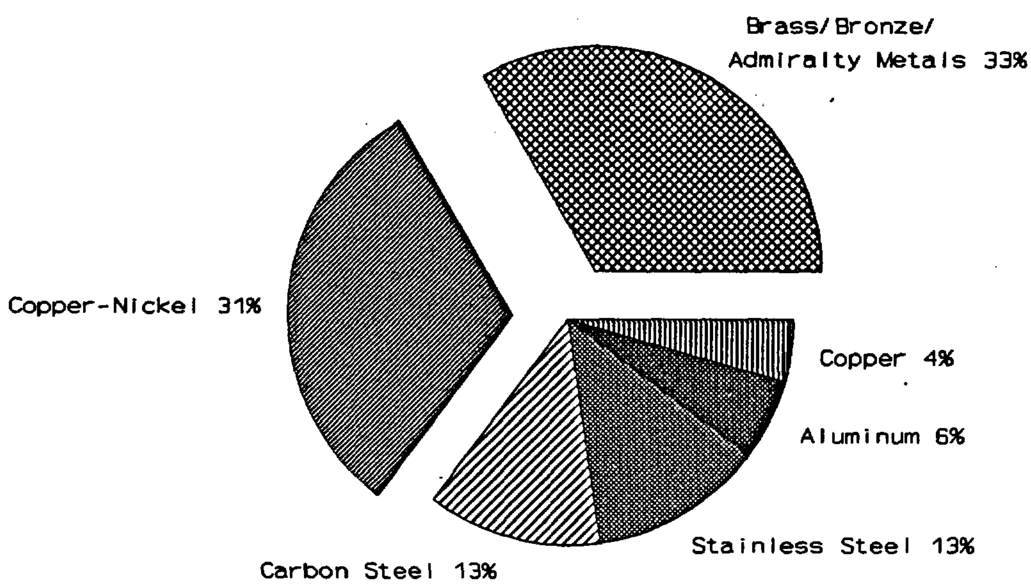

Figure 3.2 Heat exchanger tube and tubesheet materials (NPRDS 1974 to 1987)

Table 3.1 Typical CCW heat exchanger design conditions[12]

Reactor Vendor	Tube Side			Shell Side		
	Press (psig)	Temp (Deg F)	No. Passes	Press (psig)	Temp (Deg F)	No. Passes
Babcock & Wilcox	100	125	1	150	150	1
Combustion Engineering	150	200	1	150	200	1
Westinghouse	150	200	1	150	200	1

Carbon steels:

Carbon steels are widely used for shells, heads, baffles, and tie-rods. They also can be used for tubesheets and tubes under mild operating conditions. The main advantages of carbon steels are low cost and high strength. However, their corrosion resistance is not high in seawater nor in untreated water. If carbon steels are to be used in these environments, protective measures are needed, such as cathodic protection or coatings.

Copper alloys:

Copper alloys are widely used in heat exchangers because of their high corrosion resistance, high thermal conductivity, and high resistance to fouling. A number of alloys are available which combine copper with zinc, aluminum, iron, nickel, and other elements in varying degrees. Some of the more commonly used copper alloys are discussed below[13].

Admiralty metals:

Admiralty metals are composed primarily of copper (71%) and zinc (28%), with small amounts of tin (1%), and trace amounts (0.02 to 0.06%) of arsenic, antimony, or phosphorus. They have good corrosion resistance in fresh, salt or brackish water, and are used for heat exchanger tubes. Admiralty metals were developed to improve dezincification resistance by adding 1% tin to brass; the presence of arsenic, antimony, or phosphorus increases dezincification resistance further. Dezincification is a form of selective leaching of zinc from the alloy, which is a common degradation mode for brass.

Aluminum brass:

Aluminum brass is composed of copper (77.5%), zinc (20.5%), aluminum (2%) and arsenic (0.06%). This metal has good resistance to erosion from the action of high velocity salt and brackish water. Tubes of this alloy are frequently recommended for power stations where cooling water velocities are high and where admiralty metal tubes have failed because of impingement attack.

Aluminum bronze:

Aluminum bronze is composed of copper (91%) and aluminum (7%), with small amounts of iron (2.5%) and tin (0.5%). Silicon can be substituted for iron and tin. Aluminum bronzes are used for service in potable water, brackish water, or in seawater. This alloy resists oxidation and impingement corrosion because of the aluminum in the surface film. Tube sheets made of this alloy have been specified for coastal power stations.

Copper-Nickel (10%):

Copper nickel 10% is composed of copper (88.7%), iron (1.3%), and nickel (10%). This alloy has excellent resistance to corrosion and impingement attack.

Copper-Nickel (30%):

This copper-nickel alloy is composed of copper (70%), iron (0.6%), and nickel (30%). It also has excellent corrosion resistance, and the best impingement attack resistance. The 30% nickel alloy is used by US Navy for most shipboard condensers and heat exchangers.

Stainless steels:

Stainless steels have very good resistance to general corrosion and erosion, however, they are susceptible to pitting in stagnant water and stress-corrosion cracking in a chloride environment. The popular Type 304 stainless steel has a sensitization problem when welded without special precautions. For heat exchangers, a large amount of welding is required, therefore, Type 304 stainless steel is not a good choice. Instead, Type 304L, Type 347, or Type 321 stainless steel, which are less sensitive to welding, are used.

Titanium:

Titanium is probably the best material to construct heat exchangers from the standpoint of its properties. However, its use has been limited by high cost. Nevertheless, chemical plants are increasingly using this metal in heat exchangers since the extra cost can be justified by the increased life. The only disadvantage of titanium is its susceptiblilty to crevice corrosion in a chloride solution at temperatures above 175°F.

However, this disadvantage can be mitigated by proper design and precautions.

The susceptibility to various aging mechanisms for each of the materials discussed above is summarized in Table 3.2, which shows the performance rating of each alloy, on a scale of 1 to 10 (10 being excellent), based on its resistance to the failure mechanism specified. The information in this table is extracted from References 12 and 13, and is presented for comparison purposes only.

Table 3.2 Performance Ratings of Heat Exchanger Materials

Material	Resistance to Aging Mechanisms (1=Poor, 10=Excellent)						
	General Corrosion	Stress Corrosion	Erosion	Pitting (operation)	Pitting (stagnant)	Chloride Attack	Ammonia Attack
Copper	5	N/A	3	N/A	N/A	N/A	N/A
Admiralty Metals	5	3	5	8	5	7	5
Aluminum Brass	7	3	6	8	5	8	5
Aluminum Bronze	5	N/A	7	8	N/A	N/A	N/A
Copper Nickel-10%	8	10	8	10	9	10	8
Copper Nickel-30%	8	9	9	9	8	9	9
Stainless Steel	9	3	10	6	3	3	10
Titanium	10	10	10	10	10	10	10

* N/A Not Available

3.1.3 Heat Exchanger Aging Mechanisms

The heat exchanger subcomponents that are most prone to failures are the tubes, tubesheets and channel/bonnet heads. Among these, tubes are reported to fail most frequently. Tube failures can be categorized into two major modes; blockage and leakage. Blockage of tubes can be caused by aging mechanisms, such as fouling, or non-aging mechanisms, such as clams. Leakage is primarily due to aging mechanisms, such as corrosion, erosion, and wear.

3.1.3.1 Fouling

Fouling can be categorized into two major types; macrofouling and microfouling. Macrofouling is the accumulation of solid materials on the inside surface of the tubes and on the tube sheets. It is caused by clams, seaweed, mud, sand, silt, and other debris which are typically entrained in the service water.[40,41,44] Very often macrofouling causes blockage of the tubes, which increases the pressure drop across the heat exchanger, and in addition, reduces the available heat transfer surface area. It also induces crevice corrosion of the tubes and tube sheets, which occurs under debris deposits. Usually, regular maintenance to clean the tubes and the tubesheets is employed to minimize the effects of macrofouling (see section 3.1.4.5 for detailed discussion of cleaning).

Microfouling is the multiplication and accumulation of microorganisms on the inside surfaces of heat exchangers that causes microbiologically induced corrosion, MIC.[43] Although some details are disputed, the mechanisms for MIC are generally understood. Microbes do not attack metals directly, but microbial activity induces corrosion in several ways. One way is by forming "living crevices", which lead to crevice corrosion. In addition, microbial activity produces corrosive agents, such as organic acids, mineral acids, ammonia, or hydrogen sulfide. It also interferes with the cathodic half-cell reaction, which increases corrosion rate, and promotes the oxidation of metal anions to less soluble forms. Microbial activity also induces the destruction of protective coatings.

Although copper alloys are very resistant to MIC, failures of such heat exchanger tubes due to MIC still occur[14,15]. Stainless steel is also susceptible to MIC[16]. One of the necessary conditions for MIC to manifest itself is a low flow rate or stagnant condition. The periods when the CCW heat exchangers are most susceptible to MIC are during preoperational testing and standby operation, when the heat exchangers can experience stagnant conditions. Also, inadequate lay-up and improper draining procedures can provide the necessary conditions for MIC to occur. As an example, one utility reported retubing of the CCW heat exchangers after preoperational testing was completed, but a subsequent inspection revealed pitting underneath light green tubercles[11]. It is suspected that the pitting was caused by MIC, even though the utility did not discuss MIC as a root cause for the failures.

3.1.3.2 Corrosion, Erosion, and Wear

Aside from fouling, aging of a heat exchanger can also take the form of general thinning and localized failures (such as pitting, crevice corrosion) of its various subcomponents. General thinning of the tube sheets and tubes is caused by corrosion from electrochemical reactions, wear from mechanical rubbing, or erosion from high-velocity fluid and/or suspended particles in the liquid stream. Corrosion due to electrochemical reactions, and erosion are the main causes of thinning for channel/bonnet heads and tubesheets, which must operate in service water. Since the CCW water is treated, corrosion of the shell and baffles is of less concern, although they are not immune to corrosion related failures.

Localized failures are typically caused by crevice corrosion or by other localized corrosion, such as pitting, stress-corrosion cracking, and intergranular corrosion. Most heat exchanger materials are susceptible to crevice corrosion, which starts underneath deposits of foreign solid materials, such as sand, mud, and silt.

3.1.4 Failure Prevention and Mitigation

It is very important from a safety standpoint to prevent unexpected failures, and to assure continued operation of the CCW heat exchangers. The first, and possibly most important step, in preventing failure is to select the proper construction materials, which must be well suited to the operating conditions and environment in which they will operate. When the proper materials are selected, there are several methods that can be employed to increase the service life and prevent premature failures of the heat exchangers. Most of these methods are applicable to new or operating heat exchanger systems.

3.1.4.1 Coolant Water Treatment

In most cases, chlorine is used to treat service water, since it is typically supplied by a nearby river or ocean. The CCW water is usually treated with chemical inhibitors to minimize corrosion on the shell side. Chemical inhibitors may be classified into three types[17]; adsorption, scavengers, and oxidizers. The adsorption inhibitors are generally organic compounds, which adsorb onto the metal surfaces and suppress anodic and/or cathodic reactions. Scavengers inhibit corrosion by removing oxygen from the coolant; one example is sodium sulfite (Na_2SO_3). Oxidizers are used for metals which show active-passive transitions, such as carbon steels and stainless steels. These inhibit corrosion by raising the corrosion potential of the metal above the transition potential, so that the metal surface stays in a passive state. The most popular oxidizer, is chromate.

In most CCW systems, the coolant has been treated with potassium chromate to protect the shell and baffles, which are made of carbon steel. However, due to environmental concerns regarding chromates, many utilities are now searching for alternative corrosion inhibitors. Some have already instituted alternatives[18], such as sodium molybdate, sodium tolyltriazole, sodium nitrite, sodium borate, and hydrazine. Estimates indicate that approximately half of the operating PWRs use chromates, while the other half use chromate alternatives.

3.1.4.2 Cathodic Protection

Metallic components can be protected from corrosion by making them cathodes, which means that only cathodic reactions occur on the surfaces of these components. Protection can be achieved either by passing a dc current through the component, or by installing sacrificial anodes into the component. Installing zinc sacrificial anodes is the more popular method for heat exchangers. These are used to protect channel/bonnet heads and tubes made of carbon steels, as well as tube sheets and tubes made of aluminum bronze, aluminum brass, or admiralty metal.

A common problem with sacrificial anodes is that they separate from the protected surfaces. Loose anodes may damage the tubes and other parts of the heat exchanger as they are carried around by the flowing service water.

3.1.4.3 Coatings and Linings

The parts of the heat exchanger that are not critical to the heat transfer process, such as channel/bonnet heads and tube sheets, may be coated with a protective coating. The most common coating is an epoxy, although PVC liners have also been used to protect channel/bonnet heads. The coatings and linings are susceptible to erosion, and they should be regularly inspected. These coatings must be properly applied, or they can fail and cause flow blockages in the system.[42]

3.1.4.4 MIC Prevention

The CCW heat exchangers are susceptible to MIC during construction, preoperational testing, and lay-up periods. The following recommendations were made by EPRI as ways to prevent MIC[18]:

1. Clean debris and dirt during and after construction or retubing.
2. Drain the system of all water and dry it during construction.
3. Hydrotest the system with clean water and use a biocide treatment.

It is also recommended that optimum rotation schedules be developed to prevent prolonged standby periods during which MIC can occur. MIC of the operating heat exchangers also may be prevented or minimized by conducting proper preventive maintenance, as discussed in the next section.

3.1.4.5 Preventive Maintenance

Early detection and correction of problems can minimize the frequency of failures and prolong the service life of components. This can be accomplished through proper maintenance, which should include periodic cleaning of tubes, and inspection of all seals.

The inside of the tubes may be cleaned mechanically and/or chemically. Chemical methods use a solvent to dissolve deposits, usually followed by flushing with water. Mechanical methods used to clean the inside of the tubes include a high-velocity water flush (hydroblasting) using a 5,000 - 10,000 psi water jet, cleaning with a long wire brush, and in extreme cases, using cutting tools to remove hard deposits. Frequent cleaning of the tube insides will minimize fouling problems and crevice corrosion, and enhance the efficiency of a system. However, the wear on the tubes caused by cleaning should be considered, and an optimum maintenance schedule should be developed based on operation and performance data.

The prevention/mitigation methods for each aging mechanism are summarized in Table 3.3.

Table 3.3 Prevention/mitigation measures for heat exchanger aging mechanisms

Aging Mechanism	Prevention/Mitigation Measure	Advantages	Disadvantages
Macrofouling	Regular cleaning	Restores efficiency	Tube wall thinning
Microfouling	Regular cleaning	Reduces MIC	Tube wall thinning
	Proper drain and layup after preoperational tests	Reduces MIC	None
Corrosion	Coolant water treatment	Prevents corrosion on shell side	None
	Cathodic protection	Prevents corrosion of tubesheet and channel head	Not practical for tubes
	Regular cleaning	Reduces crevice corrosion	Increased tube wear
	Coatings and linings	Prevents corrosion of tubesheet and channel head	Not practical for tubes
Erosion	Minimize flow rates	Mitigates erosion degradation	Too low a flow degrades heat transfer, and allows tubericle growth and microfouling
Wear	Develop optimum cleaning schedule	Reduces wear from mechanical cleaning	None

3.1.5 Findings for Heat Exchangers

A variety of materials can be used to construct heat exchangers. Each material has a different resistance to the various aging mechanisms; therefore, the material should be selected to match the conditions under which it will operate. This will help to minimize failures and improve the system's performance.

The most common form of heat exchanger failure is leakage of the tubes, which is caused by corrosion, erosion, and wear. In most cases, the corrective action for these failures involves plugging the leaky tubes, which is a temporary solution that reduces heat transfer capability. When an excessive number of tubes are plugged, an entire retubing of the heat exchanger is required.

There are various methods to prolong the service life of a heat exchanger, and prevent unexpected, premature failures. These methods include installing a cathodic protection system, applying a protective coating or liner, and replacing the failure susceptible parts with those made of materials that perform better in the particular operating environment.

3.2 Valves

As reported in NUREG/CR-5052, valves are the most commonly failed components in the CCW system. This can be partially attributed to their relatively large population, as compared to other components in the system. However, they are also susceptible to aging, which is a significant cause of most valve failures.

The most common failure mode is leakage, including internal leakage through the valve seats, and external leakage through gaskets and packing seals. In this section, the aging of valves is discussed, emphasizing the evaluation of different materials used in valve construction and the effect of aging on them.

3.2.1 Description of Valves

There are several different types of valves used in the CCW system, including gate valves, globe valves, butterfly valves, and swing check valves. These can be further categorized into functional types, such as isolation valves, throttle valves, check valves, or pressure-relief valves. The isolation valves and the throttling valves can be controlled either by valve operators, which permit remote operation of the valve, or by handwheels, which must be operated manually.

Although the designs of the various valve types differ, there are certain basic subcomponents that are common to all valves. As shown in Figure 3.3, the common subcomponents include the body, the stem, the seat, the disk, the stem packing, and various gaskets and seals. Special trim material is usually attached to the valve seat to provide special flow or sealing capabilities. Degradation of any one of these subcomponents can affect performance and lead to failure of the valve.

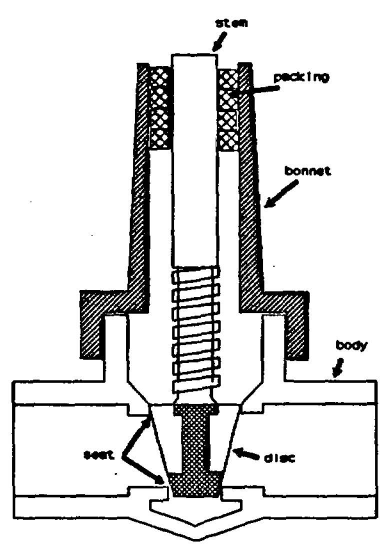

Figure 3.3 Typical valve subcomponents

3.2.2 Valve Materials and Aging Susceptibility

The valve body is a pressure containment subcomponent. Therefore, the material selected for it is dependent on operating pressure and temperature, along with the corrosive and erosive properties of the fluid media. In the NPRDS data reviewed, carbon steel (75%) and stainless steel (21%) accounted for most valve body materials. Carbon steel is strong and economical, which makes it a popular valve body material. The corrosive resistance of carbon steel is not as good as that of stainless steel and other more expensive alloys; however, in the chemically treated CCW water, this is not a major concern. Corrosion of the body materials is more problematic for relief valves because the fluid inside the valves is stagnant. Therefore, a more corrosion resistant material, such as stainless steel, might be used.

Failures caused by corrosion of the valve body were not reported in the data reviewed for this analysis. However, this does not indicate that such failures will not occur in the future. After many years of corrosion and wall thinning, it is possible that a valve body may fail. This should be considered as part of a plant life extension program, and valve body wall thicknesses should be monitored.

The valve trim parts are usually made of more noble metals (e.g., stainless steel), and are protected from corrosion at the expense of the body due to the galvanic coupling. However, corrosion of the valve body does affect the valve trim. As the body corrodes, the corrosion products deposit on the surfaces of trim, causing improper seating. This, in turn, leads to abnormal wear and leakage through the valve seat. The corrosion products also cause other valve problems, such as dirty internals and crevice corrosion. The selection of trim materials depends on flow characteristics and fluid conditions, such as temperature, corrosiveness, and erosiveness. Some of the applications of common trim materials are shown in Table 3.4[19].

Table 3.4 Valve trim materials[19]

Material	Service Fluids	Service Environment
Bronze	Mild Service: - water - air - gas - saturated steam	Mild Service: - non-erosive - non-corrosive - low pressure drop
Stainless Steel - Type 316	General Service: - steam - water - oil	General Service: - corrosive - non-erosive - moderate pressure drop
Stainless Steel - Type 410 - 17-4 PH Stellite	Severe Service: - all fluids	Severe Service: - corrosive - erosive - high pressure drop

Butterfly valves used for isolation are usually equipped with a liner on their seat. The liner is typically made of an elastomer material, and provides good sealing for the valve. The requirements for a good liner material are temperature stability, abrasion resistance, swelling resistance, and tear resistance. These liners are vulnerable to aging degradation, and any deterioration could lead to leakage through the valve seat. Table 3.5 shows the performance characteristics for some of the common elastomer seat materials[20].

Table 3.5 Characteristics of elastomer liners[20]

Material	Temperature Limits (Degrees F)	Resistance to				
		Abrasion	Gas Permeability	Lubricating Oils*	Water*	Tearing
Buna N	10 to 180	Good	Fair	Excellent	Excellent	Fair
Nordel	-30 to 250	Excellent	Fair to Good	Poor	Very Good	Good
Viton	-10 to 400	Good	Poor	Very Good	Very Good	Fair
Neoprene	0 to 175	Excellent	Good	Good	Fair to Good	Fair to Good

* Indicates ability to withstand swelling

Many failures of butterfly valves are due to aging of the rubber seat materials, which takes the form of tearing and hardening of the seat. Hardening, in turn, causes increased friction, which further increases wear. In one utility, actuator failures were reported due to increased frictional forces. The problem was mitigated by resetting the opening torque switches to allow maximum torque. This problem also raised concerns related to undersized actuators, which prompted the NRC to issue information notices 88-94 and 90-21, and generic letter 89-10 (see Section 5.3.3).

Packing leaks are a common problem with all types of valves. Valve packing prevents the process fluid from leaking up through the area where the valve stem passes through the valve bonnet. The packing is placed in a stuffing box, and a packing follower and gland are inserted on top of it (Figure 3.3). By tightening down on the packing gland, the packing material is squeezed up against the valve stem and provides a seal. As the valve is operated, the movement of the stem against the packing causes wear of the packing material, which can eventually lead to deterioration and leakage. Therefore, the packing gland must be adjusted periodically to maintain a good seal. When the packing has worn to the point that gland adjustment can no longer provide a good seal, the packing must be replaced.

In the past, asbestos was used as a packing material; it was relatively inexpensive and provided good sealing properties. However, due to environmental concerns, it is being replaced with new asbestos-free packings, such as PTFE packings, Aramid/PTFE packings, and graphite packings. Among these, graphite is the most popular and best performing packing material.

There are three different types of graphite packing rings that are commercially available[21]; laminated graphite rings, graphite ribbon rings, and braided graphite rings. Laminated graphite rings are made up of many thin, washerlike sheets of laminated graphite. Rings made from graphite ribbon are formed by winding the ribbon around a mandrel the same size as the valve stem, until the ring is large enough to fit loosely inside the packing box. Pressure

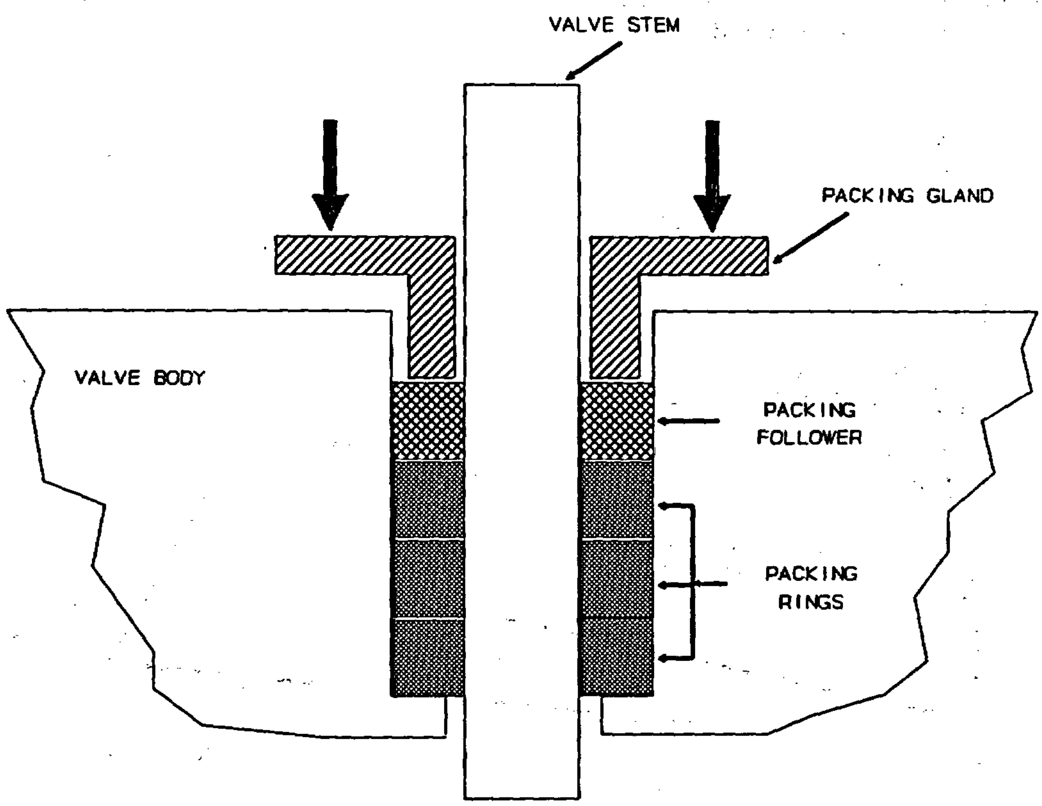

Figure 3.4 Typical valve packing arrangement

then is applied to the two sides of the foil to compress it into an accordion-like structure. Braided graphite filament rings are graphite filaments braided into a rope-like structure. The braid is cut to the proper length to make one turn around the valve stem. Pressure forces the two ends together.

In addition to the material used, the method of installation can influence the life expectancy of valve packing. In a recent study[21] it was shown that an optimum arrangement of graphite packing rings can dramatically improve the performance of the packing. When only graphite ribbon-wound rings are used as valve packing, transfer of graphite particles occurs and causes leakage (graphite particle transfer is a process which removes particles of graphite from the packing ring and deposits them on the polished stem surface). The stem surface becomes rough and causes wear of the packing rings, which results in leakage.

Packing rings made of braided graphite filament do not show particle transfer. Furthermore, they are an excellent clean-up material for the particles transferred from the laminated or ribbon rings. By installing a combination of the two types of packing rings, a dramatic improvement in life expectancy is achieved. The test results on the different combinations of laminated, ribbon, and braided graphite rings are shown in Figure 3.5[21]: the improvement in life expectancy with leak-free performance is dramatic when the optimum combination is used.

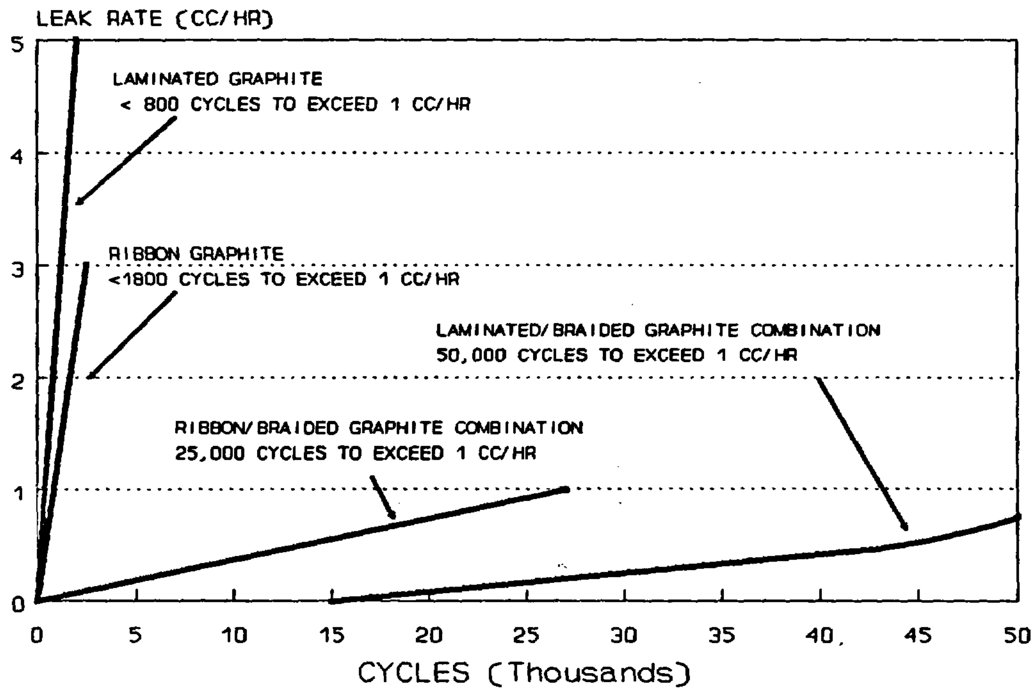

Figure 3.5 Life expectancy of packing materials[21]

Other common aging mechanisms for valve packing are wear and deterioration. Wear occurs as the valve stem moves relative to the packing, which causes frictional forces to act on the packing material, leading to a removal of material at the surface. In addition, the frictional forces produce heat, which can cause hardening of the packing surface. Both processes reduce the packings ability to provide a good seal. Further deterioration of the packing occurs if it is exposed to extreme environments, such as high pressures and temperatures, or caustic process fluids. Therefore, packing materials used in severe environments should be inspected and adjusted more frequently. Severe environments are typically not a concern in the CCW system.

3.2.3 Findings for Valves

The evaluation of valve construction materials produced the following findings:

- The severity of valve aging mechanisms is strongly influenced by the materials used. There are a variety of different materials available, providing an assortment of properties. Selection of the best material depends on many factors, including service conditions.

- Even though failures have not been reported, valve bodies are susceptible to aging degradation which can lead to failure after long periods of time. Therefore, valve bodies should receive increased attention in a plant life extension program.

- In addition to selecting the best valve packing material for the service environment, the method of installation can also be important. Combinations of different packings can improve life expectancy.

3.3 Valve Operator

Another significant contributor to valve failures is the valve operator, which consists of an actuator and various accessories. A valve operator is used on any valve which must be operated from a remote location, such as the control room. In this section, the materials used for constructing valve operators, and their associated aging mechanisms will be reviewed.

3.3.1 Description of Valve Operators

The function of a valve operator is to remotely move a valve stem linearly or rotationally. The energy source for the operator can be either stored energy in fluid, such as compressed air, or electric energy. These define the two basic types of valve operator commonly used in the CCW system; the pneumatically operated diaphragm type, and the electrically operated motor type.

An air operated valve (AOV) uses a pneumatically operated diaphragm actuator to remotely position the valve. The operator can be used on isolation valves, where the valve is either completely open or completely closed, or it can be used on control valves, where the valve may be positioned anywhere between full open and full closed. The basic operation of the pneumatic operator is such that a diaphragm is connected to the valve stem and enclosed in an air tight housing. The injection of compressed air to one side of the diaphragm creates a force on the valve stem, moving it in one direction. A combination of return springs and the exhausting of the compressed air cause the valve to move in the opposite direction. An air regulator and various solenoid valves control the air flow into the actuator. The actuator also includes various O-rings, retainers, and gaskets to prevent air leakage from the system.

A motor operated valve (MOV) uses an electrically operated valve actuator. The main components of this type of actuator are a motor mounted on top of the valve actuator, along with a gear train and screw assembly, which transmits the motor's work to the valve stem. Motorized valve operators can be used for isolation valves or control valves. The disadvantage to this type of actuator is the long stroke time typically required when used on large valves.

3.3.2 Valve Operator Materials

In pneumatic valve actuators, diaphragms and O-rings are most affected by aging degradation. When these components deteriorate, the compressed air used to operate the valve can leak out of the actuator, leading to valve failure. The failure mode for the valve would be classified as a failure to operate, while that for the valve operator would be leakage.

Elastomers are normally used to make diaphragms and O-rings. They include natural rubber and synthetic rubbers. For diaphragms, the elastomers are reinforced with fibers. Figure 3.6 shows some different types of elastomers, along with their operating temperature range[19]. The properties for the

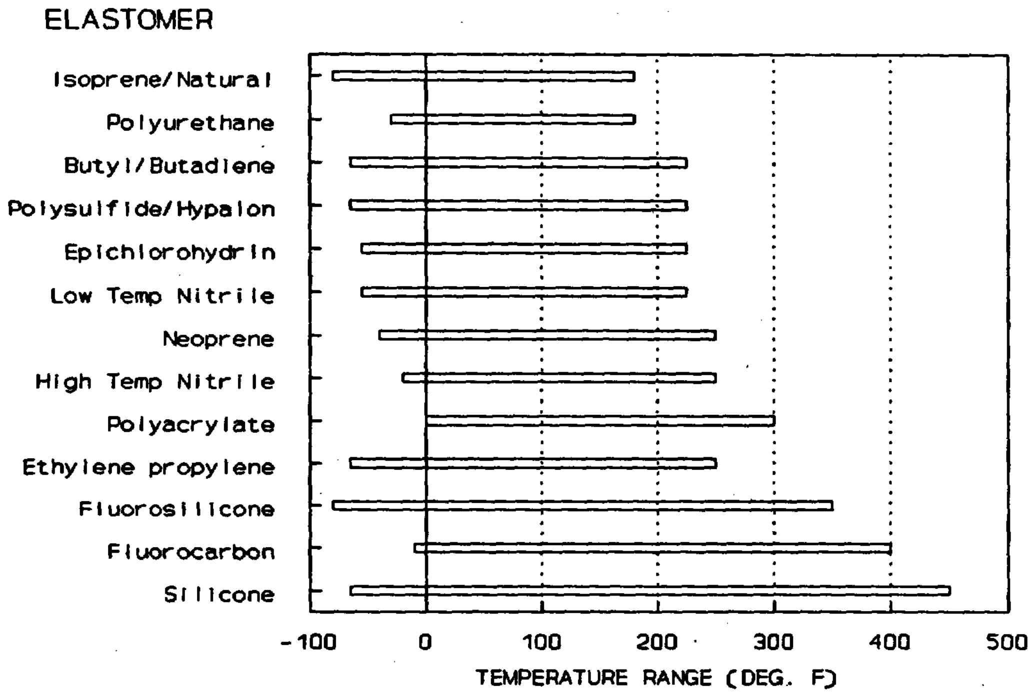

Figure 3.6 Temperature range of elastomer materials[19]

elastomers most widely used for diaphragms and O-rings are described below[19,22]:

Buna N (or Nitrile rubber): Buna N is a copolymer of butadiene and acrylonitrile. The acrylonitrile content of commercial products varies from 18 to 48%. As the nitrile content increases, resistance to petroleum base oils and hydrocarbon fuels increases, however, low-temperature flexibility decreases. Nitrile compounds are superior to most elastomers with regard to compression set or cold flow, tear, and abrasion resistance. However, they are not very resistant to ozone and sunlight. Thus, these materials should not be stored under direct sunlight or near electric motors or other equipment that might generate ozone.

Neoprene Rubber: Neoprenes are homopolymers of chloroprene. Their broad temperature range and modest cost make them popular for diaphragms, hose, seals, gaskets, and automotive V-belts.

Ethylene Propylene Rubber: Ethylene propylene rubber is an elastomer prepared from ethylene and propylene monomers. It has outstanding resistance to oxygen, ozone, and heat. Two types of ethylene-propylene copolymers are commercially available; ethylene-propylene copolymers (EPM) and ethylene-propylene-diene terpolymers (EPDM). Ethylene-propylene rubbers are used for gaskets, seals, and automobile radiator hoses.

Most valve operator manufacturers use neoprene diaphragms reinforced with fiber glass, cotton, or nylon for normal ambient conditions. For example, one company makes molded diaphragms of nylon-reinforced oil resistant elastomer. This diaphragm is described as having a long life at air pressures up to 85 psi. If the ambient conditions exceed 200 °F, higher temperature materials such as silicones, Viton, or polyacrylics with Dacron or fiberglass fabric may be used[20].

Table 3.6 shows the relative performance of the common elastomers including those discussed above.[23] The resistance of each material to important aging mechanisms, such as abrasion, compression set, oxidation, ozone damage, and swelling by water is presented.

3.3.3 Valve Operator Aging Mechanisms

In many cases, failures of pneumatic valve operators are caused by deterioration of diaphragms and O-rings, due to aging degradation of the elastomer material. The degradation that occurs over time relates to the nature of the rubber molecules, which are long, chainlike structures consisting of many smaller molecules joined together. At least three principal types of reaction are responsible for their aging[19,24]. They usually occur concurrently, but in varying degrees.

1. Scission: The molecular bonds are cut, dividing the chain into smaller segments. Exposure to ozone, ultraviolet light, and radiation causes degradation of this type. Excessive scission will result in loss of material strength and, in extreme cases, will cause elastomers to become mushy.

2. Cross-linking: An oxidation process occurs, whereby additional intermolecular bonds are formed. Exposure to heat and oxygen are principal causes of this type of degradation. Excessive cross-linking will result in material hardening and loss of resilience, which leads to cracking and brittleness.

3. Modification of side groups: A change in the complex, weaker fringe areas of the molecular structure due to chemical reaction. Moisture is one factor which can cause this type of degradation, which can result in changes to the materials strength and durability.

The aging process of air diaphragms is more complex than the simple aging of elastomers for two reasons; 1) diaphragms are made from composites of elastomers and fibers, and 2) the diaphragms are exposed to mechanical cyclic stresses, in addition to chemical degradation. The cyclic stresses cause fatigue, which is also an aging mechanism.

Table 3.6 Relative performance of common elastomers[23]

Elastomer	Resistance to Aging Mechanism							
	Abrasion	Compression Set	Oxidation	Ozone	Radiation	Water	Steam	Gas Permeability
Natural Rubber	Excellent	Good	Good	Poor	Fair	Excellent	Poor	Poor
Styrene Butadiene	Excellent	Good	Good	Fair	Good	Excellent	Poor	Fair
Neoprene	Excellent	Good	Good	Excellent	Fair	Good	Fair	Fair
Nitrile	Good	Good	Fair	Poor	Fair	Good	Fair	Fair
Hypalon	Excellent	Fair	Excellent	Excellent	Good	Good	Good	Good
Ethylene Propylene	Good	Fair	Good	Excellent	Poor	Good	Good	Fair
Butyl	Good	Fair	Excellent	Excellent	Poor	Excellent	Fair	Good
Viton	Good	Good	Excellent	Excellent	Good	Good	Good	Good
Kalrez	Good	Good	Excellent	Excellent	Very Good	Good	Excel-lent	Good
Silicone	Poor	Excellent	Excellent	Excellent	Excellent	Good	Good	Good
Polyurethane	Excellent	Good	Excellent	Excellent	Good	Good	Poor	Good

In addition to the stresses experienced during operation, elastomers also degrade while they are stored as spare parts. To minimize such degradation, the following storage conditions are recommended[19]:

1. Ambient temperature not exceeding 120 °F
2. Exclusion of air (oxygen)
3. Exclusion of contamination
4. Exclusion of light (particularly sunlight)
5. Exclusion of ozone-generating electrical devices
6. Exclusion of radiation

Table 3.7 lists the life expectancy during storage for different elastomers exposed to ambient conditions[19]. As shown, Buna N and natural rubber have a relatively low resistance, with a storage life of 2 to 5 years. Neoprene and EPDM have a better resistance, with a storage life of 5 to 10 years. These rankings are also applicable for the in-use aging resistance, even though they are strongly affected by the operational environment.

Table 3.7 Life expectancy during storage of various elastomers[18]

Elastomer	Common or Trade Name	Expected Life
Fluorosilicone	Silastic LS	Up to 20 years
Polyacrylate	Acrylate	Up to 20 years
Polysulfide	Thiokol	Up to 20 years
Silicone	Silastic, Silicone	Up to 20 years
Chlorosulfonated polyethylene	Hypalon	5 to 10 years
Ethylene/propylene/diene (EPDM)	Ethylene propylene terpolymer	5 to 10 years
Fluorocarbon	Fluorel, Viton	5 to 10 years
Isobutylene/isoprene	Butyl, Neoprene, Chloroprene	5 to 10 years
Polyvinyl Chloride	Vinyl Poly	5 to 10 years
Polyurethane	Urethane	5 to 10 years
Butadiene/acrylonitrile	Nitrile, Buna N	5 to 10 years
Butadiene/styrene	Buna S	2 to 5 years
Cis Polybutadiene	Stereo Polybutadiene	2 to 5 years
Natural Rubber	Pale crepe, smoked sheets	2 to 5 years

3.3.4 Findings for Valve Operators

The review of valve operators has generated the following findings:

- For pneumatic operators, an important cause of failure is degradation of the elastomer materials used to construct the diaphragms and O-rings. Other failures involve solenoid valves, positioners, and air regulators.

- Diaphragms and O-rings should be inspected frequently and replaced regularly, with the interval based on past operating data.

- Storage conditions, as well as operating conditions, are important in determining the life expectancy of elastomeric components. The storage of elastomeric parts should follow the recommendations discussed to provide a longer life expectancy.

3.4 Pumps

Pumps are the second most frequently failed component in the CCW system (Figure 1.2). Since a high percentage of the pump failures are related to aging, the various subcomponents in the pump are susceptible to aging degradation. In this section, the materials used for pump construction are examined and their associated aging processes discussed.

3.4.1 Description of Pumps

The pumps in CCW systems are motor-driven centrifugal pumps. The number of pumps in each system ranges from two to eight; however, the most common configuration uses three pumps. A typical pump has a flow range of 3000 gpm to 10,000 gpm, with a total developed head (TDH) of 150 ft to 225 ft. The pumps are driven by either 480 volt or 4160 volt ac electrical power, supplying 400 to 700 horsepower.

Centrifugal type pumps are supplied by several different manufacturers; however, the design principles are the same. The main components of the pump include the casing, impeller, shaft, shaft seals, wear rings, bearings, sleeves, and assorted gaskets and seals. Other accessories are also needed to support the pumps operation, including a bearing lubrication system. Figure 3.7 shows a typical horizontal, single-stage, double-suction pump.

In a centrifugal pump, the process fluid is taken into the casing through the suction or inlet piping. The fluid then enters the center of the rotating impeller, where centrifugal force drives the fluid out radially from the eye of the impeller to the volute of the pump at high velocity. Upon exiting the impeller, the fluid is slowed and the velocity energy is converted into pressure energy. The fluid then is discharged through the outlet piping to the system.

The pump shaft runs through the casing connecting the impeller with the motor driving the pump. Typically, it is supported by two bearings. The inboard bearing is located at the coupling end of the shaft, and provides radial support for the impeller. The outboard bearing is typically a thrust bearing, located on the opposite end of the shaft, which provides axial support for the impeller. The bearings are lubricated by either grease or oil. One common lubricating system uses a constant level oiler which maintains a constant oil level in the bearing cavity by gravity.

Sleeves are used to protect the pump shaft from corrosion, erosion, and wear. They are attached mechanically to the pump shaft, and are replaceable. Elastomer O-rings are used between the sleeve and the shaft to protect the shaft from corrosion.

Wear rings are located between the impeller and casing to protect the casing from wear due to the constant rotation of the impeller. They also provide a seal between the high-pressure discharge side of the pump and the low-pressure suction side of the pump. Worn wear rings can be replaced with new ones. They can be mounted either on the casing or on the impeller, or on both.

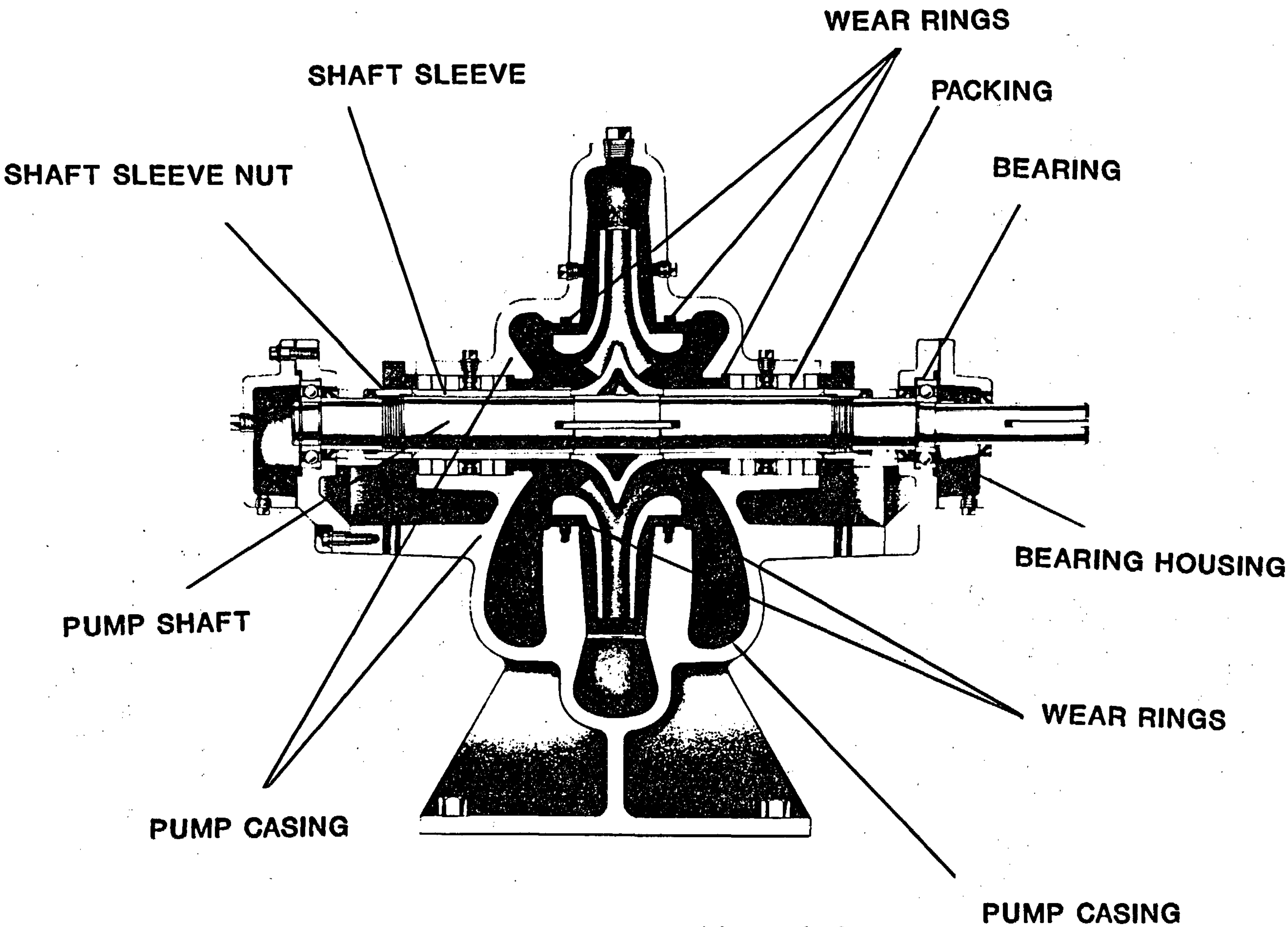

Figure 3.7 Typical horizontal single-stage double suction pump

As the pump operates, the shaft seals prevent the process fluid from leaking around the shaft circumference and out through the pump casing. Typically, there are two shaft seals; an inboard and an outboard seal on each end of the pump shaft. In addition, there are oil seals to prevent leakage of the bearing lubricating oil. These are located on each bearing.

Two types of shaft seals are commonly used on the pumps; mechanical seals and packing gland seals. Of the two, mechanical seals are the most widely used because they provide a tight seal while minimizing shaft (or sleeve) wear. As shown in Figure 3.8, the main parts of the mechanical seal are a stationary sealing ring, a secondary seal for the stationary ring, a rotating sealing ring, a secondary seal for the rotating ring, and a spring or bellows to press the two ring faces together[23]. The components most prone to failure are the sealing rings; however, all of the components are susceptible to aging degradation. As shown in this illustration, the leakage path for mechanical seals is between surfaces that are perpendicular to the shaft axis. This is in contrast to packing gland seals, in which the leakage path is parallel to the shaft surface.

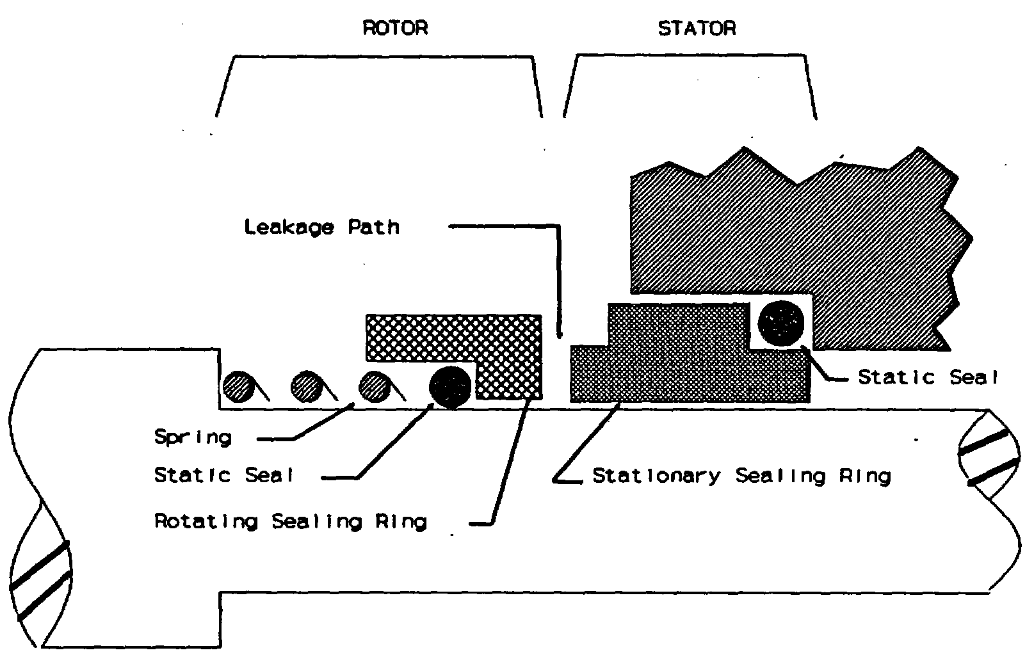

Figure 3.8 Subcomponents of a mechanical seal[23]

3.4.2 Pump Construction Materials

A variety of materials are used to construct the pump subcomponents. In this section, these materials are discussed and their susceptibility to aging is evaluated.

The materials used in constructing a pump must be based on the operating conditions expected, as well as the properties of the fluid being pumped. Some of the requirements typical for pump materials are:

1. Corrosion resistance
2. Abrasion/wear resistance
3. Cavitation/erosion resistance
4. Favorable casting and machining properties
5. High Strength
6. Fatigue resistance
7. Low notch sensitivity
8. Favorable galling characteristics

To meet these requirements, several different combinations of materials may be used for pump construction. Table 3.8 presents a sample listing of the materials used[26].

Bronze is widely used for wear rings since it has good resistance to galling where metal-to-metal contact occurs. Seal ring bodies, spring housings, and springs are usually made of stainless steel, bronze, or other corrosion-resistant materials (e.g., Hastelloy C, titanium)[23]. The subcomponents most susceptible to deterioration are the primary and secondary seals, which prevent the process fluid from leaking through the seal. Table 3.9 shows some of the combinations of the materials used for rotating sealing rings (RSR) and stationary sealing rings (SSR) in a mechanical seal, along with their relative resistance to wear in water[23]. Selection of the secondary seal materials is based on the operating temperatures; Table 3.10 lists some materials used for secondary seals, along with their temperature limits.

Over 40% of pump failures are due to seal problems (Figure 1.7). Table 3.11 shows the various aging mechanisms that are experienced with seals, and their corresponding cause[23]. A good maintenance and monitoring program should check for these aging mechanisms.

Packing is sometimes used on pump shafts in place of mechanical seals. As for valve packing, asbestos yarns formerly were the standard packing material; however, they are being replaced by new, non-asbestos materials. The aging mechanisms for pump packing are similar to those discussed for valve packing (section 3.2.2). Some of the newer packing materials being used for pump seals are the following[23]:

PTFE Packing: PTFE packings have low friction, and are chemically inert. The disadvantages of this material are its low strength, low thermal conductivity, and tendency to shrink with increasing temperature.

Aramid/PTFE Packing: This material consists of yarns or monofilaments of Kevlar (aramid fiber from Du Pont) precoated with PTFE dispersant, which are braided and impregnated with PTFE to make Aramid/PTFE packings. These packings offer exceptionally long life, low friction, and chemical inertness.

Graphite Packing: Graphite fiber packings can be used up to 750 °F, and have a chemical resistance similar to PTFE. These packings offer low friction and high thermal conductivity.

Two classes of bearings are used in pump construction; anti-friction bearings, and sleeve bearings. Bearing construction falls into three main categories; single metal, bimetal, and trimetal. Single metal bearings are made of one material, commonly either a copper alloy or an aluminum alloy. Bimetal and trimetal bearings have one or two surface layers, respectively. The backing layers for bimetal bearings are made of steel, lead bronze, or aluminum alloy, while those for trimetal bearings are usually made of steel. The selection of bearing material is based on the expected operating conditions, and a great deal of proprietary technology is used to formulate alloys to meet specific conditions[27]. The materials typically used are leaded or unleaded tin bronze.

Bearing degradation is another major cause of pump problems, accounting for more than 25% of pump failures (Figure 1.7). Table 3.12 shows the major aging mechanisms for pump bearings and their associated causes.

Table 3.8 Typical pump construction materials[26]

Part Name	Materials of Construction			
	Combination 1	Combination 2	Combination 3	Combination 4
Casing	Cast Iron - Class 30B			Carbon Steel-WCB
Impeller	Bronze Alloy 922	Cast Iron-Class 25B	Stainless Steel-CF8	Cast Iron-Class 25B
Impeller Rings	Bearing Bronze	Steel-AISI 1020	Stainless Steel-CF8	Steel-AISI 1020
Casing Rings	Cast Iron - Class 30B		Stainless Steel-CF8	Cast Iron
Shaft Sleeves	Bearing Bronze	Steel-AISI C1215	S/S-AISI 303	Steel-AISI C1215
Shaft	Steel-AISI 1045			
Seal Cages	Cast Iron- Class 30B		Teflon	N/A
Glands	Cast Iron-Class 30B			
Gland Studs	Stainless Steel-AISI 303			
Gland Nuts	Stainless Steel-AISI 303			
Packing	Non-Asbestos			
Stuffing Box Bushing	Steel-AISI C1215			
Shaft Sleeve Nuts	Stainless Steel-AISI 416			
Shaft Sleeve O-Ring	Buna-N			
Bearing Bodies	Cast Iron-Class 30B			
Bolts	Carbon Steel-A307 Grade B			
Gaskets	Non-Asbestos			

Table 3.9 Materials used in mechanical primary seals[23]

Face Materials		Wear Resistance
Rotating Sealing Ring	Stationary Sealing Ring	
Stainless Steel	Carbon	Low
Lead Bronze	Carbon	Low
Alumina Ceramic	Carbon	Medium
Tungsten Carbide	Tungsten Carbide	Medium
Stellite	Carbon	Medium
Chrome Oxide	Carbon	High
Tungsten Carbide	Carbon	High

Table 3.10 Materials Used in Mechanical Secondary Seals[23]

Seal Material	Temperature Limits (Degrees F)	
	Minimum	Maximum
High Nitrile Rubber	-22	248
Ethylene Propylene Rubber	-58	302
Viton Fluoroelastomer	-40	482
Kalrex Perfluoroelastomer	-58	590
PTFE	-148	482
High Temperature Polymers	-148	572
Compressed Asbestos Fibre	-148	752
Pure Graphite Materials	-328	5432

Table 3.11 Pump seal aging mechanisms and causes[23]

Seal Component	Aging Mechanisms	Cause
Primary Seal Face	Overall corrosion	- Normal operating exposure - Harsh environment
	Seal face distortion	- Operation at high pressures - Operation at high temperatures - Excessive swell of secondary seal - Contamination by foreign material - Operation at high fluid pressure/velocity values - Operation outside design limits - Loss of seal cooling
	Fracture	- Excessive thermal stress - Excessive fluid pressure - Excessive swell of secondary seal - Excessive fluid pressure/velocity values
	Edge chipping	- Excessive fluid pressure - Excessive shaft run-out, deflection, or whip - Seal faces out of square - Seal vibration
	Severe, uniform abrasive wear	- Excessive fluid pressure/velocity values - Deposition of dissolved solids - Contamination of cooling fluid - Excessive shaft end play - Loss of seal cooling - Harsh operating environment
	Heavy, non-uniform wear, galling, and grooving	- Contamination of seal cooling fluid - Excessive fluid pressure/velocity values
	Erosion	- Contamination of seal cooling fluid
	Blistering of carbon graphite faces	- Excessive or cyclic fluid pressure/velocity limits - Inadequate seal cooling
Secondary Seal	Extrusion	- Excessive pressure - Excessive temperature - Excessive swell
	Cracking	- Excessive temperature - Chemical attack - Ozone attack
	Cuts, tears, splits	- Material operating outside design limits
	Corrosion of interface	- Crevice corrosion - Fretting corrosion due to vibration

- Bearings are another subcomponent which are subject to aging degradation and can cause the pump to fail. Table 3.12 presents the major aging mechanisms acting on bearings, and their causes.

- Pump-casing failures were not found in the data; however, there is a potential for casing failures to occur during later years of operation. Casings are commonly made of cast iron or carbon steel, which are subject to corrosion and erosion. Over many years of operation, wall thinning can occur, leading to weakening of the walls and possible failure. This should be addressed in a life extension program.

4. SAFETY SYSTEM FUNCTIONAL INSPECTIONS OF CCW

Since 1985 the U.S. Nuclear Regulatory Commission (NRC) has performed Safety System Functional Inspections (SSFIs) at various nuclear power plants in the United States. The purpose of these inspections is to evaluate the readiness of safety systems to perform their design function when called upon. However, SSFIs can also be useful for evaluating how effectively a plant is managing the effects of aging. The inspections focus on systems which are critical to plant safety during normal or emergency conditions. Since they began, the CCW system has been included in five SSFIs.

As part of this phase II aging analysis, the CCW SSFI reports were examined to determine if any information related to aging of CCW systems was identified. The data were categorized to determine what types of problems are most commonly identified. In addition, the SSFI methodology was evaluated to determine if it is well suited to identifying aging-related problems. This section presents the results of these analyses, along with recommendations for improvements in the SSFI structure to make it more effective at addressing aging concerns.

4.1 SSFI Structure and Methodology

In principle, the SSFI should be well suited for identifying the effects of aging degradation in systems and components since its goal is to verify that the system will perform its function when called upon. To achieve this goal, the SSFI begins by evaluating plant practices in two major areas; maintenance and surveillance testing. Table 4.1 summarizes the SSFI activities which could provide useful information for identifying aging problems. For example, during the system walkdown the components are visually inspected to verify operability. This inspection can also provide information on component degradation. Indicators such as water or oil leaks, unusual noise or vibration, surface corrosion on components, and excessive temperatures provide insight into the condition of the components and the adequacy of the maintenance practices used.

The review of corrective and preventive maintenance actions also provides useful information for identifying aging concerns. The corrective maintenance performed shows what types of failures are most common for each particular component, and whether they recur. This information can be correlated with the preventive maintenance practices to determine if any modifications are needed to the program to better control component degradation. By trending the corrective maintenance data, the failure frequency of the various components can be determined. An increasing failure frequency with age would then indicate that aging degradation is not being properly controlled and further actions need to be taken.

The examination of functional test procedures and results gives a good indication of how well a system performs. By comparing the results to a baseline and trending them over time, the effects of aging degradation on system performance can be determined. Although the system may meet its performance requirements, a decreasing trend will suggest how long various components can remain in service before they are replaced or overhauled.

Table 4.1 SSFI inspection areas and subtasks related to aging

SSFI AREA	SUBTASK
Maintenance	1. System Walkdown: - provides gross determination of equipment operating condition
	2. Review of Corrective Maintenance History: - identifies equipment with repetitive or frequent failures - determines if appropriate root causes were identified
	3. Review of Preventive Maintenance History: - determines if PM activities are adequate - determines if PM frequency is adequate
	4. Review of Vendor Maintenance Recommendations: - determines if recommendations have been appropriately incorporated into plant maintenance procedures
Surveillance Testing	1. Evaluation of Periodic Functional Tests: - determines if the tests adequately verify the functional status of the system
	2. Evaluation of Test Results: - determines if the results indicate deterioration of function - determines if adequate programs are in place to identify and correct such deterioration

The NRC inspection manual for SSFIs[28] was reviewed to determine where explicit or implicit methodology for evaluation of system or component aging is described. Table 4.2 lists the sections in the manual and the evaluation methodology, and gives a short discussion of the relationship to detecting or mitigating the effects of aging.

The review of the structure and methodology of the SSFI shows that these inspections can be useful for evaluating how effectively a plant is managing aging. The SSFI can identify weaknesses in the plant's maintenance and monitoring techniques and provide insight into what improvements can be made. Therefore, it is recommended that the SSFI be used more extensively to perform evaluations. Some insights provided by past SSFIs are presented in the following section.

Table 4.2 Sections of NRC SSFI manual related to aging

Manual Section	Section Description	Relationship to Aging
II.A	Review the design basis requirements for the selected system and determine the operating conditions under which each active component will function during accident or abnormal conditions.	This step in the methodology establishes the baseline from which any aging analysis could start.
II.B.2	Determine if system modifications implemented since initial licensing have introduced any unreviewed safety questions. For example, determine if modified components have been evaluated for environmental equipment qualification considerations, such as temperature, radiation, or humidity.	This step can identify any new aging stresses imposed on the system due to design modifications.
II.C.2	Review the maintenance and test records for the selected system. Determine if the system components are being adequately maintained to ensure their operability under all accident conditions.	This step provides an evaluation of test and maintenance practices as to their effectiveness at detecting and mitigating aging degradation.
II.C.3	Determine the adequacy of the licensee's preventive maintenance program.	This step provides an evaluation of PM practices for managing aging.
II.E.4	Determine if surveillance test procedures comprehensively address required system responses.	This step provides an evaluation of test practices for detecting aging effects.
II.F	Review of operating experience for the selected system.	This step provides a correlation of actual experience with failures and component degradation.
II.F.1	Determine the historical reliability of the system and its components based on the review and analysis of the operation experience.	This step evaluates the effects of aging on system and component reliability.
II.F.2	Determine if the licensee has aggressively pursued, identified, and corrected root cause of failures.	This step determines if aging has been considered, or identified as a cause of system failures.
II.F.3	Determine the extent of the maintenance backlog and ascertain if the licensee has a program to identify, prioritize, and perform timely safety-related maintenance.	This step verifies that procedures are in place to control aging in a timely manner.

4.2 CCW SSFI Findings Related to Aging

To date, five CCW SSFIs have been performed by the U.S. NRC, and 23 items related to aging of systems and components were identified. This section gives a brief discussion of some of the more significant findings related to inadequate control of the effects of aging. The results of an SSFI conducted by a utility are also included to illustrate the types of observations made by a self-assessment.

4.2.1 Increasing System Leakage Leads to Potential Inoperability

In one of the plants inspected, the CCW system was designed to be a "zero leakage" system. Because of this design, the makeup system to CCW was not classified as a safety system and was not designed to be seismically qualified. Therefore, in the event of an accident, the makeup system must be assumed to be unavailable. A Final Safety Analysis Report (FSAR), based on a leakage rate of 0.008 gpm for pump seals and valve seat/stem leakage, determined that the CCW system could operate for 122 days without makeup. During operation, problems were experienced with the CCW heat exchangers because marine debris and marine life on the salt-water cooling side of the CCW heat exchanger began to cause leakage and fouling of the heat exchanger tubes. The leakage was calculated to be 0.142 gpm; however, documentation in the plant files indicated that even higher leakage was occurring. With a leakage rate of 0.142 gpm, the CCW system could only operate for seven days before makeup would be required. Since this was unacceptable from a safety standpoint, a temporary makeup system was installed, using a fire truck and hoses, pending installation of a permanent, seismically qualified system.

This incident shows how safety concerns can arise if aging degradation is not taken into account in the original design. The original calculation for the leakage rate simply took vendor-listed values for pump seals, and valve stems and seats. The calculation did not take into account component degradation, such as erosion of the heat exchanger tubes, which eventually led to an increased leakage rate. Also, it did not account for increased pump seal leakoff, internal leakage of the valve due to seat or disk erosion, and increased valve stem leakage due to degradation of the packing. Each of these aging mechanisms is common and should have been anticipated. Therefore, to properly address aging, its effects must be understood and accounted for, not only in the operation and maintenance of a system, but also in its design.

4.2.2 Design Change Potentially Increases Component Aging Rate

In several plants, the CCW system provides cooling to the reactor coolant pump (RCP). A modification was made at one plant to the isolation valve to the RCP loop to allow jogging control of the actuator. This modification would allow CCW flow to be controlled, thus reducing the potential for thermal shock. In the original design, a "seal-in" was provided that caused the valve to go to the fully open or fully closed position once activated. In the new design, the operator could jog the valve to intermediate positions. However, the modification did not consider whether the Limitorque valve operator had been designed or qualified for jogging service. The SSFI team was concerned that the different thermal duty cycle that was imposed on the motor, and the mid-travel operation of any "hammer-blow" features provided with the actuator, were not considered when the change was made. During the inspection, information was received from the manufacturer verifying that the valve actuators were acceptable for jogging duty, provided that no more than 20 starts were made for the 15 minute duty rating of the motor.

Although the component was eventually found to be capable of performing in the new operating mode, this incident demonstrates how a design change can inadvertently impose new aging stresses on a component. If the valve actuator was not capable of performing in jogging service, the design modification could have led to an increased aging degradation rate and premature failure. Therefore, design modifications must address the effects of aging.

4.2.3 Potential for Stress Corrosion Cracking Identified

When improved analytical methods were instituted, one utility found that the chloride content of its CCW water (1.0-1.5 ppm) was much higher than originally measured by the old method (0.15 ppm). The old method had been used for the past 11 years of operation under the mistaken belief that the readings were accurate. The chlorides appeared to originate from the original corrosion inhibitor used in the system. High chloride levels pose a serious threat of stress corrosion cracking to stainless steel components. The utility has not been able to assess the potential stress corrosion damage to the stainless steel safety-related portions of the CCW system (e.g., RHR heat exchangers, letdown heat exchangers, and reactor coolant pump thermal barriers).

In this instance, the SSFI uncovered an aging stressor that the plant operators were unaware of. The many years of operation with this aging mechanism uncontrolled may have shortened the life of some of the components. However, now that it has been identified, the problem can be monitored and controlled to mitigate any future problems.

4.2.4 Undetermined Causes for Calibration Discrepancies

A review of the preventive maintenance calibration records in one plant revealed that, despite obtaining as-found calibration readings that were beyond the instruments' acceptability criteria, several safety-related instruments were calibrated and returned to service without correction. No root-cause analyses were performed. The history of various out-of-calibration instruments revealed that deviations had occurred several times before, and some instruments were in service even after the calibration had exceeded the acceptability criteria.

This is an instance where aging degradation was not detected and controlled due to inadequate trending and analysis of calibration discrepancies. Ideally, the root cause of the calibration drift should have been determined and corrected before the instruments were recalibrated and returned to service.

4.2.5 Untested Check Valves Added to Design

There are numerous check valves in the typical CCW system. During normal operation, most of these valves are required to perform their two basic functions, which are to stop flow in one direction while allowing flow in the opposite direction. For these valves, aging degradation resulting in a failure to perform either of these functions could be detected any time the system is operating. However, some check valves in the system only perform one of their functions during normal operation; the other function may not be required unless there is an accident. Aging degradation in these valves would be difficult to detect unless special tests are performed specifically for that purpose. Consequently, their availability to function is not known and an undetected failure may exist. One such existing failure, together with a single failure in a redundant train, could render the CCW system inoperable.

One SSFI determined that six check valves had been added to the CCW system. However, they were not added to the surveillance test program. The check valves were, therefore, vulnerable to aging degradation, which may never have been detected until an accident condition arose.

4.2.6 Incomplete Procedure for Motor Operation

As part of the SSFI at one plant, the operating procedure for one of the CCW pump motors was examined. It was found that the procedure did not include the manufacturer's recommendations for the maximum number of consecutive motor starts allowed and the required interval between starts. Without this information, the potential for overheating the motor insulation exists. Overheating is an aging mechanism that can rapidly reduce the life of the motor's insulation and lead to premature failure. This incident demonstrates how the SSFI can help to mitigate aging stresses.

4.2.7 Throttling of Valves Causes Accelerated Aging of Seats

The CCW system design at one plant uses butterfly valves as inlet and outlet isolation valves on various heat exchangers in the system. During an SSFI on this CCW system, it was determined that the butterfly valves were being used to throttle flow to the heat exchangers, which is not what they were designed for. Discussions between the utility and the valve manufacturer indicated that when the valve is less than 20 degrees open, the water velocities may increase substantially and result in cavitation at the valve seat, which would reduce the expected life of the valve. The manufacturer recommended a formal analysis be performed to determine if the specific application would cause unacceptable seat damage.

This is a case where operation of a component outside its design specification could lead to accelerated aging and premature failure. The SSFI identified this problem so that the condition could be analyzed and any potential aging degradation mitigated.

4.2.8 Insights from a Utility Self-Assessment SSFI

In a CCW system SSFI conducted by a utility for self-assessment, several important observations were made. These observations demonstrate the usefulness of this type of inspection, as well as the potential areas of vulnerability of CCW systems in older plants.

One observation was that the CCW system was capable of performing its safety functions during normal operating conditions. However, from a mechanical design perspective, it had not been demonstrated that the CCW system could adequately perform its safety function during postulated emergency conditions. There were two reasons for this.

The first issue was related to the CCW flow rates to the shutdown cooling heat exchangers and the containment coolers. The flow rates from the flow balance test were approximately 25% less than the values assumed in the containment response analysis for a loss of coolant accident (LOCA). These flows are critical since CCW is the only means of post accident heat removal from the containment. The team pointed out that "...inadequate heat removal could potentially result in exceeding containment structural design parameters and/or result in a more severe environment (e.g., temperature, pressure) than what safety related equipment is qualified for..." This finding raises two issues appropriate for the aging study:

1. Flow measurements to safety-related components should be periodically verified, and,

2. The acceptance criteria for system flow capacity tests should be based on postulated accident conditions, if they are greater than normal operating values.

The second issue of significance to aging from the self-assessment SSFI concerns the environmental qualification of the CCW pump motors. The room where the pump motors were located was determined to be a mild environment, based on the lack of high energy lines in the immediate vicinity. A maximum temperature of 110°F was assumed. However, the team found that the room's ambient temperature could reach 150°F following a loss of the non-safety-related ventilation. This ventilation system would not be operable during a design basis LOCA, because it is not automatically loaded onto the emergency bus. The long-term performance of the CCW pump motors, which remove decay heat, could not be assured.

There was another observation from the utility SSFI related to aging, but of lesser significance. The inspection team observed that one of the more frequently maintained components of the system was the CCW heat exchangers. Fouling of the tube side from marine growth resulted in the need for periodic cleaning of the head and hydrolasing of the tubes. Leaking tubes accounted for more than 10% tube plugging on one of the heat exchangers. Analysis at this plant indicates that up to 15% plugging can occur before the heat removal capability is jeopardized. Non-destructive examination (NDE) had noted a marked increase in degradation of tube wall thickness in the last several years. One heat exchanger required a re-tubing after 13 years of operation because the 15% plugging criteria was exceeded.

4.2.9 Summary of SSFI Findings

NRC SSFI reports have been useful in identifying problems in the design, operation, and maintenance of the CCW system that are related to aging. Some examples include the following:

- An inadequate makeup supply to the CCW system existed due to a design assumption of a "zero leakage" system. This failed to address the effects of aging on pump seals and valve packings.

- The modification of the control logic of an MOV from a seal-in to a jogging circuit did not consider the additional stresses imposed on the motor.

- Numerous cases of out-of-calibration instrumentation were not analyzed to determine the root cause. Aging effects, such as calibration drift, were not detected nor managed satisfactorily.

- Butterfly valves in the CCW system at one plant were being used to throttle flow, an operation for which they were not designed. Increased wear on the seats of these isolation valves resulted.

- The design operating temperature for the CCW motors was lower that the temperature expected during an accident when the non-safety related ventilation system would not be in service. Therefore, the long-term performance of the system could not be assured.

The findings indicate that the SSFIs can be a useful tool for determining how effectively the effects of aging have been addressed. Table 4.3 summarizes the areas where SSFIs can be useful for identifying aging problems, and presents the lessons learned from the SSFI reviews discussed.

Table 4.3 Areas where SSFIs provide useful aging information

Area Affected By Aging	SSFI Useful?	Lesson Learned From Previous SSFI
Original Design	Yes	Aging degradation can be a factor in determining the original system design. Aging effects must, therefore, be understood and accounted for in design calculations.
Design Modifications	Yes	When design modifications are made, new aging stresses may inadvertently be introduced into the system. These new stresses must be mitigated by modifying existing ISM&M practices or adding new ones.
Corrective Maintenance	Yes	When corrective maintenance is performed, the root cause of failure should be determined whenever possible. If it isn't, aging degradation can go undetected and the failures can reoccur.
Preventive Maintenance	Yes	Preventive maintenance procedures should include manufacturer's recommendations to avoid imposing unnecessary aging stresses on components.
Monitoring Methods	Yes	Monitoring methods are not always comprehensive enough to detect aging degradation in an incipient stage before it results in degraded performance.

4.3 Recommended Additions to the SSFI Methodology

The SSFI was not intended to identify aging problems in nuclear plants. However, a significant number of age-related conditions were found in previous inspections, even without an aging focus. It is not clear whether the conditions identified represent all of the aging problems or just a small portion. However, it is clear that the SSFI can be a useful tool for helping to uncover age-related problems in CCW, and probably in other safety systems. To focus the inspections on aging concerns more directly, a list of recommended additional information to obtain during the SSFI has been prepared (Table 4.4); their inclusion in future SSFIs could more clearly determine if there are additional aging phenomena beyond the types that are currently identified. It should be noted that the information requested is not intended to indicate that there are regulatory requirements related to control and identification of aging degradation; the additions are recommended only as a means of determining the extent to which aging of systems and components is addressed at a particular plant.

The review of CCW SSFIs did not identify common aging phenomena from plant to plant, however, it did identify potential aging related problems that could occur at more than one plant. While all of these conditions would not be expected to affect any one CCW system, individual conditions would be expected to affect a number of plants and could reduce the reliability of the CCW system if left unchecked.

Table 4.4 Recommended additions to SSFIs

SSFI Area	Additional Information to Obtain
System Walkdown	Determine the following: - do systems and components appear to be well maintained and functioning properly (e.g., are there any visible signs of unchecked aging degradation) - is aging related degradation a possible cause of any malfunctions observed
Preventive Maintenance	Determine the following: - are components properly maintained such that compensations are made for expected wear and tear - are frequencies adequate to mitigate aging degradation leading to failures
Corrective Maintenance	Determine the following: - are failure rates being calculated and trended - are failure rates higher than expected - are modifications or compensating measures being pursued to deter increasing failure rates - are root cause analyses being conducted
Design Modifications	Determine the following: - have unforeseen aging stresses been added to the system that could lead to accelerated aging of systems and components (e.g., hot spots, more frequent or longer durations of operation, higher radiation dose rates) - have compensating measures been added to address any new stresses - have analyses been performed to determine the effect on the aging and operation of associated systems and components (e.g., addition of fire barriers can effect the environment of surrounding components)
Operation	Determine the following: - are systems or components operated beyond design limitations such that stresses are in excess of those expected and premature aging is possible - are system and component parameters being properly monitored for signs of deterioration, and are data being appropriately evaluated - have acceptance criteria been developed for the monitored parameters - have appropriate actions been taken in response to identified trends indicating deterioration of performance - when aging degradation is detected during an inspection, how serious is degradation with respect to acceptable performance, and will operability be affected

5. ASSESSMENT OF REGULATORY AND INDUSTRY REQUIREMENTS

The component cooling water (CCW) system is classified as one of the reactor auxiliary systems required for safe shutdown during normal or accident conditions. The design, operation, testing, and maintenance of this system are, therefore, governed by regulations and industry standards, such as the General Design Criteria in the Code of Federal Regulations (10CFR Part 50), NRC regulatory guides, the NRC Standard Review Plan, and various codes, standards, and guides published by the professional societies. In addition, for certain types of components, manufacturer's recommendations and guidelines are considered for proper operation and maintenance of the equipment. Past operating experience has identified problems requiring modifications to the design, operation, and maintenance of the system. This section discusses these requirements and assesses their adequacy for assuring continued reliable functioning of the CCW system as the plant ages. Table 5.1 summarizes the documents reviewed in this section.

5.1 CCW System Design Requirements

After the Three Mile Island (TMI) accident in 1979, the importance of the CCW system to remain functional in supplying cooling water to the Reactor Coolant Pump or Recirculation Pump seals was recognized. It became evident that there were various concerns about the designs, as Generic Issues 23, 65, and 130, and Unresolved Safety Issue A-44 were issued during the last decade. In addition, other design deficiencies, such as over-pressurization of the CCW system and inadequate cooling to the RHR pump seals in certain configurations were noted, and disseminated to individual licensees via NRC Information Notices. Therefore, the design requirements of the CCW system are critical and must continue to be reviewed and improved.

The design of the CCW system is governed by various design criteria, included in the Code of Federal Regulations, whose purpose is to ensure reliable system performance during normal or accident conditions. It is important that these design criteria be followed for safety systems because of the adverse impact that a failure in one of these systems could have on plant safety. The design requirements for the CCW system are examined in this section, along with some of the potential safety concerns related to a failure of the system. These safety concerns are identified in various NRC generic letters and information notices.

5.1.1 General Design Criteria

Although the basic design requirements of the CCW system follow the 10CFR Part 50 General Design Criteria (GDC) and the NRC Standard Review Plan (SRP), its configuration and the loads to which it provides cooling water vary widely from plant to plant. ANSI/ANS-59.1-1986[29] provides requirements in the areas of design, materials, fabrication, placement and testing of the CCW system. This standard also identifies other relevant industry standards that govern the design requirements for the system. However, none of these documents include any specific requirements for addressing aging. The only requirement for aging management is that equipment used in the system must remain operational throughout the life of the plant.

Table 5.1 Regulatory and industry documents related to the CCW system

CCW System Status	Standards/Guides/ Issues/Notices	Subject Addressed	Aging Topics
Design	General Design Criteria 2	Seismic requirements	None
	General Design Criteria 4	Missiles, pipe whip, pipe break, flow instabilities	None
	General Design Criteria 5	Interfacing systems and components	None
	General Design Criteria 44	System redundancy	None
	Generic Issue 23	RCP seal failure due to insufficient cooling	N/A
	Generic Issue 65	Probability of core melt due to CCW failure	N/A
	Generic Issue 130	Essential service water pump failure causing CCW heat exchanger failure	N/A
	NRC Standard Review Plan	Review of system design	None
	Unresolved Safety Issue A-44	Station blackout	N/A
	Information Notice 89-54	Over pressurization of CCW system	N/A
	Information Notice 89-71	Inadequate cooling of RHR pump seals	N/A
Operation/ Testing	General Design Criteria 45	In-service inspection	None
	General Design Criteria 46	In-service test	None
	ASME OM Standards ANSI/ANS-59.1-1986	Operation and maintenance - general discussion of aging effects on pumps, HXs, and piping	Yes
	NRC Regulatory Guides 1.26 and 1.29	Classification of system components	None
	Technical Specifications	General system operating limits and test requirements	None
	Generic Letter 89-10	Testing requirements for motor-operated valves	None
	Generic Letter 89-13	System performance testing requirements	None
Maintenance	INPO Good Maintenance Practices	Maintenance	None

N/A Not Applicable

Specific sections of the General Design Criteria (GDC) to which the CCW system must conform are 2, 4, 5, and 44 of Appendix A to 10 CFR Part 50. Based on these criteria, the CCW system must be designed to accommodate the following:

GDC 2: The structures housing the system and the system itself must be capable of withstanding earthquakes. NRC Regulatory Guide 1.29 defines the safety-related and nonsafety-related portions of the system.

GDC 4: The system must be capable of withstanding the effects of missiles from inside and outside the containment, pipe whip, pipe breaks, and flow instabilities during normal plant operation, as well as during upset or accident conditions.

GDC 5: The shared systems and components must be capable of performing their required functions without impairing the ability of the CCW system to perform its safety functions.

GDC 44: Suitable redundancy in components and features, and suitable interconnections, leak detection, and isolation capabilities are required to assure that, for on site and off site electrical power system operation, the system safety function is accomplished, assuming a single failure.

After the TMI accident, a requirement was added to GDC 44 that the design of the CCW system must withstand a loss of power without damage to RCP seals. This is in accordance with the TMI action plans II.K.2.16 of NUREG-0718, and II.K.3.25 of NUREG-0737.

5.1.2 Generic and Unresolved Safety Issues on RCP Seal Cooling

Several potential safety concerns related to failure of the CCW system have been identified from a review of the system designs. These concerns have been addressed in various NRC letters, bulletins, and notices. They indicate the importance of the CCW system to plant safety and identify weaknesses in the system designs. These issues were reviewed and the results are discussed in the following paragraphs.

Increasing attention has recently been focussed on the integrity of reactor coolant pump (RCP) seals in the event that cooling flow to the seals is lost. In Westinghouse and B&W plants, primary seal cooling is provided by an injection flow directly into the seal assembly. As a secondary means of seal cooling, a thermal barrier heat exchanger is included inside the pump housing that is cooled by the CCW system. If the seal injection flow is lost, hot reactor coolant would be cooled by the thermal barrier heat exchanger before flowing through the pump seals. Although designed to provide redundant methods of seal cooling, loss of either the seal injection system or the thermal barrier cooling system would necessitate stopping the reactor coolant pumps within a limited time to prevent pump damage.

Generic Issue 23, "Reactor Coolant Pump Seal Failures" discusses the potential safety consequences of a failure in PWR primary coolant pump seals and

BWR recirculating pump seals. It was found that seal degradation resulting in mechanical failure of the seal can result from a loss of cooling to the seal, that in turn could lead to leakage. Although seal failures have not resulted in a direct threat to public health and safety, there is the potential for a seal failure to cause leakage of primary coolant to containment; this has been classified as a small LOCA.

Failure of the CCW system, in conjunction with a loss of seal injection, will result in immediate exposure of the seals to hot reactor coolant. If the seals fail after prolonged exposure to reactor coolant, and if the pumps used for seal injection are also cooled by the CCW system, a LOCA without makeup capability could result. In addition, if containment fan coolers are cooled by CCW, containment integrity could be jeopardized. From this sequence of events, Generic Issue 65, "Probability of Core Melt Due to Component Cooling Water System Failures", has emerged and is expected to be resolved as part of Generic Issue 23. As concluded in NUREG-0933, based on the PRAs associated with the Zion, Indian Point, and Sizewell plants, even the lower bounds of the parameters are in the medium priority category, and the "best" estimates are well into the high priority. Therefore, maintaining the CCW system in operation is classified as HIGH priority.

In another scenario, complete loss of the CCW system, seal injection system and reactor makeup systems could result from loss of all AC power to the plant. This condition is being evaluated as part of USI A-44, "Station Blackout", and further investigated as part of Generic Issue 23.

Generic Issue 23 is in the process of being resolved, and a Generic Letter is likely to be issued addressing the following proposals:

- to treat the RCP seal assembly as a safety-related component, similar to other reactor coolant pressure boundaries, applying QA requirements consistent with Appendix B of 10CFR Part 50.

- to provide procedures for normal and off-normal conditions, and the instrumentation needed to implement these procedures.

- to provide RCP seal cooling during off-normal plant conditions involving loss of all seal cooling, such as stated in station blackout.

5.1.3 IN 89-54: Potential Over Pressurization of CCW System

Information Notice 89-54 was issued to all operating reactor licensees on a design deficiency in the CCW system at the Surry Power Station. The deficiency results from under-design of the relief capacity for the CCW lines connected to the thermal barrier heat exchangers on the reactor coolant pumps. The CCW piping adjacent to the reactor coolant pumps at Surry is of schedule 160 carbon steel and is designed to withstand full reactor system pressure. The low-pressure sections of the CCW system within containment and within the auxiliary building are designed for 150 psig.

In the event of reactor coolant system inleakage (design basis of approximately 275 gpm), the low-pressure sections of CCW piping are protected from over-pressure by a check valve on the upstream side of the RCP thermal barrier, and by a fast-closing AOV on the downstream side. The isolation valve is designed to close on a high CCW flow signal, while a relief valve located on the upstream side of the thermal barrier is designed to open at 150 psig. The air-operated isolation valve is not safety-related, and the relief valve is designed to pass 167 gpm. Failure to isolate the leak inside containment or to provide adequate relieving capacity could lead to a reactor coolant leak outside the containment building that cannot be isolated.

5.2 System Inservice Inspection and Testing Requirements

The ASME Section XI inservice inspection and testing requirements for the CCW pressure retaining components and their supports are included in the plant technical specifications to assure the operability of the system. In addition, General Design Criteria 45 and 46 of Appendix A to 10CFR Part 50 require the following:

GDC 45: The system must permit periodic inspection of important components, such as heat exchangers and piping, to assure the integrity and capability of the system.

GDC 46: The system must be designed to permit appropriate periodic pressure and functional testing to assure (1) the structural and leaktight integrity of its components, (2) the operability and the performance of the active components of the system, and (3) the operability of the system as a whole under all design basis conditions.

In addition, the test control criteria of Section XI in Appendix B to 10 CFR Part 50 require that a test program be established to assure that all testing required to demonstrate that structures, systems, and components will perform satisfactorily in service is identified and performed in accordance with written test procedures, which incorporate the requirements and acceptance limits contained in applicable design documents.

These test and inspection requirements are very general and can be applied to three specific areas; preoperational testing, inservice inspections, and inservice testing. Each area will be discussed separately.

5.2.1 Preoperational Test Requirements

The ability of the system to perform all of its design functions is tested prior to starting normal plant operation. The preoperational requirements cover prerequisite tests, station configuration, integrated system functional test, and post-testing conditions. The requirements ensure that each component or group of components has been tested in all specified combinations, either in the system test or as a prerequisite.

ASME/ANSI OM-S/G-1990,[30] Part 2 and ANSI/ANS-59.1-1986[29] standards delineate system tests for both the cold and hot conditions which should be performed on CCW components as preoperational test requirements. These standards also include system-level tests, such as heat balances and flow adjustments. If the actual heat loads are not available at the time of testing, then estimated values are used and later verified as the heat loads are made available. These activities are commensurate with the requirements given in the General Design Criteria listed above.

The ASME standard lists pump flow, system flow, heat exchanger performance, heat capacity, automatic control functions and their calibrations, and emergency power operation tests for load shedding and sequential loading tests. Minor deviations are corrected either by determining equivalent test methods and retesting, or by making system adjustments and retesting. On the other hand, major deviations are corrected by performing engineering evaluation to change acceptance criteria, or by changing the system design and retesting in the new conditions.

5.2.2 Inservice Inspection Requirements

According to Regulatory Guide 1.26, the components in the CCW systems are classified as Quality Group C; the corresponding ASME Code Class is 3. However, some portions of the system that penetrate containment are classified as class 2. As required by GDC 45 and 46, and 10 CFR 50.55(a), an inservice inspection (ISI) program for the CCW system is provided in accordance with Section XI of the ASME Boiler and Pressure Vessel Code.

To assure the structural and leaktight integrity and capability of the system, pressure retaining components are visually inspected during hydrostatic and leakage tests. Hydrostatic tests are performed at a pressure above normal system operating pressure, and are required every 10 years. System leakage tests are performed at normal system operating pressure, and are required every three to four years. Additionally, the system supports and their integral attachments are visually examined as part of the in- service inspection requirements.

5.2.3 Inservice Testing Requirements

The inservice testing (IST) program for the CCW system requires periodic functional testing to assure the operability and performance of the active components of the system, in accordance with GDC 46. Pumps and valves are tested in accordance with ASME Boiler and Pressure Vessel Code Section XI, Division 1. Reference values are established when the pump or valve is known to be operating correctly. Test values are compared to the reference values to determine component operability.

Snubbers are functionally tested in accordance with Section XI and the technical specifications. A representative sample from various locations in the plant is tested. Service and environment are considered in selecting the sample. Aging of snubbers is specifically addressed as part of the snubber service life monitoring program, as required by the technical specifications.

There are other factors which are part of an effective surveillance program. Normal periodic data logging should be included so that the data on heat exchanger fouling, or branch flow changes can be trended. Components not in operation, such as standby heat exchangers, should be scheduled for periodic operation to ensure operability.

It should be noted that the ASME Section XI inservice test requirements will be replaced by the ASME Operation and Maintenance (O & M) Code. In particular, pumps will be tested in accordance with ASME OM Code, Subsection ISTB, which replaces Section XI, Subsection IWP. Valves will be tested in accordance with ASME OM Code, Subsection ISTC, which replaces Section XI, Subsection IWV. Snubbers will be tested in accordance with ASME OM Code, Subsection ISTD. As plants update their inservice test programs, the OM Code requirements will be incorporated.

Performance test guidance for the CCW system is included in part 2 of the ASME/ANSI-OM-S/G-1990 standard. This standard provides guidance on what tests should be performed and what data should be recorded; samples of data recording sheets are also included. Evaluation of the test results and acceptance criteria are also discussed. In Appendix D of this standard, there is guidance for analyzing system degradation with a discussion of pipe friction increases due to degradation, heat exchanger fouling, and pump head and capacity degradation with time. Measurements to be made and calculations that can be performed are also presented. Every five years, tests should be performed to evaluate the heat removal capability of the system and degradation of system components. This is included in the ASME OM standard which relates to aging of the system, and is consistent with the requirements of Generic Letter 89-13. The particular type and frequency of tests are selected based on the aging characteristics established for the particular application of the equipment within the CCW system.

Instrumentation and controls should be calibrated periodically to ensure proper indications. Nominal tests are performed at a minimum of once every 18 months to demonstrate system operability, in accordance with technical specifications. These tests include:

- Auto pickup of standby pump or heat exchanger, or both
- High and Low flow alarms
- Surge tank auto level controls and alarms
- Process radiation or monitoring alarm interlock, or both
- Local or remote controls, or both
- Low suction pressure (NPSH) alarm

5.2.4 Generic Letter 89-13 on Service Water System Problems

As an example of a safety issue related to testing, Generic Letter 89-13, "Service Water System Problems Affecting Safety-Related Equipment" discusses testing, maintenance, design, and human factor issues related to the CCW system, and the lack of compliance with GDC 44, 45, and 46. The recommended action items in the generic letter address the age-related problems associated with CCW heat exchangers. These action items require 1) a test program be conducted to periodically verify heat exchanger heat transfer capability, 2) verification that the system will perform its intended function, and 3) verification that maintenance practices, procedures, and training are adequate. Utilities are required to implement the recommended actions, or submit alternatives. Operating experience and studies indicate that CCW systems may experience significant fouling from aging-related in-leakage of service water, along with erosion or corrosion. The requirement for periodic testing of the heat transfer capacity of heat exchangers serviced by the CCW system has not been considered necessary because of the assumed high quality of chemistry control programs for the CCW water. However, if the adequacy of these chemistry control programs cannot be confirmed over the total operating history of the plant, or if any unexplained downward trend in the heat exchanger performance is identified that cannot be remedied by maintenance of the SW system, it may be necessary to selectively extend the test program and the routine inspection and maintenance program outlined in the ASME OM standard.

5.3 System Maintenance Requirements

As indicated in GDC 44, GDC 45 and GDC 46, the design integrity and operational capabilities of the CCW system should be maintained throughout the life of the plant to ensure the successful performance of its safety functions. The periodic ISI and IST programs discussed above are the tools for determining if these goals are being met. However, a well balanced maintenance program is necessary to mitigate problems caused by degradation, such as aging, human errors, or natural catastrophes. This section reviews the industry standards and operating experience relating to maintenance of the CCW system.

5.3.1 Industry Maintenance Standards

Various industry standards were reviewed to determine if any direction is provided for performing preventive and corrective maintenance on the CCW system. Although there are various standards for preventive maintenance of certain components, such as the Institute of Nuclear Power Operations (INPO) good maintenance practices, there is no standard which specifically establishes requirements for preventive maintenance. Preventive maintenance practices are typically based on past operating experience and component manufacturer's recommendations.

Corrective maintenance is performed when a failure occurs. Typically, either the component is repaired or refurbished, based on the assessment of its condition at the time of failure, or the component is replaced at a fixed interval, which is established by the requirements of the equipment qualification program.

5.3.2 IN 90-21: Potential Aging Failure of Motor-Operated Butterfly Valve

An example of a safety issue involving testing and maintenance is discussed in Information Notice 90-21, which was issued to all licensees to alert them to a potential increase in friction forces on valve seats. This could result from maximum seat hardening that exceeds the amount assumed when selecting the motor actuators and setting the torque switches. The systems in which these valves are located include the CCW system, SW system, and various ventilation systems of Catawba Units 1 and 2. Failure of these MOVs could cause a loss of cooling water to the RHR system heat exchangers. This underestimation of the friction forces could lead to the common cause failure of a large number of motor-operated butterfly valves to open on an electrical signal.

As a result of this concern, Generic Letter 89-10, "Safety-Related Motor-Operated Valve Testing and Surveillance," requested that the utilities establish a program for testing, inspection, and maintenance of motor-operated valves in safety systems. One factor contributing to the need was the uncertainty in the analytical estimations used to select the motor actuators for valves and setting their torque switches.

5.4 Summary of Findings

Regulatory documents and industry standards address the design and operational requirements for the CCW system. The utilities are continuing to modify the design and the operating procedures for the system as they find deficiencies either from NRC notices and bulletins, or from their own experience. An area which is not adequately addressed is aging degradation of the system.

The aging of components, systems, and structures in nuclear power plants has been receiving more attention as they approach the end of their licensing period. However, most documents guiding the design, operation, testing, and maintenance of such facilities do not explicitly address aging considerations. The revised SRP for plant license renewal (SRP-PLEX), the technical specification for snubbers, and the ASME OM standard are the only documents which contain some guidance for managing aging.

The ISM&M requirements currently contained in the various industry codes and plant technical specifications are able to detect degradation from many of the aging mechanisms that commonly lead to failures. However, the results of the phase 1 CCW system study show that, even with current requirements for inspections and tests in place, a large fraction of failures are related to aging. Therefore, current requirements are not comprehensive enough to completely control all aging mechanisms. Methods of more effectively managing aging are discussed in Section 7.

6. ADVANCED ISM&M PRACTICES

In addition to the routine practices which are performed at all plants, there are other ISM&M practices which may detect and mitigate aging degradation. Many are already used by most utilities, although not routinely. Other practices are still under development and have not yet been applied. In this section, a brief discussion of these advanced practices will be presented along with their applicability to the CCW system.

For the CCW system, several ISM&M techniques which can indicate equipment or system degradation were evaluated. These include techniques which have application to heat exchangers, pumps, valves, and piping. While the emphasis is on pumps, valves, and heat exchangers, the long term degradation of tanks and piping should also be considered when planning a supplemental maintenance program.

6.1 Ultrasonic Testing

Airborne ultrasonics is an effective test for locating and diagnosing mechanical problems. It has been proven to be a very versatile test and accurately spots potential bearing failures, as well as locates all types of pressure and vacuum leaks. It is also effective in detecting internal leakage in valves[31].

Ultrasonic leak detection is based on the principle that forcing a fluid through a small opening creates turbulence on the downstream side. This turbulence generates a "white noise" that has strong ultrasonic components. Most of the audible sounds of a leak might be masked; however, the ultrasonic signals will be readily detectable, even when loud ambient noise is present. Sounds above 20 Khz are the most crucial in detecting wear or leakage in machinery, while humans can only hear sounds in the 20 to 20,000 Hz range.

Another advantage of ultrasonic detection is that audible sound waves are long, therefore, they can penetrate walls and machine parts, and are reflected off other surfaces. These attributes make it difficult to trace them to their sources. However, ultrasonic sound waves are extremely short and travel in straight lines. They cannot penetrate solids, although they do filter through the tiniest of openings. These properties of ultrasonic sound waves enable ultrasonic detectors to be largely unaffected by even the loudest machinery. They are practical to use in plants where noise can be extreme[32].

Since the ultrasonic detector is sensitive only to ultrasound, it is able to pinpoint the sources of high frequency emissions. This is important since wearing parts produce ultrasound long before they produce audible sounds. Therefore, machine wear can be detected at a very early stage before much damage is done. In using the detector, an operator listens for ultrasound through earphones and gauges its intensity by the deflection of an analog meter.

6.1.1 Detecting Heat Exchanger Tube Leaks

Ultrasonic testing can be used to detect heat exchanger tube leaks in three different ways[33]:

1. On-Line: By touching the instrument to the outer shell, the heat exchanger can be monitored for a normal turbulent flow. When a leak occurs in the tubes, the change in turbulence generally produces popping sounds that facilitate the detection of the onset of leakage. Smaller leaks in the peripheral tubes are more readily detectable than are leaks in the central tubes, where mostly gross leaks are detected.

2. Off-Line, Tone Generation: While the heat exchanger is off-line, ultrasonic transmitters are placed in the inlet and outlet ports to flood the internal shell around the tube bundle. Should a tube leak, the sound will penetrate the leak hole and carry through the length of the tube. Tube-to-tube sheet integrity may also be tested in this manner.

3. Off-Line, Pressure Test: In this off-line test, the heat exchanger is pressurized with air, and standard leak detection methods are incorporated. A scan of the tube sheet for the telltale rushing sound will indicate leakage.

6.1.2 Detecting Valve Internal Leaks

A poorly seated valve can be detected through the ultrasound created by the fluid flowing through the seat. If the valve is correctly seated, no flow will occur and no ultrasound will be detected. When the ultrasound detector probe is touched to the body of a leaking valve, the recognizable sound of liquid flowing through an opening will be heard. The noise of a leaky valve is more evident on the downstream side of the leak because of the turbulence created when the liquid flows from the high pressure side, through the leak, to the low pressure side. The same technique can be used for relief valves.

6.1.3 Detecting Bearing Degradation

Ultrasonic inspection and monitoring of bearings is one of the most reliable methods for detecting incipient bearing failure. Experiments performed by NASA revealed that changes in frequency from 24 kHz through 50 kHz in a bearing provided a warning long before other indicators, such as increases in temperature or vibration.

The structural resonances of one faulty component, such as the repetitive impact of a ball passing over the pit of a fault in the race, produces similar increases in amplitude as balls get out of round. The repetitive ringing of the flat spots is also detected as an increase in amplitude of the monitored frequencies. Generally, a good bearing makes a rushing or hissing sound. Loud rushing sounds similar to those of good bearings, only slightly rougher, indicate lack of lubrication. Cracking or rough sounds mean that the bearing is on the verge of failure.

There are two basic procedures for testing bearings: comparative and historical. The first involves testing two similar bearings and comparing the differences. Historical testing involves monitoring a given bearing over a period of time to establish its history. Patterns of wear at particular frequencies become obvious and allow for the early detection and repair of problems. Sensitivity levels and meter readings, as well as frequency settings are recorded on a chart for reference. Decibel levels can be determined from one reading to the next. NASA has determined that a bearing has entered the failure mode when the ultrasound level increases 10 decibels or more over the initial base line reading.

6.1.4 Detecting Pump Degradation

Ultrasonic testing also detects pump degradation. For example, a chemical plant reported that before it started using ultrasonic testing it had to wait until the pump's efficiency decreased by at least 5% before degradation could be detected. Now with the ultrasonic detector, degradation can be detected before the pump loses more than 2% of its efficiency. Although routine vibration surveys on all pumps are taken every six months, the ultrasonic tests detect signs of degradation before it is picked up on the vibration surveys. When wear between an impeller ring and its companion case ring occurs, the pump gives out a high pitched sound caused by the water sliding under the ring and having its pressure reduced. In this case, a whir or unusual noise will be detected. Every pump has its own record; the velocity and level of any ultrasonic signals detected during inspections is recorded and kept on file.

6.2 Eddy Current Testing

When an electromagnetic field is placed around a surface, any interaction of a high frequency surface wave with a defect in the surface will cause a perturbation in the electromagnetic field. This perturbation can be detected by a receiving coil and used to produce an indication on a meter. This principle is the basis for eddy current testing, which is used to detect surface and near surface flaws in materials. The process requires information on the characteristics of electromagnetic signals possible in the material[34].

One use of eddy current testing is to check heat exchanger tubes for cracks or defects. This is accomplished using a probe that is inserted into the heat exchanger tubes and pulled or pushed through the tubes. The tubes usually are cleaned before testing to remove scale or debris build-up that can affect the results or block the probe. The eddy current's magnetic field cuts through the coils in the probe and induces an electrical current through them. This current is returned to the eddy current instrument, which amplifies it, electrically processes it, then displays the signal on a CRT. As the signals appear, the technician analyzes the amplitude, phase angle, and shape to identify the specific defect. Each defect, such as pitting, wall thinning, support damage, and cracks generates its own signal.

It is important to note that eddy current testing is normally conducted only on non-magnetic tubing, which is the most common type for CCW heat exchangers. However, if the tubes are made of ferrous (magnetic) material, a similar approach to eddy current testing may be used. This is the remote field technique, which is discussed in the next section.

6.3 Remote Field Technique

The Pennsylvania Electric Company, with the support of EPRI, evaluated the techniques available for detecting, characterizing, and quantifying defects associated with known failure mechanisms in heat exchangers constructed of carbon steel tubes[35]. The basic process which was found to be most successful is the remote field technique (RFT). It was demonstrated that the method could identify the following degradation modes in a heat exchanger:

- gradual outside diameter (OD) wall loss (usually associated with corrosion)
- one-sided OD wall loss (normally caused by debris damage within the heater)
- OD circumferential defects (typically found at baffle locations as a result of tube vibration)
- small volume circumferential grooves (typical of fatigue cracking between support baffles)
- large volume OD pitting

The RFT inspection technology uses permanent, high-energy magnets contained in the probe to magnetize a segment of tube. Both internal and external defects produce a localized perturbation of the magnetic field in the tube. These perturbations induce a signal in the probe's sensor coils that is amplified and displayed on a CRT or strip chart recorder. An additional sensor measures total magnetic flux in the tube wall to detect gradual wall thinning due to wear or erosion. The RFT system is illustrated in Figure 6.1.

Demonstration of this test over six years revealed several limitations. A calibration standard, which accurately represents the anticipated defect is essential for evaluating the readouts. As illustrated in Figure 6.2, a significant error can result due to the calibration standard that is used. For example, a predicted wall loss of 15% could translate into an actual loss of 70% by using a standard featuring a gradual wall loss to evaluate one-sided tube defects. Even with the standards, some loss of sensitivity was found to occur at baffle locations, and erroneous readings were sometimes obtained due to magnetite buildup on the tubes. Therefore, a prerequisite was established that tube cleaning be conducted before RFT testing. High pressure cleaning techniques such as a 4000 psig water jet proved to be effective, removing internal magnetite deposits without damaging the tube inside diameter.

While the RFT technique has some limitations, experience shows that when it indicates that a tube is acceptable (no indication of defects exceeding 10% wall thickness), the tube is fit for service. However, defects exceeding 10% of wall thickness may or may not represent a risk, depending on the nature of the defect. In these cases, the utility is advised to use a more sophisticated type of RFT, an Internal Rotary Inspection System (IRIS). The IRIS technique uses a rotating probe and an ultrasonic beam for inspection from the tube inside diameter. Testing showed that the method can readily characterize the shape of the defects, which can be used to improve the interpretation of the RFT results.

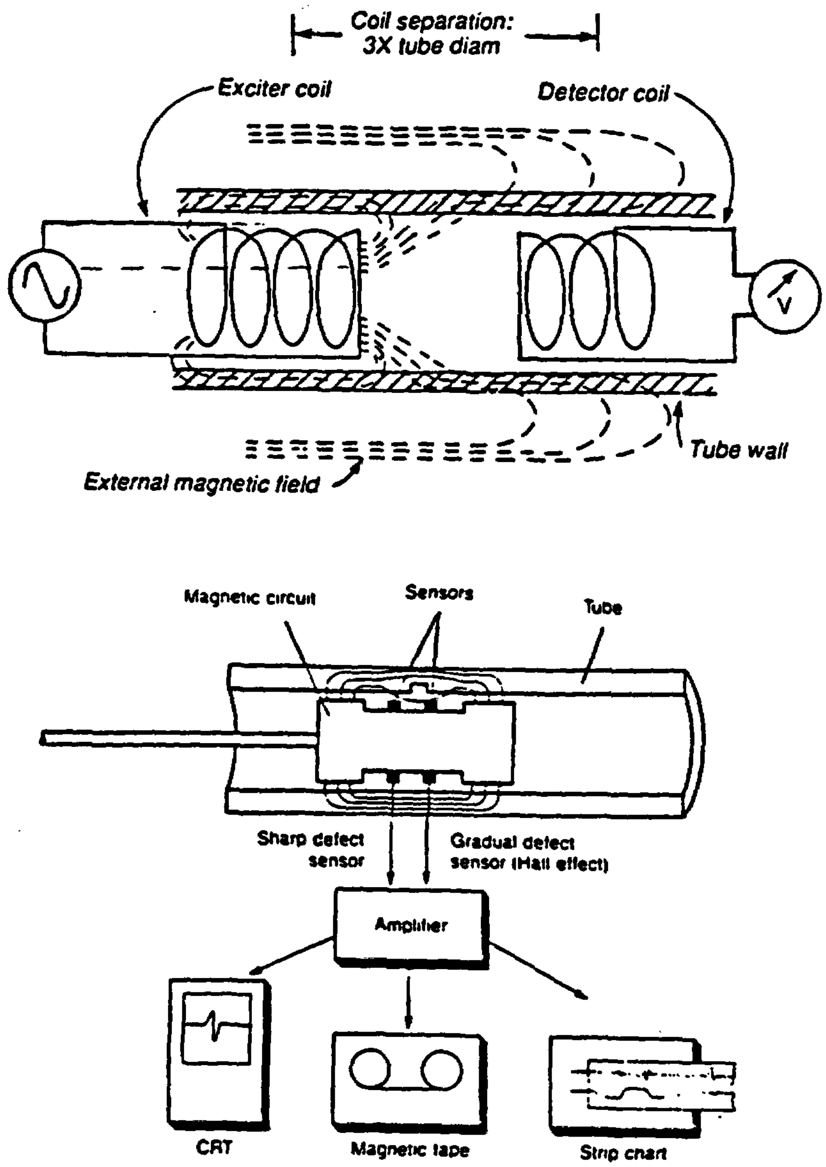

Figure 6.1 Remote field technique concept[35]

However, this process was found to be very slow and is recommended for use only as confirmation of questionable RFT findings.

6.4 Vibration Monitoring

Most plants use vibration monitoring instrumentation to monitor the condition of rotating equipment, such as pumps and motors. Each time a rolling element passes over a defect, an impulse of vibration is generated. All of the vibration monitoring techniques are fundamentally based on the recording and quantification of these vibration impulses. This technology continues to be improved in its sensitivity and diagnostic capability. One of these refinements

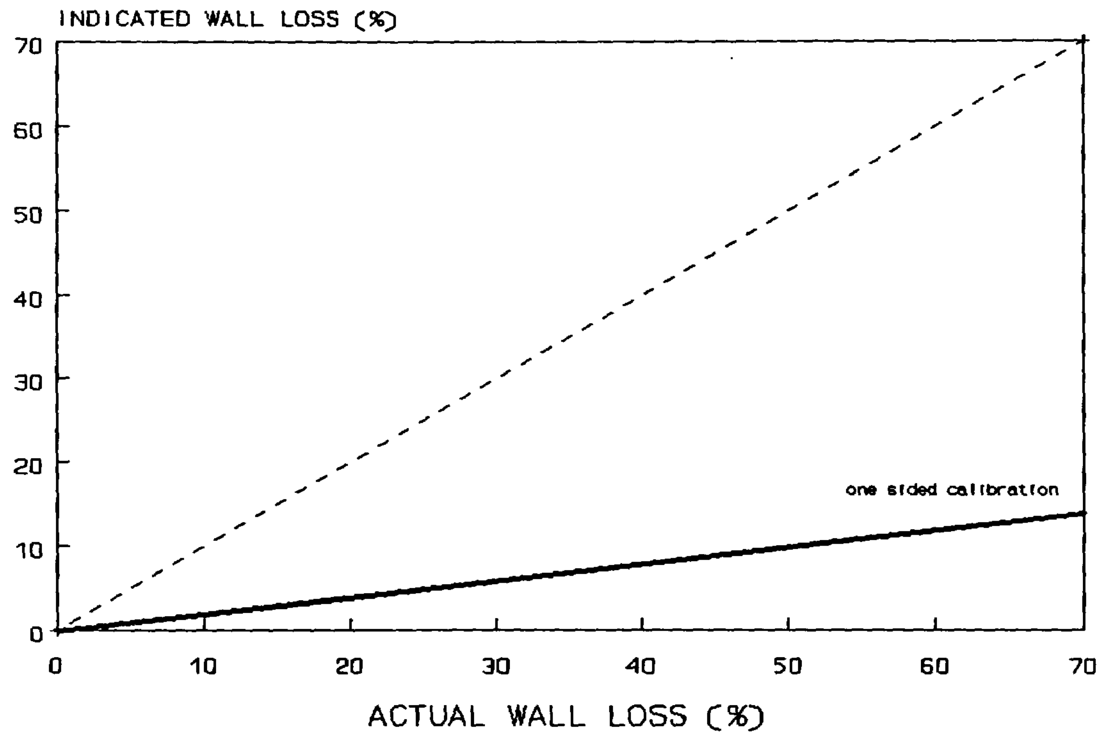

Figure 6.2 Sample calibration standard used for RFT[35]

is the method used for processing the signal.

The vibration impulses generated by a defect create a higher frequency signal than vibration caused by other parts of the driver[36]. As a result, since the vibration energy produced by the impulses is concentrated into a relatively narrow band, it is more readily detected than the energy distributed over the entire frequency range. The high frequency signal is processed to determine the recurrence rate of these impulses. As illustrated in Figure 6.3, a seemingly random vibration pattern can reveal a specific pulse amplitude and frequency. This pattern can be used to more accurately trend the data and determine the root cause of the problem.

The advanced vibration technology owes its high degree of sensitivity to a mechanically tuned transducer that senses ultrasonic pulses. The pulses of a typical bearing can be as much as 1000 times higher when failure is imminent, as compared to when a bearing is new. The principle of operation of the transducer is similar to an accelerometer except that a single frequency is selected where the resulting signal is strongest. Therefore, it is possible to filter out all other vibration frequencies which may be caused by background conditions and which could otherwise mask the degradation in the bearing.

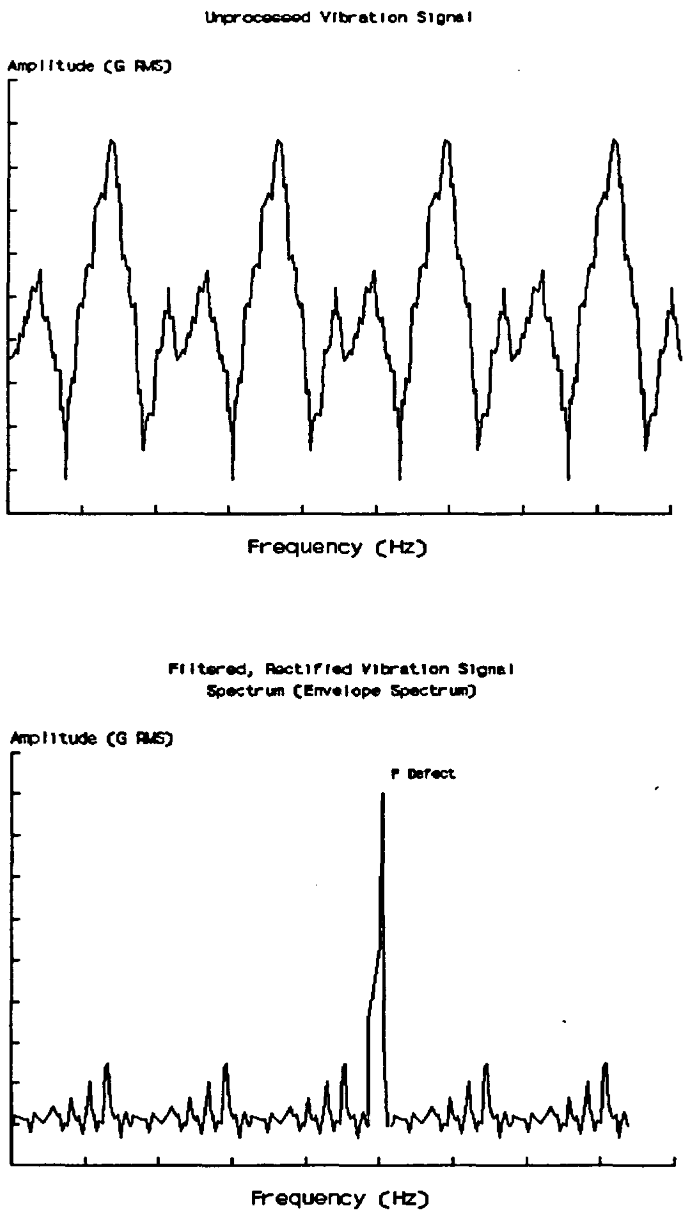

Figure 6.3 Sample vibration patterns

This method has also proved useful in determining the condition of the lubricating oil. In the loaded part of a bearing, the contact areas of raceways and rolling elements are under high pressure. The behavior of the lubricant film in the contact area is described by the theories of elastichydrodynamic lubrication. This means that the pressure distribution in the contact area does not follow a smooth curve. Therefore, pressure waves are generated in every rotating bearing, even when test measurements show that there is no metallic contact between rolling element and raceway. The amplitude of the signal produced by the pressure wave increases as the oil film between the two surfaces decreases. This change can be detected by the transducer.

6.5 Tracer Technology

The Tracer Technology Center at Brookhaven National Laboratory has developed a perfluorocarbon tracer (PFT) technology over a 15-year period, which has been applied in various atmospheric, hydrological, and subsurface applications. PFTs are detectable at extremely low levels and have been used extensively as tracers of gas and liquid flow.

A review of the operating experience shows that chemical analysis is commonly used by utilities to detect leakage in heat exchangers. An extension of this philosophy is the PFT technology in which a tracer is inserted into a process fluid to provide leak detection information. In particular, this technology has been successfully used to detect leakage in high voltage cables, which are filled with a dielectric fluid medium to cool and insulate them. This is done by tagging the dielectric fluid with a small amount of the PFT tracer, a carbon compound saturated with fluorine. When a leak occurs, the harmless PFT vapor rises to the street surface, acting as an invisible chemical flag. PFTs can be detected in minute quantities by analyzers also developed at BNL[37].

PFTs are non-toxic and inert, and are over four orders of magnitude more sensitive than fluorescent dyes. In the CCW application, the tracer could be added to the closed loop part of the system while monitoring the open loop service water system. Any leakage from the CCW system would be detected through routine sampling. This type of application is being explored on an experimental basis at a fossil power plant's steam condensing system. In this case, a tracer added to the service water system is detected in the condensate system if a minute tube leak exists in the condenser. This method is much more sensitive than standard chloride leak detection instrumentation. In a study performed in cooperation with EPRI[37], the results demonstrated the practicality and sensitivity of this method.

7. UTILIZATION OF RESEARCH RESULTS

This study has provided insight into the measures available for the detection and mitigation of aging degradation in CCW systems. This section discusses how the results of this research can be used to 1) evaluate the effectiveness of existing plant programs for managing aging, and 2) provide a means of strengthening any weaknesses identified.

7.1 CCW System Performance Assessment

An important step in evaluating a plant's aging management is to assess the performance of the system under study. This assessment can be done by reviewing maintenance records and failure data to identify aging mechanisms that are not being properly controlled. One method is to use the "time-line" type of analysis, as demonstrated in Section 2.2.4 (Figures 2.10 to 2.12). The comparison of corrective and preventive maintenance events made in this method identifies weaknesses in the plant's maintenance and monitoring programs. Once these weaknesses have been identified, improvements can be made to the ISM&M programs to correct them.

In addition to the review of maintenance data, a review of the materials used for construction of the various system components helps identify aging mechanisms which the components may be susceptible to. The materials research presented in this report identified several aging mechanisms. Once the characteristics of the materials are known, the maintenance and monitoring programs can be tailored to control aging. Table 7.1 summarizes the information available in this report related to CCW component materials and their susceptibility to aging. The subcomponents most susceptible to aging degradation within each of the major components are identified.

Table 7.1 Reference of component material information

Component	Subcomponent	Material Information*
Heat Exchanger	Tube Bundle Tubesheet Shell	Section 3.1.2 Table 3.2
Valve	Body/Bonnet	Section 3.2.2
	Trim	Table 3.4
	Liners	Table 3.5
Valve Operator	Diaphragm O-Ring	Figure 3.6 Table 3.6 Table 3.7
Pumps	Primary Seals Secondary Seals	Table 3.9 Table 3.10 Table 3.11
	Bearing	Table 3.12

*These tables and figures are in Section 3.

One additional area which should be addressed in an ISM&M program is the identification of important components. In reviewing the various CCW system designs for this aging analysis, some components were found to be more important than others in terms of system reliability. For example, some components in the system have a double or triple redundancy included in the design. Therefore, failure of these components would not immediately result in the system being unavailable. However, failure of some components in critical locations could result in system failure, and they should receive additional monitoring and maintenance. For this reason, each CCW system design should be reviewed on a case-by-case basis to identify important components, and this information should be factored into the ISM&M program.

7.2 Evaluation of ISM&M Practices

The survey of PWRs performed for this study provided an excellent overview of the ISM&M practices currently being used in nuclear plants. This information can be used as part of a review of current plant programs to determine what, if any, practices could be added to make the programs more effective at managing aging. By comparing one plant's practices with others, potential deficiencies and subsequent improvements can be identified. Table 7.2 summarizes the information available on ISM&M practices in other plants.

Table 7.2 Reference of ISM&M information

Component	Tests	Maintenance/ Operation	Monitoring/ Inspection
Pump	Table 2.1	Table 2.8 Table 2.17 Table 2.23 Section 5.3	Table 2.4 Table 2.14 Table 2.20 Figure 2.1 Section 5.2
Valve	Table 2.2 Table 2.15	Table 2.9 Table 2.15 Table 2.24 Section 5.3	Table 2.5 Table 2.15 Table 2.21 Figure 2.1 Section 5.2
Heat Exchanger	Section 2.2.2 Section 2.3.2	Table 2.18 Table 2.25 Table 3.3 Section 5.3	Table 2.6 Table 2.16 Figure 2.1 Section 5.2
Instrumentation/ Controls	Table 2.10 Table 2.11	Table 2.10 Table 2.11	Table 2.7
System	Table 2.3	Table 2.12 Section 5.3	Table 2.13 Table 2.19 Figure 2.1 Section 5.2

This study showed that two levels of activities exist within the plants: 1) basic activities, which are performed in most plants, and 2) supplemental activities, which vary based on many factors related to the plant. The basic activities provide a general indication of component health, and are typically required by technical specifications or engineering codes. These activities are useful for providing information on aging degradation, although that is not their primary purpose. Trending the results of these basic activities can indicate if aging degradation is increasing and when it may reach an unacceptable level.

One area that is not covered in the basic activities is long-term monitoring of passive subcomponents, such as pipe walls, pump casings, and valve bodies. Since these subcomponents are vulnerable to wear, erosion, and corrosion, wall thinning may occur after many years of service. If the problem is severe enough and goes undetected, wall thinning could lead to failure, therefore, long-term monitoring for wall thinning should be included in the basic ISM&M activities every five to ten years. A list of the recommended basic practices is presented in Table 7.3. This list is based on practices currently used at plants, along with additional practices recommended from this study. The frequencies are based on information obtained from plants that are currently performing these practices, as well as the requirements specified in the various codes and standards.

In addition to the basic practices, there are a variety of supplemental activities. These vary among plants, and are usually selected based on manufacturers' recommendations or plant experience. The supplemental activities were reviewed to determine if they could be used to help in the detection or mitigation of aging degradation. They were then correlated with the aging mechanisms they detect or mitigate, and generic listings were generated. This was done for each of the major CCW components and the results are presented in Tables 7.4, 7.5, and 7.6 for pumps, valves, and heat exchangers, respectively.

In evaluating a plant's maintenance and monitoring program, the equipment history and corrective maintenance actions performed should be examined, as discussed in section 7.1. From this, any aging mechanisms that are not being properly managed can be identified. In addition, all the aging mechanisms common to the CCW system components should be identified by reviewing this study, the phase I study, and experiences of other utilities. Once the aging mechanisms are known, the information in Tables 7.4, 7.5, and 7.6 can be used to determine if the proper ISM&M techniques are in place. If not, they can be added to the plant's current practices. If they are already in place, their frequency can be adjusted or redundant practices can be included. The equipment's performance should then be trended to ensure that failures are being controlled. To have an effective ISM&M program, at least one technique should be included to detect and mitigate each of the aging mechanisms the system is susceptible to.

Table 7.3 Recommended basic ISM&M practices for the CCW system

Component	ISM&M Practice	Frequency	Aging Mechanism
Pumps	Monitor Vibration	1 to 3 Months	- Wear/degradation of bearings
	Measure Developed Head	1 to 3 Months	- Wear of impeller, wear rings
	Check Lube Oil Level	Daily to Weekly	- Deterioration of oil seals
	Check for Unusual Noise	Daily to Weekly	- Distortion of internals
	Check for Excessive Leakage	Daily to Weekly	- Degradation of shaft seals - Deterioration of gaskets
	Grease Bearings/Couplings	6 to 18 Months	- Wear of bearings/couplings
	Perform Lube Oil Analysis	6 to 18 Months	- Wear of bearings - Deterioration of oil seals
	Inspect Casing/Shaft/Internals for Cracks, Warping, Corrosion, Erosion	12 to 60 Months	- Corrosion/erosion of parts - Distortion of internals
	Check for Casing Wall Thinning	5 to 10 Years	- Wear of casing material
Valves	Valve Stroking	3 to 18 Months	- Corrosion of internals - Distortion of components
	Check for excessive leakage, corrosion	Daily to Weekly	- Deterioration of gaskets - Wear of packing
	Adjust Torque/Limit Switches	12 to 24 Months	- Calibration Drift
	Lubricate Moving Parts	6 to 18 Months	- Wear of components
	Check Body Wall Thinning	5 to 10 Years	- Wear of wall material
Heat Exchangers	Monitor Flow	Daily to Weekly	- Corrosion/fouling of internals
	Monitor Outlet Temperature	Daily to Weekly	- Fouling of Tubes
	Check for Excessive Leakage, Corrosion	Daily to Weekly	- Deterioration of gaskets - Cracking/corrosion of shell
	Clean Tubes	As Needed	- Fouling of Tubes
	Check for Shell/Tube Thinning	5 to 10 Years	- Wear of shell/tube material
System	Monitor Surge Tank Level/Makeup	4 to 24 Hours	- Corrosion/cracking of welds, walls, pressure boundaries - Deterioration of seals, gaskets
	Monitor Temperature at Loads	4 to 24 Hours	- Fouling of Heat Exchangers
	Monitor Flow to Loads	4 to 24 Hours	- Degradation of pump performance
	Check for Pipe Wall Thinning	5 to 10 Years	- Wear of pipe wall material
	Hydrostatic Test	5 to 10 Years	- Corrosion/cracking of welds, walls, pressure boundaries

Table 7.4 Pump ISM&M practices versus aging mechanisms

PUMP AGING MECHANISMS	
1. WEAR OF BEARINGS/BUSHINGS	8. BINDING OF IMPELLER/SHAFT
2. WEAR OF INTERNAL CONTACT SURFACES	9. CAVITATION DAMAGE TO IMPELLER/CASING
3. EROSION/CORROSION OF INTERNALS	
4. VIBRATION INDUCED LOOSENING/MOVEMENT	
5. DISTORTION OF INTERNALS	
6. DETERIORATION OF PACKING/SEALS/GASKETS	
7. FATIGUE/THINNING OF CASING	

ISM&M PRACTICE	AGING MECHANISM DETECTED/MITIGATED								
	1	2	3	4	5	6	7	8	9
BEARING TEMPERATURE MEASUREMENT	X							X	
FLOW RATE MEASUREMENT	X		X		X				X
MOTOR AMP/WINDING TEMP CHECK	X	X				X		X	
TRACK TIME AT MINIMUM FLOW		X			X				
PACKING/SEAL LEAKAGE MEASUREMENT						X			
NDE FOR CASING SHAFT CRACKS/FLAWS							X		
DISASSEMBLY INSPECTION/OVERHAUL	X	X	X		X	X	X		X
BOLT TORQUE MEASUREMENT				X					
ROTOR TORQUE MEASUREMENT		X						X	
THERMOGRAPHY EXAMINATION	X	X						X	
CHANGE LUBE OIL	X								
REALIGN PUMP/DRIVER		X			X				
REPLACE BEARINGS	X								
RETORQUE BOLTS				X					
REWORK IMPELLER			X						X
REPLACE GASKETS/SEALS						X			
REPLACE WEAR RINGS		X							
REPLACE SHAFT SLEAVES		X							
LUBRICATION SYSTEM PM	X								

Table 7.5 Valve ISM&M practices versus aging mechanisms

VALVE AGING MECHANISMS	
1. WEAR OF BEARINGS/BUSHINGS	8. DETERIORATION OF MOTOR WINDINGS (MOV)
2. WEAR OF STEM CONTACT SURFACES	9. FATIGUE/THINNING OF CASING
3. EROSION/CORROSION OF SEAT/DISK/INTERNALS	10. BINDING OF STEM/DISK
4. VIBRATION INDUCED LOOSENING/MOVEMENT	11. SETPOINT DRIFT
5. DISTORTION OF INTERNALS	12. DETERIORATION OF AIR DIAPHRAGM (AOV)
6. DETERIORATION OF PACKING/SEALS/GASKETS	13. DEGRADATION OF ELECTRICAL CONTACTS/WIRES
7. CALIBRATION DRIFT OF TORQUE/LIMIT SWITCHES	

ISM&M PRACTICE	AGING MECHANISM DETECTED/MITIGATED													
	1	2	3	4	5	6	7	8	9	10	11	12	13	
INSPECT/CLEAN CONTACTS/WIRES													X	
SEAT LEAKAGE TEST			X		X									
PRESSURE DIFFERENTIAL TEST			X							X				
STEM TORQUE MEASUREMENT					X					X				
BOLT TORQUE MEASUREMENT				X										
PACKING/SEAL LEAKAGE MEASUREMENT						X								
NDE FOR CASING CRACKS/FLAWS									X					
STEM PLAY MEASUREMENT		X												
VALVE OPERATOR ALIGNMENT CHECK				X	X									
MOTOR SIGNATURE ANALYSIS (MOVs)	X				X			X		X				
MOTOR AMP/VOLTAGE MEASUREMENT	X				X			X		X				
MOTOR MEGER/SURGE/CAPACITANCE								X						
DISSASSEMBLY INSPECTION	X	X	X	X	X	X			X	X		X	X	
BENCH TEST (RELIEF)											X			
REPLACE PACKING						X								
REALIGN OPERATOR				X										
COMPLETE OVERHAUL	X	X	X	X	X	X	X			X		X	X	
REPLACE/REWORK SEATS		X												
REPLACE SEALS/GASKETS/PACKING						X								
RETORQUE BOLTS				X										
REPLACE DISK			X											
REPLACE TORQUE/LIMIT SWITCHES							X							
REPLACE MOTOR	X	X												
REPLACE AIR DIAPHRAGM			X											

Table 7.6 Heat Exchanger ISM&M practices versus aging mechanisms

HEAT EXCHANGER AGING MECHANISMS

1. EROSION/CORROSION OF TUBES	8. FOULING OF TUBES
2. DETERIORATION OF GASKETS	
3. PLUGGING OF TUBES	
4. CRACKING OF TUBES	
5. CRACKING/THINNING OF SHELL	
6. LOOSENING OF BOLTS OR INTERNALS	
7. EROSION/CORROSION OF INTERNALS	

ISM&M PRACTICE	AGING MECHANISM DETECTED/MITIGATED							
	1	2	3	4	5	6	7	8
DISSASSEMBLY INSPECTION/OVERHAUL	X	X	X	X	X	X	X	X
EDDY CURRENT TEST				X	X			
ULTRASONIC TEST				X	X			
ACOUSTIC MEASUREMENT						X		
DYE PENETRANT TEST				X	X			
MONITOR FOR CCW CHEMICALS IN SW	X			X				
PRESSURE DROP MEASUREMENT	X		X					
HEAT BALANCE	X		X					X
APPLY PROTECTIVE COATINGS							X	
REPLACE GASKETS/SEALS		X						
REPLACE/MONITOR SACRIFICAL ANODES	X						X	
RETORQUE BOLTS						X		

In addition to the practices discussed above, there are several advanced monitoring practices which may be used to manage aging. These practices typically require special equipment, and can be time consuming to perform. They should be selected for inclusion in an ISM&M program using the same procedure described for the supplemental practices. Table 7.7 summarizes the practices examined in this study.

Table 7.7 Advanced monitoring practices

Technique	Use	Comments
Ultrasonics	- Detects internal valve leakage - Detects heat exchanger tube leaks - Detects bearing degradation - Detects pump degradation	- Can be used in areas with high background noise - Can locate sources of high frequency emissions typical of wearing parts
Eddy Current Testing	- Detects material flaws (e.g., pitting, cracks, fractures) - Used for heat exchanger monitoring	- Only applicable for non-magnetic materials - Heat exchanger tubes can be inspected by inserting probe down tube
Remote Field Technique (RFT)	- Detects wall loss, material defects, circumferential grooves, cracks - Used for heat exchanger monitoring	- Can be used on magnetic materials - Requires accurate calibration standard
Internal Rotary Inspection System (IRIS)	- Used for heat exchanger monitoring - Detects material defects	- Helps interpret questionable results from RFT - Process is very time intensive
Vibration Monitoring	- Used to monitor rotating equipment (e.g., pumps, motors) - Detects bearing, support degradation	- Sensitivity can be improved using new methods of processing signals
Tracer Technology	- Can be used to detect leaks in heat exchangers and piping	- New technique still under development - Uses injection and detection of perfluorocarbons

It should be noted that the list of practices presented in this report are not intended to represent all possible practices available to the industry. The practices discussed herein are the most commonly known and used. In evaluating a plant's ISM&M programs, other sources of information should also be consulted, such as manufacturer's literature and other research studies.

8. CONCLUSIONS AND RECOMMENDATIONS

The Phase I analysis of Component Cooling Water systems characterized the effects of aging on the performance and reliability of the system. In this Phase II analysis, the question of how to detect and mitigate aging degradation was addressed. The techniques currently being used, along with new techniques available were investigated in relation to their ability to manage the effects of aging. The conclusions and recommendations from this analysis are discussed in the following paragraphs.

8.1 Conclusions from the Review of ISM&M Practices

The review of inspection, surveillance, monitoring, and maintenance practices has provided an overview of what is currently being done in plants to maintain reliable performance of the CCW system. Many of these practices are useful for detecting and/or mitigating aging degradation. The following conclusions were made as a result of this review:

- Maintenance and monitoring programs typically include basic practices which are common to all plants. These basic practices are usually required by technical specifications or codes.

- In addition to the basic practices, each plant has several supplemental activities that are performed as part of their maintenance or monitoring program. These supplemental activities may be included because of plant experience, or manufacturer's recommendation.

- In general, no specific actions are in place to address long-term aging of the CCW components. The failure data do not indicate any failures of heat exchanger shells, pump casings, or valve bodies. However, this is a potential concern for extended life operation. Over many years of operation, wall thinning occurs which could weaken these components. Consideration should be given to including monitoring techniques that would address such concerns as pipe wall thinning, and valve and pump case thinning.

- A standardized maintenance or monitoring program which requires all plants to perform the same actions would not be practical due to differences in plant designs, operating conditions, and environment. An optimum program should include the basic practices, along with supplemental and advanced practices specifically chosen to address particular problems or weaknesses at the plant.

8.2 Conclusions From the Review of Component Materials

There are many different materials used in the construction of CCW components. The review of these materials shows that the susceptibility of the system to aging degradation is directly related to the materials selected. While some materials may provide excellent resistance to the aging mechanisms present in the CCW system, others may not. By knowing the characteristics of the materials used, and their susceptibility to aging degradation, maintenance and monitoring programs can be tailored to most effectively control the effects of aging. Conclusions made during the review of component materials include the following:

- The majority of heat exchanger failures are due to corrosion and wear of the tubes, which are directly related to the materials selected and the operating environment. Since all tubes in the tube bundle are typically made of the same material, and are exposed to the same environment, once tube failure begins, the number of failures can increase dramatically in a short time.

- Several methods of extending the life of heat exchangers are available, including cathodic protection and protective coatings or liners. If the material selected for construction is incompatible with the operating conditions or environment, aging degradation will proceed rapidly. In these cases, the material should be replaced with one more suitable for the service conditions.

- A valve subcomponent that is extremely susceptible to aging is the packing. Several different materials are available for packing; however, installation can also be important. Using combinations of different materials can increase the life expectancy of the packing.

- Two valve operator components that are susceptible to aging are the diaphragm and O-rings used in pneumatic operators. The materials most commonly used are neoprene and buna-N. These components should be inspected regularly and replaced periodically to prevent failures while in service. These materials degrade even while in storage, therefore, proper storage conditions should be maintained.

8.3 Conclusions From the Review of Codes and Standards

The various codes and standards that govern the design, operation, testing, and maintenance of the CCW system also contribute to the proper management of aging. A review of these items resulted in the following findings:

- The design of the CCW system is governed by the General Design Criteria in the Code of Federal Regulations. Although the criteria address items related to safety, there are no specific requirements addressing the issue of aging.

- Inservice Inspection requirements for the CCW system are governed by ASME Section XI, and are included as part of the plant's technical specifications. All the major pressure retaining components in the system, and their supports must be inspected. However, the required inspections are limited and include only visual inspections for leakage while the system is pressurized.

- Inservice testing of the CCW system is governed by ASME Section XI and is part of the plant's technical specifications. Periodic testing of pumps, valves, and snubbers is required to verify that the system can perform its design function if called upon.

- Guidance on the performance testing of the CCW system is provided by ASME-OM-S/G-1990, Part 2, however, this standard is not a requirement. The guidance provided includes the evaluation of aging degradation. This information is useful for evaluating the long-term effects of aging, and it is recommended that this information be trended and used as an aging indicator.

- The General Design Criteria require that the CCW system be maintained throughout the life of the plant; however, no specific guidance on how to accomplish this is given. No codes or standards on system maintenance exist, although standards on good maintenance practices for various components are available.

8.4 Conclusions From the Review of SSFIs

From the review of the NRC Safety System Functional Inspections, the following conclusions were made:

- Insights on the subject of aging in the CCW system have been gained through the review of SSFI reports. Maintenance and surveillance testing were the two inspection areas which provided the most useful information for identifying aging problems.

- The SSFI process is well suited for identifying the effects of aging on the performance of a system. It can be effective in determining how licensees manage aging with the inclusion of the recommendations presented in Table 4.4.

- One SSFI determined that CCW system design leakage may be underestimated in several plant designs. For instance, one plant did not design the makeup portion of the system as safety-related because zero leakage was expected. However, experience has shown that as valves, pumps, and heat exchangers age, leakage increases. This aging process should have been considered in the system design.

- One SSFI determined that the expected ambient temperature in the CCW pump areas during an accident were not accurately represented at one plant. A review indicated that the ventilation system would not be operable in a postulated event, which would expose the CCW pump motors to higher temperatures than they had been designed and tested for. The long-term performance of CCW at this plant was essential for decay heat removal. The SSFI report indicated that the stresses which could affect operation of CCW had not been addressed completely. The high temperature could impose aging mechanisms on the equipment resulting in premature wear and failure. The equipment should have been designed and tested to operate under these conditions.

8.5 Recommendations

The results of the Phase I and Phase II aging studies show that the Component Cooling Water system is susceptible to aging degradation. As the system ages the likelihood of failures increases, which can adversely affect the reliability of the system. However, there are measures that can be taken to monitor and mitigate the effects of aging degradation. The following recommendations will help ensure that plants have the most effective maintenance and monitoring programs in place to manage aging.

- Personnel cognizant of the CCW system performance should understand the characteristics of aging degradation presented in the phase I study. This understanding will give them insight into what should be monitored and what indicators should be expected for their particular system.

- Cognizant utility personnel should review past operating and failure data to determine if any aging trends are evident, such as increasing failure rates. This review will help to identify the extent and magnitude of aging mechanisms present, along with any weaknesses in the current maintenance program.

- Current maintenance and monitoring programs should be reviewed in relation to the aging mechanisms identified for a particular CCW system. The review should ensure that effective techniques are in place to detect and/or correct any aging conditions. The ISM&M information presented in this phase II study can be used for this purpose.

- Consideration should be given to incorporating techniques to detect and monitor the effects of long-term aging, such as pipe wall thinning and pump or valve body degradation. This type of aging degradation takes many years to manifest itself, and is a potential concern for extended life operation.

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APPENDIX A

Survey of PWRs

Enclosure I

CCW QUESTIONNAIRE RESPONSE BY PWR PLANTS

(Unless otherwise noted, numbers in parentheses are the number of units responding. The number of units responding to a particular parameter, activity, etc. may not add up to the number of units responding to a questionnaire issue because not all respondents addressed the same parameters, activities, etc.)

1. CCW Periodic Testing and Frequency

a. Pump Testing* — Yes (12) No (0)

Parameter:	Frequency in Months (# of units):
- Pump dP	1(3),3(10)
- Suction P	1(3),3(8)
- Flow rate	1(2),3(4)
- Vibration amplitude	1(1),3(10),12(3)
- Lubricant level	3(4)
- Lubricant temp.	3(2),12(2)
- Vibration acceleration	18(2)
- Motor driver bearing temp.	3(5)
- Pump performance test	3(1),12(1)
- Motor current, voltage	1(1), 3(1)

b. Valve Testing* — Yes (12) No (0)

Parameter:	
- MOV stroke time	3(10)
- Check valve leak	3(5), 18(4)
- Check valve flow	3(5)
- Verification of remote position indicator	18(1),24(2),36(1)
- Seat leakage (Type C LLRT)	3(1)
- Relief valve setpoint verification	60(3)
- MOV signature analysis	18(1)

Comments: One utility is planning to implement an MOV signature analysis program.

c. Hydrostatic Tests — Yes (9) No (2)
120(7)

d. System Logic Response Tests — Yes (8), No (2)

Test:	
- Slave relay tests	1(2),3(3)
- Automatic actuation of components	12(1),18(7)

e. Others:

- System leakage check	3(1), 40(1)

*Pump and valve testing is performed per 10CFR50.55a(g) for ASME Code components.

2. <u>Preventive Maintenance Practices</u>

a. Pump Inspection — Yes (10) No (2)

Activities:

- Check lube oil level and temp.	1(1), 3(1)
- Lube oil system preventive maintenance	6(2),12(2),18(2)
- Radial bearing oil change	6(1),12(1)
- Thrust bearing oil change	6(1),12(1)
- Coupling lubrication	12(1),60(1)
- Disassembly inspection	48(1),60(1),90(1)
- Coupling alignment	36(1)
- Gasket replacement (EQ)	84(1)
- Mechanical seal leak inspection	12(2)

b. Heat Exchangers — Yes (5) No (7)

Activities:

- External visual inspection	Not Specified (1)
- Performance test	18(1)
- Open/inspect	12(1)
- Flow balance	18(2)
- Eddy current tubes	18(1)

c. Electrical Components — Yes (12) No (0)

Activities:

- Check lube level and clean air filters	6(1)
- Motor IR	12(3),18(2)
- Bearing lubrication	6(1),12(1),18(4)
- Switchgear circuit breaker maintenance	12(2),18(2)
- Pump circuit breaker maintenance	12(1),24(1)
- Motor inspection	48(1),60(2)
- Panel meter calibrate	36(2)
- Motor space heater check	12(1),18(2)
- Protective relay functional tests	18(3),24(1)
- Measure stator current	12(1)
- Thermoscan	60(1)
- Motor disassembly/inspection	120(1)
- Motor vibration measurement	3(2)
- EQ Inspections	40(2)
- Motor winding phase/polarization index	18(2)

d. Instrumentation & Control — Yes (10) No (0)

Activities:

- Calibration (CAL) surge tank level/alarms loop	12(1),18(6),24(1),48(2)
- CAL flow indicators	12(1),18(6),24(1),48(2)
- CAL heat exchangers flow loops	12(1),24(1),36(2)
- CAL header pressure switch	12(1),36(2),48(2),96(1)
- CAL react. cool. pump (RCP) ret. flow indicators	12(1),24(1),36(2)
- CAL RCP thermal barrier temp. loop	12(1),24(1),36(2)
- CAL temperature indicating/alarm units	12(1),24(1),36(2),48(2)
- CAL contain. spray pump seal flow control	12(1)
- CAL pump suction pressure loop	24(1),36(2)
- CAL pump discharge press. transmitter	12(1),18(6),96(1)
- CAL heat exchanger outlet temp. loop	12(1),24(1)
- CAL RCP oil cooler return flow indicators	36(2)
- CAL motor stator temp. loops	120(2)
- CAL motor bearing temp. loops	120(2)
- CAL pump bearing temp. loops	120(2)
- CAL RHR heat exchanger flow alarms	36(2)
- Limit switch clean contacts	60(1)
- CAL RTD probe	48(1)

e. Valves

Manual (MAN)	Yes (5)	No (6)
Air-operated (AOV)	Yes (7)	No (3)
Motor-Operated (MOV)	Yes (8)	No (2)
Check (CHV)	Yes (3)	No (7)

Activities:

- MAN clean, lube stem	3(1),12(2)
- MOV circuit breakers maintenance	12(1)
- MOV IR test	12(1)
- MOV operator maintenance	12(2),18(1),36(2)
- MOV current, timing check	12(1)
- AOV lubrication	12(1),18(2)
- MOV operator EQ maintenance	18(2),40(2)
- AOV packing replacement	48(1)
- CHV inservice testing	3(4),18(2),48(1)
- MOV packing replacement	36(1)
- AOV diaphragm replacement	60(1)
- MOV motor replacement (EQ)	60(1)
- AOV disassembly, inspection	18(1),120(1)
- AOV parts replacement (EQ)	43(3)
- MOV disassembly, inspection	120(1)
- MOV parts replacement	43(1)

f. Others:

- Relief valve setpoint verification	54(2), 120(1)
- Vacuum breaker stroke	3(1)

3. <u>Operational Activities</u>

a. Equipment Rotation

Pumps	Yes (12) No (0)

- Weekly (4)
- 2-3 wks. (1)
- As required to equalize time (2)
- Monthly (3)
- Quarterly (2)

Heat Exchangers	Yes (5) No (7)

- Rotate with pump weekly (1)
- As required to equalize time (2)
- Monthly (2)

b. Routine Readings Taken

Pump discharge pressure	Yes (5) No (7)
Pump flow	Yes (2) No (10)

- hourly by computer (1)
- once per shift (1)

Motor amps	Yes (5) No (7)
Motor winding temp.	Yes (1) No (11)
Heat exchanger dP	Yes (0) No (12)

- monitored when fouling expected (2)

Critical component flows	Yes (5) No (7)

- CCW heat exchanger flow once per shift (1)

Others:

- CCW surge tank level once per shift (3)
- CCW heat exchanger outlet temp. every 4 hrs. (1)
- CCW heat exchanger dT 1 hr by computer (1), once per shift (3)
- Valve lineup verification monthly (1)

c. Is Chemical Treatment Performed	Yes (13) No (0)

- Chromate (7)
- Hydrazine (1)
- Nitrite borate (3)

4. Reliability or Trend Analysis Program   Yes (10) No (2)

- No program, but NPRDS, ISI/IST, PM data evaluated (4)
- Valve stroke times; pump dP, vibration, and bearing temp. (2)
- Pump flowrate dP and vibration, motor IR (1)
- ISI/IST data (3)
- Pump vibration (2)

5. Procedure Copies

See Attachment 1 for procedure highlights. Copies of procedures from volunteer plants are also attached.

6. Corrective Maintenance Summary Responding units (7)
( ) indicates number of occurrences reported

a. Pumps

- Rebuilt shaft and impeller (2)
- Realigned to eliminate excessive vibration (2)
- Repair leaking seals (10)
- Repair oil leak (8)
- Repair water leak L.O. cooler (3)
- Repair oil flow indicator (1)
- Realigned bearing (2)

b. Valves

- Repaired seat leak (31)
- Replaced or lubricate stem bushing (4)
- Repaired/replaced packing (15)
- Repaired body-bonnet leak (3)
- Adjusted limit switch (19)
- Adjusted torque switch (8)
- Actuator repair EQ (5)
- MOV repair mechanical (8)
- AOV repair mechanical (6)
- Actuator repair electrical (8)
- Adjust relief valve setpoint (3)
- Replaced MAN valve (1)

Comment: Almost all MOV torque or limit switch adjustments that affect valve closure require a seat leak test.

c. Instrumentation and Control

- Replaced failed level transmitter (1)
- Adjusted controller response band for temp. control valve (1)
- Reset temperature switch for solenoid valve (1)
- Repaired loose solenoid causing improper valve operation (1)
- Reset air flow to isolation valve controller (1)
- Vented total flow transmitter and recalibrated (1)
- Recalibrated numerous instruments due to drift
- Recalibrate pressure switch (4)
- Repair fluid leak at transmitter (4)

d. Electrical

- Replaced relay (4)
- Replaced motor on MOV (1)
- Repair breaker (11)
- Replace breaker (6)
- Replace ammeter (2)
- Repair motor cooler water leaks (not specified)
- Replace pump motor bearings (2)

e. Heat Exchangers:

- Performed eddy current exam, plugged tubes (13)
- Replaced anodes on service water side (4)
- Inspected/cleaned tubes/tube sheet (20)
- Sand blast, recoat water box (6)
- Repair flange leak (6)
- Replaced nozzles (1)
- Weld repair end bell (3)

f. Other:

- Replaced rad. monitor power supply (1)
- Replace snubber (7)
- Repair snubber (5)

7. <u>Effect of System Degradation on Tech. Specs</u>

72 hour LCO for one of two trains out of service (4)
24 hour LCO for one of three trains out of service (2)

8. <u>Three Parameters Assuring Operational Readiness</u>

a. Pumps/Motors

- Inlet pressure (1)
- Differential pressure (3)
- Flow rate (3)
- Vibration amplitude (1)
- Lubrication (1)
- CCW pump testing (7)

b. Valves

- Surveillance (IST) procedures (8)
- Valve lineup (1)

c. Instruments

- testing, calibration, PMs (3)

d. Heat Exchangers

- dP check (2)

e. Operator/Supervisor plant tours (1)

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11. ABSTRACT (200 words or less)

A two-phase aging analysis of component cooling water (CCW) systems in pressurized water reactors (PWRs) was performed. In phase I, which was published separately as NUREG/CR-5052, the effects of aging on the CCW system were characterized, and the predominant failure modes, aging mechanisms, and components susceptible to aging degradation were identified. Failure rate trends were examined, and their effect on time-dependent system unavailability was investigated.

In phase II, which is the subject of this report, the methods used to manage aging degradation in the CCW system were studied. Information was collected and analyzed on inspection, surveillance, monitoring, and maintenance techniques from a survey of operating PWRs. The results are presented herein. Advanced techniques that may help detect and mitigate aging degradation also are included. A detailed examination of the materials of construction and their relationship to various aging mechanisms is discussed.

In addition, the various standards, codes, and regulatory requirements that govern the design, construction, and operation of the CCW system were investigated. Recommendations to better manage aging degradation in component cooling water system are discussed.

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