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The Effects of Age on Nuclear Power Plant Containment Cooling Systems

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

A study was performed to assess the effects of aging on the performance and availability of containment cooling systems in U.S. commercial nuclear power plants. This study is part of the Nuclear Plant Aging Research (NPAR) program sponsored by the U.S. Nuclear Regulatory Commission. The objectives of this program are to provide an understanding of the aging process and how it affects plant safety so that it can be properly managed. This is one of a number of studies performed under the NPAR program which provide a technical basis for the identification and evaluation of degradation caused by age.

The effects of age were characterized for the containment cooling system by reviewing and analyzing failure data from national databases, as well as plant-specific data. The predominant failure causes and aging mechanisms were identified, along with the components that failed most frequently. Current inspection, surveillance, and monitoring practices were also examined.

A containment cooling system unavailability analysis was performed to examine the potential effects of aging by increasing failure rates for selected components. A commonly found containment spray system design and a commonly found fan cooler system design were modeled. Parametric failure rates for those components in each system that could be subject to aging were accounted for in the model to simulate the time-dependent effects of aging degradation, assuming no provisions are made to properly manage it. System unavailability as a function of increasing component failure rates was then calculated.

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EXECUTIVE SUMMARY

An aging assessment of containment cooling systems in commercial nuclear power plants has been performed as part of the Nuclear Plant Aging Research (NPAR) program. The NPAR program is sponsored by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Engineering. Its goal is to provide a technical basis for understanding and managing the effects of aging in nuclear power plants. Containment cooling systems are one of several systems selected for study under this program due to its importance to plant safety during normal, as well as accident conditions.

The containment cooling function is performed by several different systems, depending on the type and design of the plant. The two systems focused on in this study are the containment spray system, which is used in pressurized water reactors (PWRs) and boiling water reactors (BWRs), and the fan cooler system, which is used in PWRs. These systems were selected since they are the primary means of removing containment heat during accident conditions. While the suppression pool cooling system is also an important means of containment cooling in BWRs, it is an operating mode of the residual heat removal system, which was studied previously under the NPAR program.

The goal of this phase I aging analysis is to determine if aging degradation is a concern for the containment cooling system, and to characterize its effects. To accomplish this, a planned approach was taken based on previous phase I studies performed. This included 1) an extensive review of existing FSARs to identify the different system designs, 2) identification of the operating and environmental stresses imposed on the systems, 3) an analysis of failure data from national databases covering all PWRs and BWRs in the U. S., 4) an analysis of plant-specific data from one PWR, and 5) a system unavailability analysis on one common containment spray system design and one common fan cooler system design to evaluate the potential time-dependent effect of aging on system unavailability.

One of the national databases used for this study is the Nuclear Plant Reliability Data System (NPRDS). Over 50% of the approximately 2200 NPRDS records reviewed (data for all U.S. PWRs and BWRs from 1986 to 1991) were related to degradation caused by aging. These failures typically result in a degraded operating state for the system, or a loss of redundancy. Other findings from the data analysis are summarized in Table S.1. The results of this work show that aging is a concern for the containment cooling system and should be addressed in plant programs.

Failure modes and aging mechanisms were identified for several of the most frequently failed components in each system. For each of the component failure modes, a potential detection method was also identified. This information can be used to evaluate current plant monitoring programs to ensure that aging degradation is being properly controlled.

Table S.1 Summary of Data Analysis Results

Analysis Finding	Containment Spray System	Fan Cooler System
Sample size	1368 records	808 records
Percentage of failures related to aging	59%	52%
Most frequently failed components	Valves (47%)	Circuit Breakers (32%)
Predominant failure cause	Normal Service (74%)	Normal Service (60%)
Predominant effect of failure	Degraded Operation (60%)	Loss of Redundancy (57%)
System status during failure detection	Test (57%)	In Service (64%)
Predominant failure detection method	Test Results (58%)	Abnormal Operation (31%)

From the unavailability analysis performed on one common PWR containment spray system design, the dominant contributor to system unavailability was found to be a non-aging related event; namely a human error involving failure to reposition manual valves following surveillance testing. For components that could be affected by aging, pumps and MOVs were found to be important to system unavailability. Increases in their failure rate produce a noticeable increase in system unavailability. For a ten fold increase in pump failure rate, system unavailability increases by a factor of three, and the pump contribution to system unavailability exceeds that of the human error. Similarly for MOVs, a ten fold increase in failure rate also increases system unavailability by a factor of three. It is therefore important that aging of pumps and MOVs be carefully monitored and controlled.

The unavailability analysis of one common PWR fan cooler system design showed no dominant, single contributor to system unavailability. The largest single contributor was a common mode failure of the fan motors. Based on cumulative contributions from all potential failure scenarios in which it appears, unavailability due to maintenance was the largest contributor to system unavailability, followed by dampers failing to open, circuit breaker malfunction, and fan motor failures. The parametric analyses showed that for a ten fold increase in damper failure rate, system unavailability increases by a factor of approximately 66. The exponential increase in unavailability is due to the redundancy of the components in the system design. When circuit breaker failure rate increases by a factor of 10, system unavailability increases by a factor of approximately 13. Therefore, proper aging management of dampers and circuit breakers is important and should be addressed in plant programs.

This phase I aging analysis has provided a basis for understanding the effects of aging in containment cooling systems. Conclusions and recommendations resulting from this study are summarized below:

- Aging degradation exists in containment cooling systems and is a significant contributor to failures. Since these systems play an important role in accident mitigation, plant programs should specifically address the proper management of aging in containment cooling systems. Each of the aging mechanisms identified in this study should be addressed by at least one monitoring technique.

- The failure data show that most containment spray system failures are detected by surveillance tests and inspections. This is significant since it shows the importance of performing tests and inspections on standby systems to detect degradation before it results in an operational failure.

- There are a number of operational and environmental stresses that cause the various aging mechanisms to become active and lead to degradation. The predominant stresses have been identified, and can be used to develop an effective monitoring program.

- The failure data show that the most common human error type failure occurs during or as a result of maintenance activities. It is recommended that, if efforts to reduce human errors are made, they should be concentrated in the area of maintenance.

- The review of industry and plant specific data has shown that the failures occurring in the containment cooling systems were not severe enough to result in a complete loss of system function. Typically, the most severe failure will result in a loss of redundancy, however, the system is still able to perform its design function. No aging related failures were found in the data analyzed (1986 to 1991) that resulted in a complete loss of system function. However, one event was found in 1980 where corrosion of cooling coils led to a loss of fan cooler system function. This finding shows the importance of designing these systems with sufficient redundancy.

- Failure trends identified from NPRDS for most of the major system components show a trend for increasing failures with age. This increasing trend will result in a corresponding increase in system unavailability with age, if the trend is not properly controlled. Therefore, plant programs should include a similar plant specific analysis to identify any time-dependent trends in component failures so they can be properly managed.

- It is recommended that a phase II study be performed to identify the most effective methods for detecting and mitigating aging degradation in containment cooling systems. The results of the phase II study would be useful for evaluating existing programs and practices, and would provide a means of addressing any weaknesses found in the aging management process.

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ACRONYMS

ALEAP	Aging and Life Extension Assessment Program
AOV	Air Operated Valve
BNL	Brookhaven National Laboratory
BWR	Boiling Water Reactor
CC	Containment Cooling
FSAR	Final Safety Analysis Report
GPM	Gallons Per Minute
HEPA	High Efficiency Particulate Air
Hx	Heat Exchanger
I&C	Instrumentation and Controls
IS&M	Inspection, Surveillance, & Monitoring
ISM&M	Inspection, Surveillance, Monitoring, & Maintenance
LER	Licensee Event Report
LOCA	Loss Of Coolant Accident
MOV	Motor Operated Valve
MSLB	Main Steam Line Break
NPAR	Nuclear Plant Aging Research
NPRDS	Nuclear Plant Reliability Data System
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
PSIG	Pounds Per Square Inch Gauge
PSID	Pounds Per Square Inch Differential
PWR	Pressurized Water Reactor
RHR	Residual Heat Removal
RWST	Refueling Water Storage Tank
SAR	Safety Analysis Report

1. INTRODUCTION

1.1 Background

Nuclear power plants are designed to be reliable and safe, and use a great deal of "state-of-the-art" engineering technology to accomplish these goals. However, as these plants become older there is some uncertainty as to how degradation due to aging will affect their reliability and safety performance. Therefore, the U.S. NRC, Office of Nuclear Regulatory Research, Division of Engineering has instituted the Nuclear Plant Aging Research (NPAR) Program to provide an understanding of the aging process.

The goal of the NPAR program is to improve the operational readiness of nuclear plant systems and components that are important to safety by understanding and managing the effects of aging degradation. To accomplish this, the NPAR studies are typically performed in two phases. In phase I, the effects of aging are characterized by identifying the predominant failure modes and mechanisms, along with the components most frequently failed. The potential effects of improperly managed aging degradation are also reviewed in terms of the impact on system availability and component importance. If aging is found to be a concern, a phase II study is performed in which methods of detecting and mitigating aging degradation are reviewed. From the results of these studies recommendations can be made on how to properly manage aging in a particular component or system. Specific tasks for each phase are shown in Figure 1.1. The structure of the NPAR program is discussed in detail in NUREG-1144[1].

The systems and components studied under the NPAR program are selected based on their importance to plant safety. In this study the containment cooling system is examined since its design function is to mitigate the consequences of any accident which can result in an increase in containment pressure and/or temperature, such as a loss of coolant accident or a main steam line break. By controlling the pressure and temperature inside containment, the containment cooling system helps to maintain the integrity of the containment structure and mitigate releases of radiation to the environment following an accident. Therefore, it is important that aging degradation in this system be properly understood and managed.

1.2 Objectives

The objectives of this phase I aging study of containment cooling systems are to characterize the effects of aging, and determine if appropriate measures are in place to effectively manage these effects. This is accomplished by analyzing operating experience and identifying predominant failure modes, aging mechanisms, and components that most frequently fail. The impact of these failures on system availability is also examined. In addition, a preliminary review of inspection, surveillance, monitoring, and maintenance (ISM&M) methods is performed to understand what steps are currently being taken to manage aging degradation.

Once the effects of aging are characterized, a determination can be made as to whether aging is a concern in this system, and whether additional work is needed to study ways of more effectively managing aging degradation. If aging is found to be a significant contributor to system failures and unavailability, a phase II study will be recommended to study inspection, surveillance, monitoring, and maintenance practices in more detail. Recommendations will then be made on how to more effectively control the effects of aging through improved ISM&M programs.

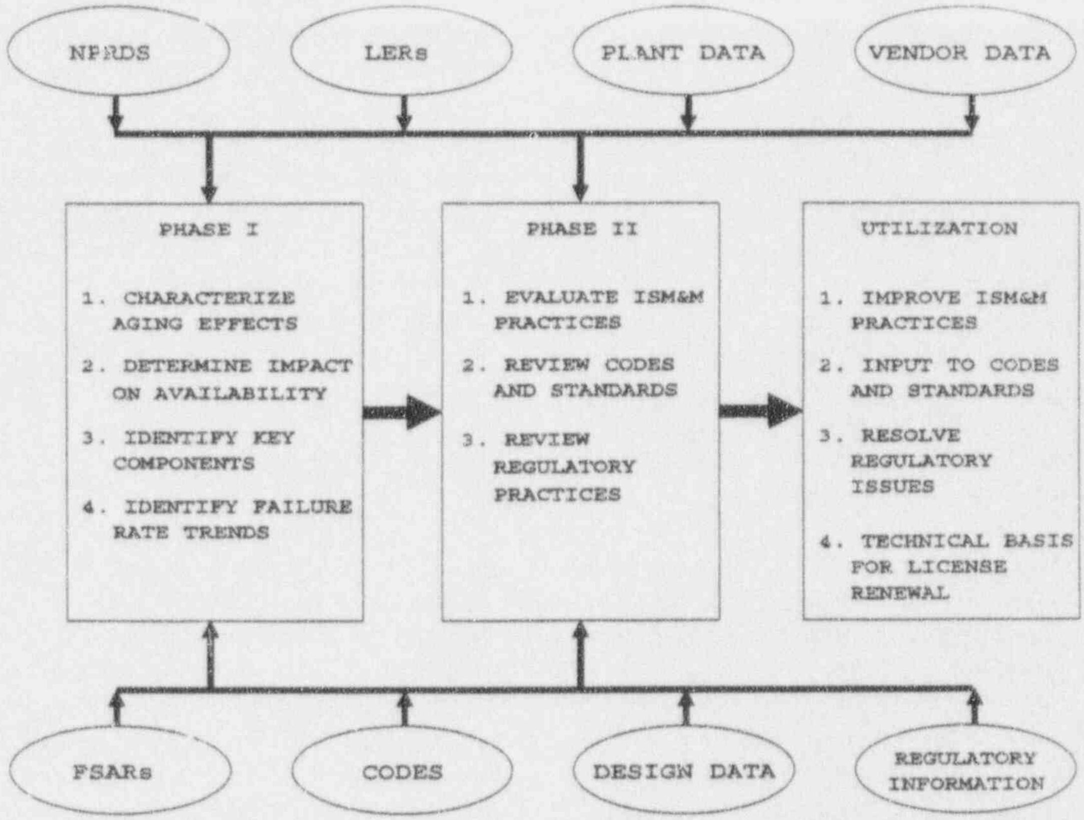


Figure 1.1 NPAR program strategy

1.3 Research Approach

In order to provide a comprehensive analysis and achieve the goals previously discussed for the phase I study, a systematic research approach is needed. The Aging and Life Extension Assessment Program (ALEAP) plan[2] developed at BNL established the approach used for initial phase I NPAR system studies[3-4]. With each study performed, the analysis methodology was refined to concentrate more heavily on those analysis techniques providing the most useful results. As a result, the current research approach was obtained.

As shown in Figure 1.2, the first step in performing the aging analysis is to define the system. This is required so that boundaries can be established to identify what should and should not be included in the analysis. Once this is done, three separate review steps are taken to characterize aging effects. In the first step, NRC documents, such as Generic Letters, Information Notices, Generic Issues, and Bulletins are reviewed to identify any specific areas where aging of the system has led to a safety concern. If any are found, the analysis can be focused in that area to help resolve existing problems.

In the second step, final safety analysis reports (FSARs) are reviewed to identify the various design differences that exist between plants. This is important since different designs can have different susceptibilities to the various aging stresses acting on the systems. Design differences may also require

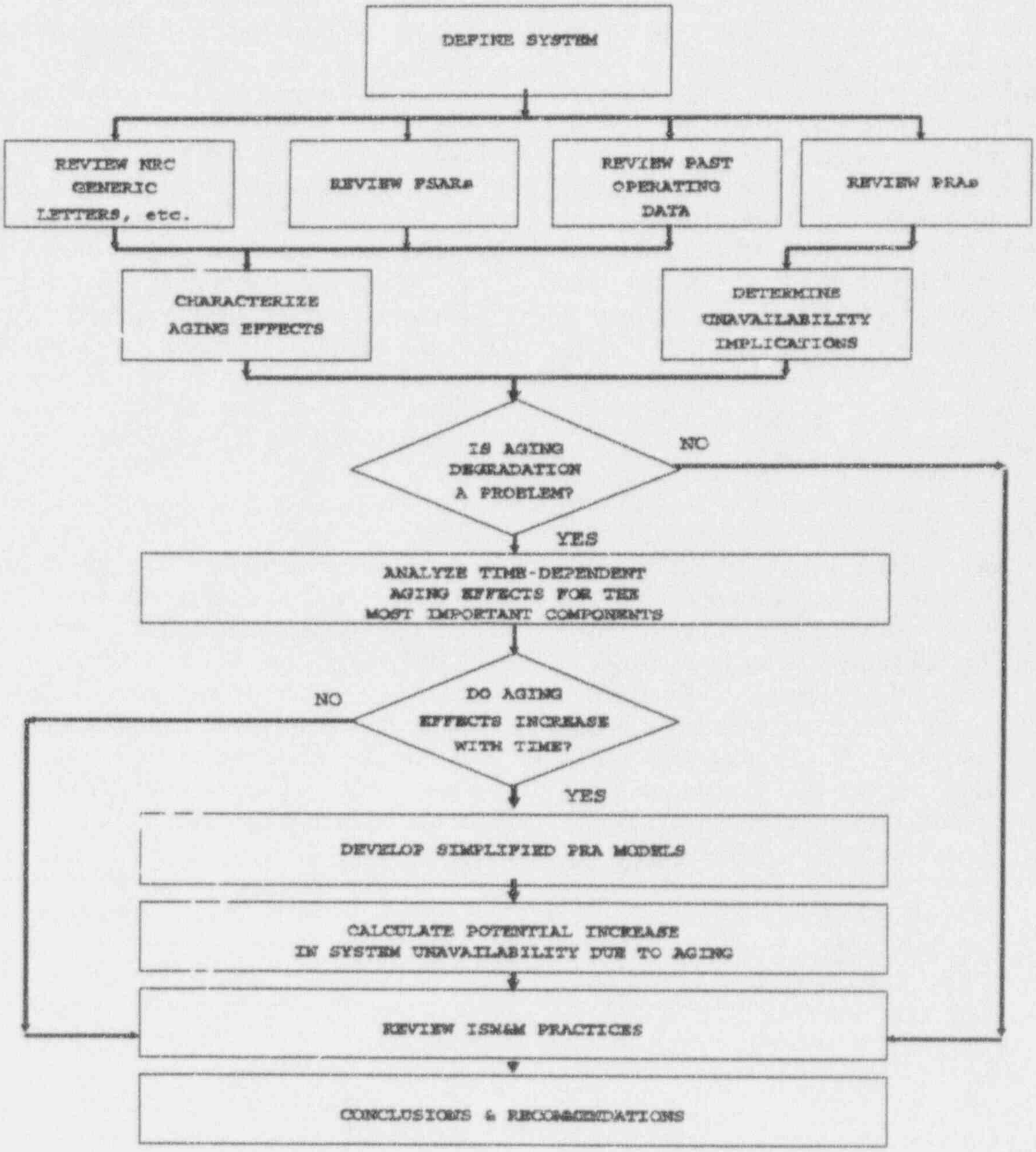


Figure 1.2 Phase I research approach

different operating procedures, which can impose unique stresses on the system.

The third analysis step requires a review of past operating experience. This involves the collection of failure data from national databases, as well as from several operating nuclear power plants. The data are analyzed to identify failure modes and causes, along with the various aging mechanisms present in the system. The operating experience review also helps to determine which components in the system are the most susceptible to aging and, thus, require the most attention in terms of monitoring and maintenance. Using the results of this analysis, along with the results of the first two analysis steps, the effects of aging on the system can be characterized.

A fourth analysis step, which is used to determine unavailability implications, is also performed. This involves the review of selected plant probabilistic risk assessments (PRAs). From these reviews, the importance of the system to plant safety, and the implications of system aging can be determined. In addition, the components which are most important to system availability can be identified. This information can then be correlated with the results of the other analyses to identify specific aging concerns.

If aging is found to be a concern, the data are further analyzed to determine if there are any time-dependent increases in aging degradation. If so, simplified PRA models are used to examine the potential implications to system unavailability.

As a final part of the phase I analysis, a preliminary review of ISM&M practices is performed. From this review, those practices which may help to detect and mitigate aging degradation can be determined. Conclusions and recommendations for future work are then made based on the combined results of the analysis.

The analysis methodology was applied separately to the containment spray system and the fan cooler system for this study. The following subsection discusses the system definitions and boundaries. In Section 2 the various systems supplying the containment cooling function are discussed in detail. Section 3 discusses the operational and environmental stresses acting on the system. Sections 4 and 5 present the analysis results of the national database and plant specific data, respectively. In Section 6 the safety significance and time-dependent unavailability impact of containment cooling system aging is discussed. Section 7 summarizes the findings of the study and presents recommendations for future work. Section 8 presents the conclusions reached from this work on the effects of aging in containment cooling systems.

1.4 System Definition and Boundaries

Containment cooling systems perform the function of removing heat from containment to control pressure and temperature. In PWRs, they also assist in fission product cleanup by removing radioactive iodine from the containment atmosphere following an accident in which radiation leakage occurs, such as a loss of coolant accident (LOCA) or main steam line break (MSLB).

The containment cooling function can encompass several different systems depending on the type of containment, and the design and age of the plant. Some of these systems function only during normal plant operation to maintain normal containment atmospheric conditions, while some are required to operate during and/or following an accident to mitigate the consequences of the accident. For this study, the definition of containment cooling system used herein limits the systems addressed to those that are required to function to mitigate the consequences of an accident. Containment cooling systems that operate only during normal plant operation are not addressed. The systems included in this study are discussed in more detail in the following sections.

1.4.1 Containment Cooling in PWRs

The containment structures used for pressurized water reactors (PWRs) are generally classified into three types; 1) large dry (or vapor containments), 2) subatmospheric, and 3) ice condenser containments. The large dry containments are designed such that the free volume is sufficiently large to accommodate a worst case accident (LOCA or MSLB) while mitigating containment pressure increases. The subatmospheric containment uses the same principal as the large dry containment, however, it includes provisions to condense a sufficient amount of steam in the containment atmosphere following an accident to maintain the containment pressure less than atmospheric. This further reduces the probability of radiation leakage to the environment. The ice condenser containments use ice beds that are constantly maintained inside the containment structure to perform a pressure suppression function in the event of an accident. This enables the size of the containment structure to be reduced. Of the 80 PWRs in the U.S., 63 use the large dry containment (Figure 1.3). Ice condensers (10 units) were not addressed in this study due to their small population. Subatmospheric containments were included in the study since the containment cooling systems are similar to those used in the large dry containments.

In all PWRs except one (Yankee Rowe), containment cooling is provided by a containment spray system which operates by pumping water through spray nozzles located at the top of the containment structure to cool the containment atmosphere. In most PWRs, containment fan coolers are also provided as a backup to the containment spray system. The fan coolers blow the containment air across cooling coils to remove heat. Each of these systems will be addressed in subsequent sections of this report. In addition to these two systems, a containment vent system is also available to control containment pressure. This system would only be used as a last resort following a release inside containment, and is not included in this study since it is not a primary means of accident mitigation.

1.4.2 Containment Cooling in BWRs

With the exception of one plant (Big Rock Point), which uses a large dry containment, all BWRs in the U.S. use a pressure suppression containment. This design includes a large pool of water inside the containment structure, called the suppression pool, and a drywell structure in which the reactor is housed. Any steam produced as the result of an accident is forced from the drywell into the suppression pool and is condensed, thus mitigating pressure increases inside the containment. This design feature allows the size of the containment structure to be much smaller than PWR containments.

There are three types of pressure suppression containments. The oldest design is the Mark I, which uses a separate torus shaped suppression pool. In the subsequent Mark II and Mark III designs, the suppression pool is an integral part of the containment structure. In Mark IIs, it is cylindrically shaped and is located directly beneath the reactor. In Mark IIIs, it is annular in shape, with the reactor pressure vessel in the middle. The distribution of BWR plants using each type of containment is shown in Figure 1.4.

In the pressure suppression containments, cooling is provided by a containment spray system to both the drywell and the suppression pool sections, similar to that used in PWRs, along with a suppression pool cooling system. The suppression pool cooling function is typically provided by the residual heat removal (RHR) system. The design and function of the containment spray and suppression pool cooling systems will be discussed in more detail in subsequent sections of this

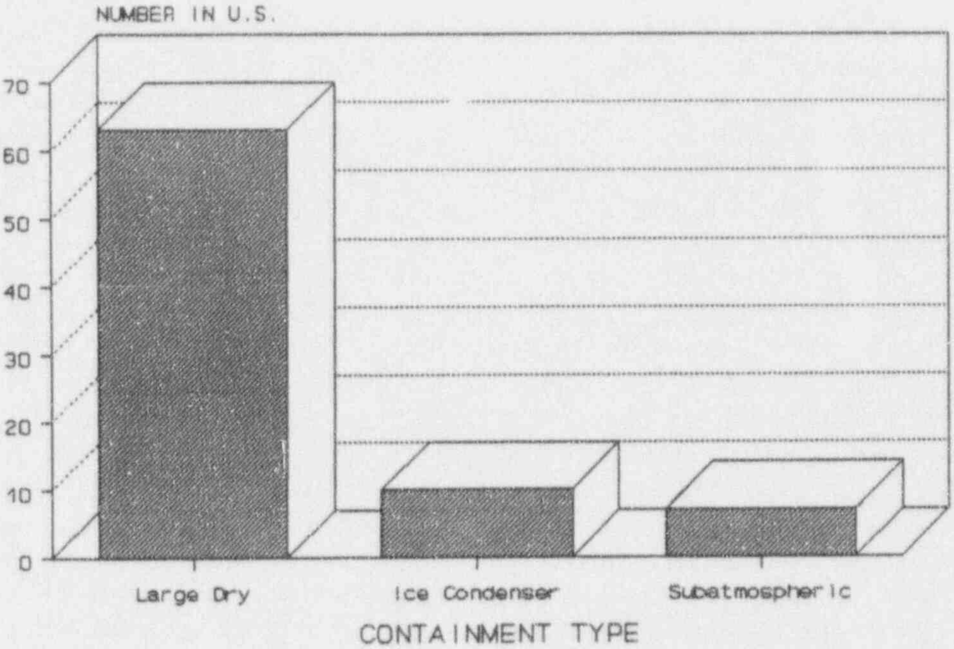


Figure 1.3 Distribution of PWR containments

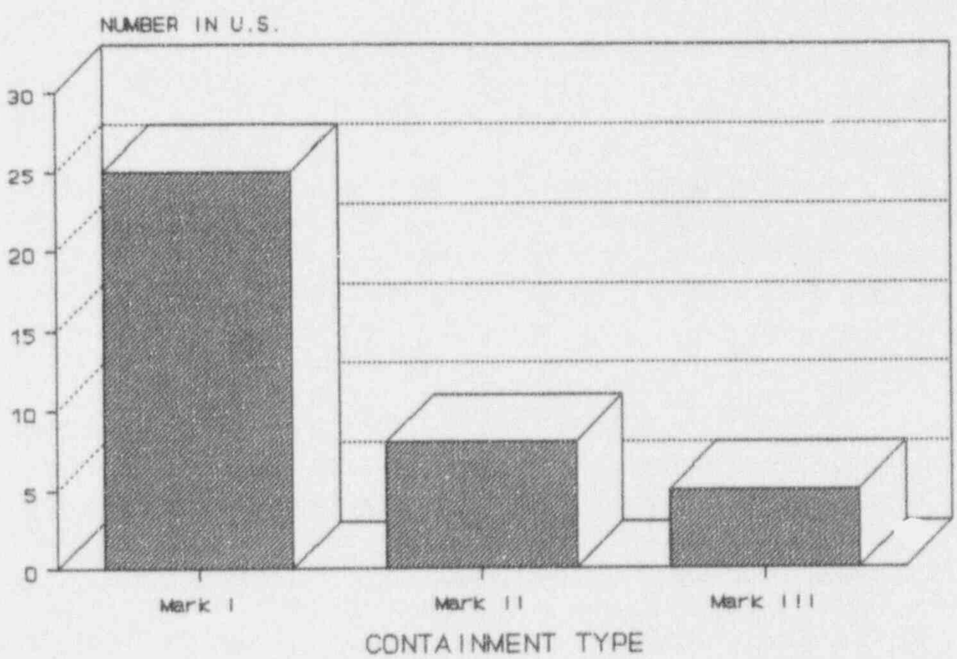


Figure 1.4 Distribution of BWR containments

report. Aging of the major components used in these systems is addressed in Reference 4.

As with PWRs, the BWR containments also have containment vent systems which can be used to control the pressure inside containment during severe accidents. These systems are not the primary means of mitigating temperature and pressure increases inside containment following a design-basis accident, and are not addressed in this study.

1.4.3 System Boundaries

The various systems used to perform the containment cooling function interface with several other systems throughout the plant. For example, the electrical system provides power to the various pumps and fans, and the service water or component cooling water system provides cooling water to the various heat exchangers. In order to provide a clearly defined system for this study, boundaries must be established to identify which components should be included in the analysis and which should be eliminated. Therefore, the following interfacing systems and boundaries have been identified.

1.4.3.1 AC electrical power

AC electrical power is supplied to the various pumps, fans and motor operated valves (MOVs) within the systems. The source of this power is either from off-site power or from the emergency diesel generators. The boundary for AC power will be at the first circuit breaker from the component being supplied, and will include the circuit breaker and any breaker logic. It should be noted that the class 1E power system has been studied separately as part of the NPAR program[8].

1.4.3.2 DC electrical power

DC electrical power is supplied to the instrumentation and controls used to monitor and operate the containment cooling systems. The source of this power is typically from two or more independent battery banks that are periodically recharged using battery chargers and inverters. The boundary for DC electrical power will be at the first circuit breaker or fuse from the component being supplied. It should be noted that battery chargers and inverters have been studied separately as part of the NPAR program[19].

1.4.3.3 Cooling water system

Cooling water is supplied to the cooling coils in the containment fan coolers to remove heat from containment. Cooling water is also used to cool the containment spray pumps. The source of this water is typically from the component cooling water system or the service water system. The boundary for the cooling water systems will be at the first block valve from the component being supplied, and will include the block valve. The component cooling water and service water systems have been studied under the NPAR program[3,9,10].

1.4.3.4 Instrumentation

A number of different instruments are used to monitor and control the containment cooling function. These instruments may be dedicated specifically to the containment cooling function, or they may be used for several different purposes. Any instrument required to perform the containment cooling function will be included in this analysis. The boundary for all instruments will be at the first circuit breaker or fuse from the instrument, and will include the circuit breaker or fuse. NPAR studies have been performed on several different types of instruments and controls[11-17].

1.4.3.5 Structures and buildings

The various systems used for containment cooling typically run through several different areas and buildings within the plant. These systems are typically mounted or supported so that they will withstand seismic shocks. The structures and buildings to which these systems are attached are not included in this study, however, the supporting hardware is included. Therefore, the boundary is just beyond the supporting hardware.

1.5 Review of Generic Letters, Bulletins, and Information Notices

As a precursor to the aging analysis, a review of NRC Generic Letters, Bulletins, and Information Notices was performed to identify any past or present regulatory concerns related to aging degradation of containment cooling systems. Three Information Notices and one Inspection and Enforcement Correspondence were found that dealt with aging problems.

Information Notice 79-34 deals with the inadequate design of safety-related heat exchangers. A plant identified defects in four containment spray heat exchangers. The heat exchanger tube bundles were damaged by excessive vibrations of the tubes against each other. These vibrations were caused by a support arrangement that allowed excessive unsupported tube lengths. The large amplitude vibration resulted in reductions in wall thickness and some tube leakage. To correct this condition, the leaking tubes had to be plugged and supports were placed on the tube bundle to mitigate the vibration.

This incident presents an example of how a design error can result in an aging-related failure. Although the root cause of the failure was inadequate support of the tube bundle, this allowed an aging mechanism, namely vibration, to cause degradation of the tubes and eventually lead to failure. If a monitoring practice had been in place to detect tube vibration in the heat exchanger, this failure may have been avoided. One possible monitoring method that may have been useful in this case is acoustic emission monitoring.

Information Notice 80-37 deals with the flooding of the reactor cavity due to leaks in the cooling coils of the containment fan coolers. Upon entry into containment at one plant it was discovered that a significant amount of water was collected on the containment floor, in the containment sumps, and in the cavity under the reactor pressure vessel. This condition resulted from a number of concurrent failures, which included multiple service water leaks from the containment fan cooling units directly onto the containment floor. These coolers have a history of such leaks, which cannot be detected by supply inventory losses since the supply system (service water system) is not a closed system. Subsequent analyses determined that the water had entered the cavity below the reactor vessel and flooded it to a level at which the bottom nine feet of the reactor vessel were wetted. This led to concerns of chloride stress corrosion and thermal shock of the vessel.

The fan cooler units involved in the aforementioned event have air conditioner type cooling coils consisting of 90-10 Cu-Ni pipe headers and tubes, along with copper plate type fins. The cooling water to the coils is supplied by the service water system, which uses untreated river water as its source. The cause of the leaks was corrosion due to the quality of the cooling water, as well as improper installation techniques for the supply line and coil tubes. Corrosion is a common aging mechanism leading to degradation and subsequent failure of heat exchangers. This event demonstrates how uncontrolled aging degradation can lead to a failure of the fan cooler system with significant consequences to the plant.

Information Notice 83-46 deals with failure of valves which admit service water to the recirculation spray coolers. At one plant, seven of eight motor-operated, 30 inch butterfly valves failed to open during surveillance tests of the recirculation spray subsystem. The failures were attributed to the use of brackish and silty service water, which led to corrosion and marine growth on the valves. In addition, infrequent testing was cited as a contributor to failure since the valves had only been stroke tested during refueling outages. The failures were corrected by cleaning the piping and valve internals, applying marine inhibitor paint on the valve discs, and installing new motor operators with a higher torque output. In addition, the valve test frequency was increased to quarterly testing. This is a typical example of aging degradation for valves operated in poor quality water. Corrosion and marine growth are typical aging mechanisms associated with this degradation.

Inspection and Enforcement Correspondence 79-19 discusses the problem of cracking in safety-related stainless steel piping systems and portions of systems which contain oxygenated, stagnant, or essentially stagnant borated water. These cracks occurred in the weld heat affected zone of type 304 material in the spent fuel pool cooling system piping. The cracks were found as a result of local boric acid buildup and were due to Intergranular Stress Corrosion Cracking. As a result, ultrasonic examinations of other potentially affected systems, including the reactor building spray system, were performed. This event identifies a potential aging problem for containment spray systems which use borated water.

2. CONTAINMENT COOLING SYSTEM DESIGNS

Containment cooling systems perform the functions of containment heat removal and pressure control. In addition, they can assist in fission product cleanup in the event of a release inside containment. In pressurized water reactors these systems usually take the form of a containment spray system and several fan cooler units, while in boiling water reactors they are usually comprised of containment spray and suppression pool cooling systems. While the basic function of the systems is comparable, the designs vary from plant to plant. This section will discuss the various designs currently in use for each of the systems, along with the operation of the system and a description of its major components.

2.1 Containment Spray Systems

2.1.1 Containment Spray System Description

Containment spray system designs vary from plant to plant. The design variations reflect improvements in technology, as well as modifications to the General Design Criteria specified in the Code of Federal Regulations. The basic function of the system is to pump water through spray nozzles located circumferentially near the top of the containment structure. The water spray condenses steam produced as a result of a LOCA or MSLB inside containment, thus mitigating any increase in containment pressure and temperature.

In a typical PWR containment spray system design, two or more containment spray pumps deliver water from the refueling water storage tank (RWST) to the containment spray headers (Figure 2.1). The headers direct the water to a number of spray nozzles from which the water is injected as a fine mist to the containment atmosphere. This is commonly referred to as the injection phase of containment spray. When the RWST reaches a specified low level, the spray pumps are realigned to take suction from the containment sump. The sump water is then delivered to the same spray headers and nozzles. This is referred to as the recirculation phase since the water pumped to the spray headers eventually collects in the containment sump and is recirculated.

Some common design variations include the use of the residual heat removal (RHR) pumps for the recirculation phase instead of the containment spray pumps, which are tripped and isolated after the injection phase is completed (Figure 2.2). Also, some of the designs include the use of a heat exchanger, through which the water passes before being delivered to the spray headers. Some designs include dedicated containment spray heat exchangers, which are used during both phases of containment spray, while other designs use the RHR heat exchangers only during the recirculation phase. Still other designs have two separate systems; a quench spray system for the injection phase, and a recirculation system for the recirculation phase. In this type of arrangement each system is independent and has its own dedicated set of pumps and spray headers.

In order to assist in fission product cleanup following a LOCA or MSLB, many PWR containment spray systems include a means of injecting a chemical additive, such as sodium hydroxide or hydrazine, to the spray water. These chemicals help to convert radioactive iodine to non-volatile compounds, such as iodide and iodate, that can be kept in solution in the sump water. One method of doing this is to have a chemical addition system and eductors, which entrain the chemical additive in a small recirculation flow taken from the containment pump discharge and delivered back to the containment pump suction (Figures 2.1 and 2.2).

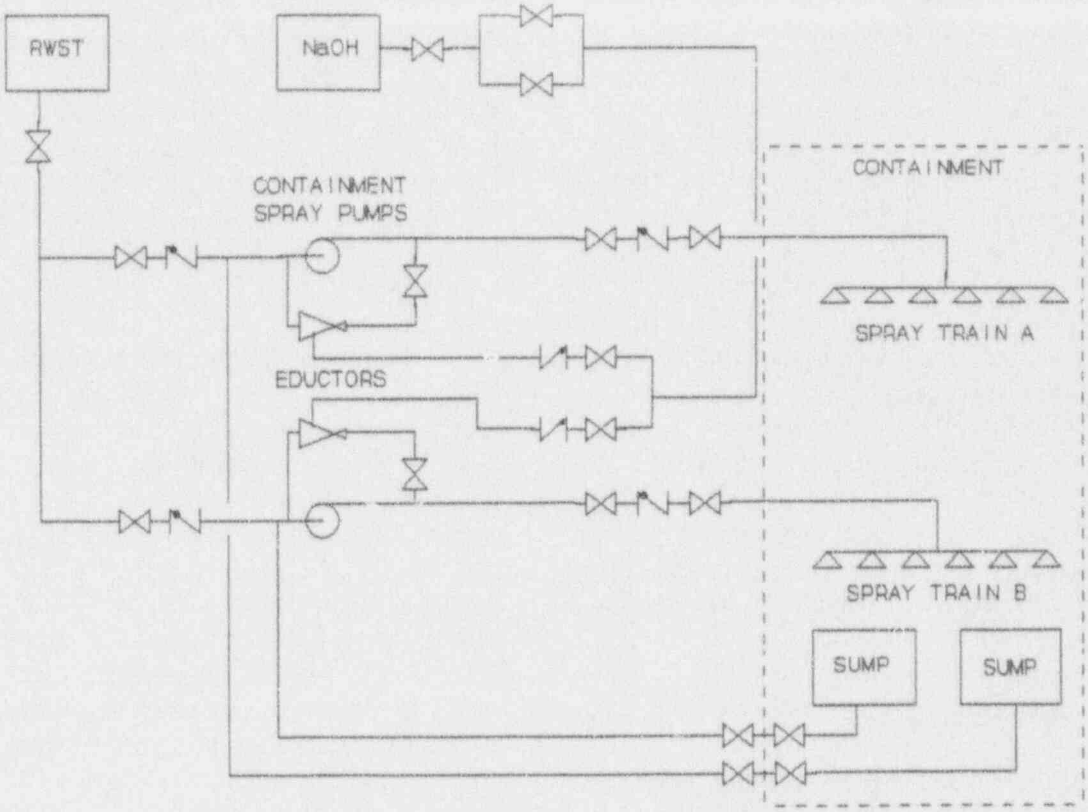


Figure 2.1 Common PWR containment spray system design

Containment spray systems in BWR plants are similar to those described for the PWRs, with a few exceptions. In a BWR the RHR system is typically used for containment spray. The RHR pumps are aligned to take suction from the suppression pool and deliver spray water to the RHR heat exchangers, where it is cooled (Figure 2.3). The cooled water is then delivered to the spray rings. In Mark I and Mark II containments there are three spray rings, with two in the drywell and one in the suppression chamber. In most Mark III containments there are also three spray rings, however, none are in the drywell. Some BWR plants use an emergency ventilation system, which removes iodine by circulating the air through carbon filters. BWR plants do not have a chemical injection system.

2.1.2 Containment Spray System Operation

In PWR plants the containment spray system is actuated by a signal initiated manually from the control room, or automatically on coincidence of two out of four (two out of three for older units) high containment pressure signals. The initiation signal starts the containment spray pumps, opens the discharge valves to the spray headers, and opens the valves between the spray eductors and the spray additive tank, for those units that have this feature. A small portion of the total spray flow is recirculated through the eductors then back to the spray pump suction. As this

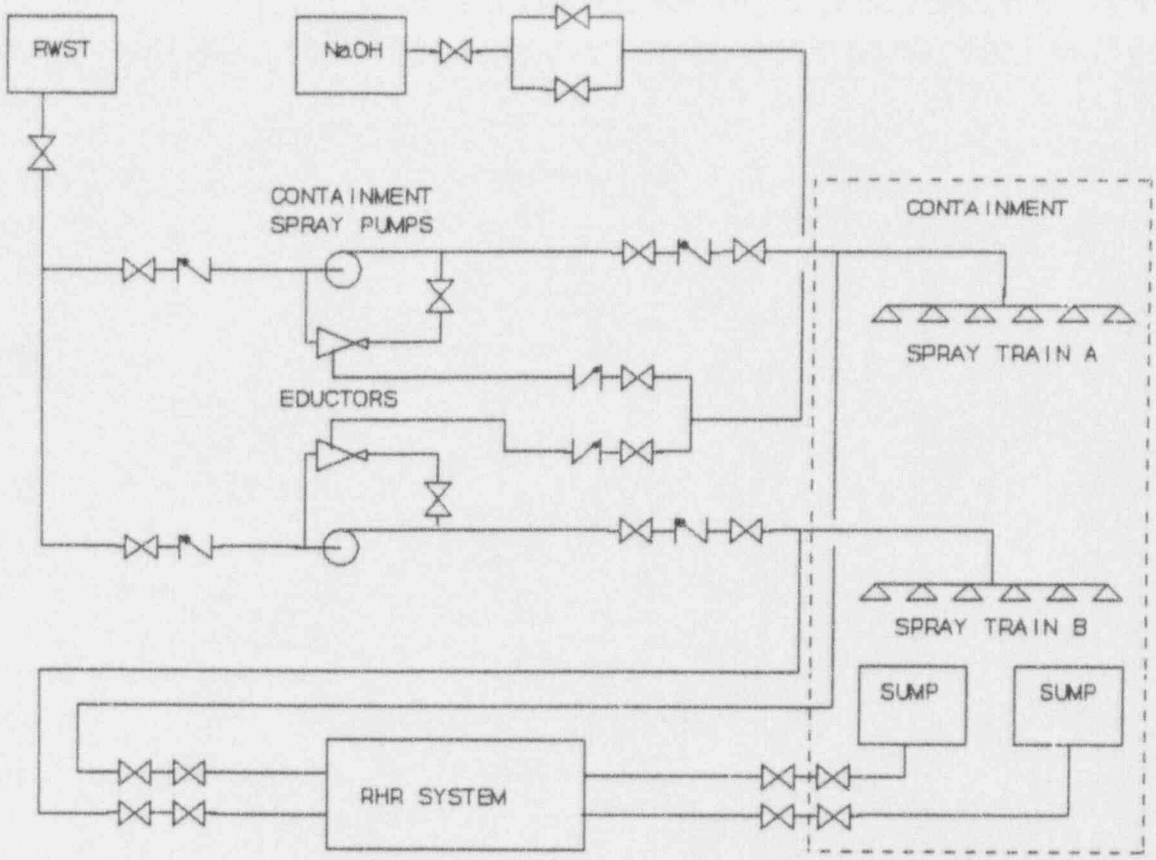


Figure 2.2 Alternate PWR containment spray system design

recirculated fluid flows through the eductors it entrains the chemical additive in the spray flow.

When the RWST is nearly empty, the injection phase is terminated and the recirculation phase is begun. For units that use the RHR pumps for recirculation, the containment spray pumps are manually tripped and isolated. The RHR system is then aligned for containment spray and the RHR pumps are started. Throttle valves in the injection lines are used to split the recirculation flow and deliver a portion of the flow to the reactor core to provide decay heat removal. This mode of operation can then be continued as long as required to maintain containment pressure and temperature, and complete iodine removal from the containment atmosphere.

In newer plants that use the containment spray pumps for both phases, recirculation is initiated when the low-low RWST level signal is received. This typically is done manually when the RWST level reaches 10%. Switch over at this point ensures that the system piping remains full of water and that adequate net positive suction head (NPSH) for the spray pumps is maintained. The operator manually realigns the spray pump suction from the RWST to the containment recirculation sump. In one plant the switch over to recirculation is done automatically, and is initiated by a safety injection signal concurrent with a low-low RWST level signal.

In BWR plants with Mark I or Mark II containments, the containment spray system is actuated manually from the control room.

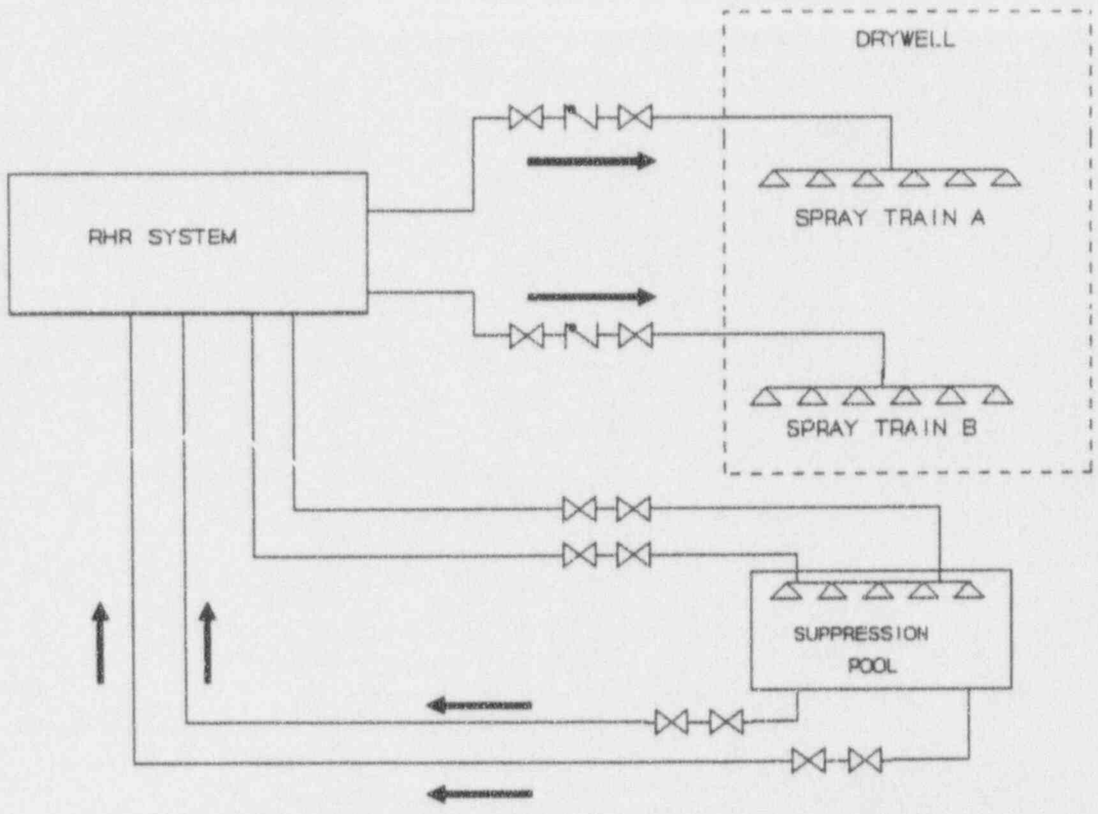


Figure 2.3 Containment spray mode of RHR in BWR plants

There are no signals that automatically initiate the spray function. The RHR system is aligned for containment cooling after the reactor vessel water level has been recovered. For plants with a Mark III containment, the containment cooling function may be initiated manually, or it may be initiated automatically. The containment spray mode is automatically initiated on high containment pressure if LOCA and high drywell pressure signals are present.

2.1.3 Major Containment Spray System Components

Refueling water storage tank (RWST): This tank serves as a source of emergency borated cooling water for injection and containment spray in PWRs. It is normally used to fill the refueling canal for refueling operations. During all other plant operating modes it is aligned to the suction of the emergency core cooling pumps and the containment spray pumps. The RWST is typically an austenitic stainless steel tank containing borated water at a concentration of 2,000 ± 50 ppm boron. The capacity of the tank varies from 250,000 to over 700,000 gallons. It is maintained at atmospheric pressure, and is vented directly to the atmosphere. Provisions are made to prevent the tank contents from freezing. Tank level indication and high/low level alarms are also provided.

Containment Spray Pumps: The containment spray pumps are either vertical or horizontal centrifugal pumps driven by electric induction motors. Design flow rates typically range from 2000 to 3000 gpm. The motors are typically 400 to 600 horsepower. They have open, drip-proof enclosures, and are provided with sufficient insulation to allow continuous operation at 100% rated load at 50 °C. Power for the motors is provided by the emergency busses. One plant has one of three pumps driven by diesel engine. The pump casing is usually made of stainless steel.

Valves: Motor-operated gate valves are commonly used in the containment spray pump discharge lines. These are typically interlocked to open within several seconds on a containment spray signal to allow flow to the spray nozzles.
Some designs also use MOVs or AOVs as isolation valves to the RWST and the containment sump. Manual valves may also be used in the system to isolate components for maintenance purposes. In addition, there are numerous check valves in the system, including valves used to provide containment isolation.

Spray Nozzles: The spray nozzles are typically of the hollow cone design having an open throat with either a 3/8-inch or 7/16-inch spray orifice. The nozzles are not subject to clogging by particles less than 1/4-inch in size. One typical nozzle design produces a mean drop diameter of 700 microns at its rated conditions of 40 psid and 15.2 gpm per nozzle. The number of nozzles varies with the system design, ranging from approximately 150 to over 400 per unit. The nozzles are tested periodically according to technical specifications to ensure they are unobstructed.

Piping: The piping used for the containment spray systems is typically austenitic stainless steel. The joints are welded, with the exception of flange connections at the pumps and relief valves.

Containment Recirculation Sumps: The containment recirculation sumps in PWRs are typically concrete structures which are an integral part of the containment structure. They act as collecting reservoirs from which the containment spray pumps take suction during the recirculation phase of the containment spray mode. Water sprayed into the containment will drain to the containment floor and be channeled into the sumps. The sumps are located as far as possible from the reactor coolant system piping and components, which could become sources of debris in the event of an accident. The sump intakes are protected by either trash guards and fine mesh screens, or a baffle arrangement of grating, coarse screening, and fine screening to prevent floating debris and high density particles from entering.

Suppression Pool: The suppression pool in BWRs is an integral part of the containment structure in Mark II and Mark III containments. In the Mark I containment it is a torus shaped structure inside containment. The suppression pool is filled with water during all plant operating modes. In the event of an accident in which coolant or steam is released into the containment, the steam is directed through the suppression pool and is condensed, thus mitigating any pressure or temperature increases inside containment. This pool of water also serves as a source of cooling water for several systems, including the RHR system in the containment spray mode. During containment spray, the water delivered to the spray rings falls through the containment atmosphere and eventually is collected and returned to the suppression pool.

Instrumentation: Instrumentation is provided to monitor a number of system parameters. Water level is monitored by level transmitters in the containment sump, as well as in the RWST and suppression pool, with indication provided in the control room. Spray pump suction and discharge pressure is monitored by local pressure gauges. Pump flow and recirculation flow to the eductors is also monitored via flow transmitters. Containment pressure and temperature are monitored by several pressure and temperature transmitters located throughout the containment to indicate the effectiveness of the containment cooling system.

Chemical Addition System: In those designs that use one, the chemical addition system provides a means of injecting a chemical additive into the spray water. This system typically includes a chemical storage tank, piping, valves, and spray eductors. Typically, a bleed flow is taken from the discharge side of the pump and circulated through the eductor, which allows chemicals to be drawn into the flow. The chemical laden flow is then returned to the suction side of the pump, and is mixed with the main flow for delivery to the spray nozzles.

Additional design information on PWR and BWR containment spray systems is included in Appendix A.

2.2 Fan Cooler System

2.2.1 Fan Cooler System Description

Unlike the containment spray system, fan coolers are used in PWRs and BWRs during normal plant operation to maintain a suitable atmosphere for the equipment located within the containment. In most PWR plants, and several BWR plants, fan coolers are also used as an engineered safety feature to reduce the containment temperature and pressure following a LOCA or MSLB. In most BWRs, fan coolers are not used under accident conditions. However, BWR fan cooler data was obtained and analyzed in this study since their failure modes and aging mechanisms are expected to be similar to safety-related fan coolers.

The basic design of the fan cooler units includes cooling coils, through which cooling water circulates, a fan, which blows the containment air over the cooling coils, and various duct work and dampers to direct the air flow (Figure 2.4). Older plants typically use a centrifugal fan design, while newer plants use a vane-axial fan design. Some units also have filters to help remove particulates from the air. There are typically three or more fan cooler units located within containment, depending on the plant, each with one or two fans per unit.

2.2.2 Fan Cooler System Operation

During normal plant operation the number of fan cooler units running will depend on the amount of cooling required for the containment. The operator uses the containment temperature and pressure readings to determine how many units should be operating. At full power operation, most, if not all of the units may be required, however, all units are typically run for flow distribution purposes. At cold shutdown, only one fan cooler unit may be required to maintain containment temperature at an acceptable level. Technical Specifications usually set an upper limit of 120 to 130 °F for containment temperature.

The source and amount of cooling water flow to the fan cooler units varies between plants. In some plants, the raw service water system provides cooling water to the fan coolers during normal operation and emergency conditions. In other plants, the component cooling water system provides the cooling water. These two systems are the most commonly used source of cooling water for the fan coolers. A less commonly used design employs a chilled water system supplied by refrigeration units to augment the service water system supply of cooling water to the fan coolers during normal operation. In the event of an accident, the chilled water system is isolated.

For those plants that use the fan coolers as an engineered safety feature, a LOCA or MSLB will initiate a safety injection signal which, in turn, will start any fan coolers that are not operating at the time. In the case

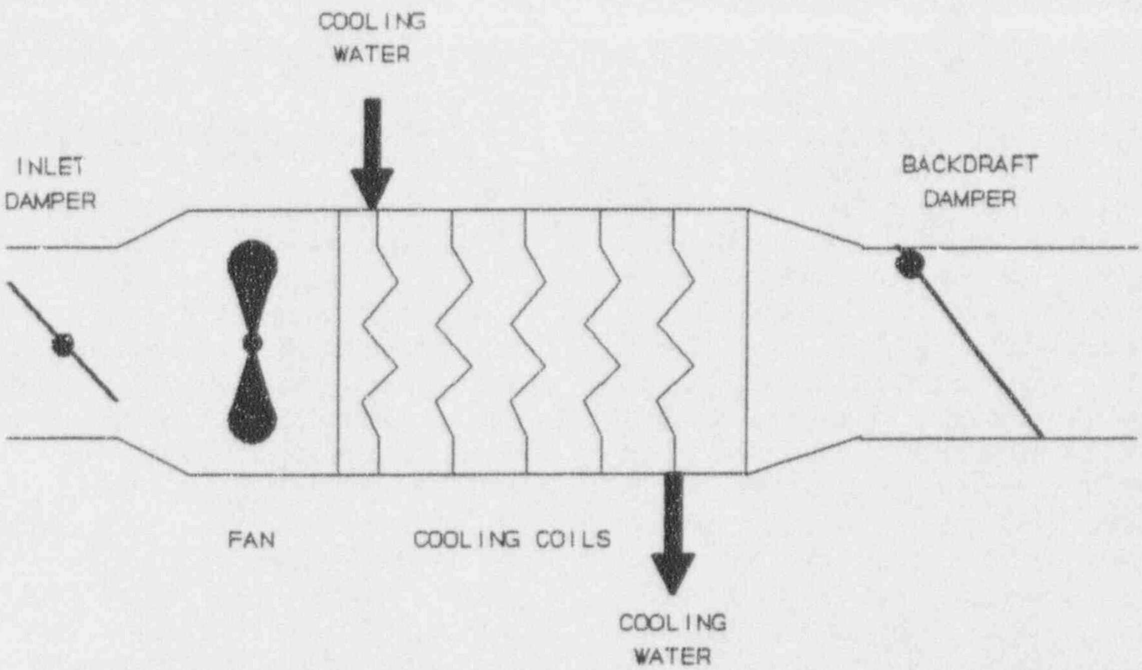


Figure 2.4 Fan cooler unit schematic

of a loss of off-site power, there will be a sequenced loading of the fan cooler units. In addition, some designs have the air dampers automatically repositioned to an accident position. This directs the air flow through a filtration section, which consists of moisture separators, high efficiency particulate air (HEPA) filters, and charcoal filters. Some designs also automatically switch the cooler fans to a slower speed to reduce horsepower requirements during the accident. An additional design feature used by some plants is fusible link plates on the fan cooler housing, which open to allow unrestricted air flow through the fan coolers. The fusible link plates are steel plates that are hinged to the duct work and held in a closed position by fusible links. When a certain design temperature is reached (typically around 160 °F) the fusible links release, thus dropping the plate from the duct work. The resulting opening exceeds the cross-sectional area of the fan providing an unrestricted flow path.

2.2.3 Major Fan Cooler System Components

Fan-Motor Units: The fans are either centrifugal or vane-axial type, with rated flows ranging from 35,000 to 85,000 cfm. They are driven by totally enclosed induction motors that typically contain an integral air-to-water heat exchanger for cooling. There are normally one or two fans per fan cooler unit. Fan-motor space heaters are provided to maintain favorable conditions of temperature and humidity during fan shutdown. The motors are typically rated at 300 to 400 horsepower. The bearings are grease lubricated, and their vibration and temperature are monitored.

Cooling Coils: The cooling coils are typically arranged in one or two banks. They are usually made of copper or a copper alloy, however, at least two plants changed to Allegheny Ludium, which is a high nickel/chrome/molybdenum alloy, due to corrosion problems. All of the coils are copper finned. Tube diameter is typically 5/8 inch. Cooling water flow through the coils for each unit typically ranges from 1500 to 2500 gpm, with an inlet temperature of 85 to 95 °F. Cooling water is usually supplied by the service water or component cooling water system.

Dampers: In addition to inlet and outlet dampers on the fan cooler units, there is usually a backdraft (or check) damper in the discharge duct work. The backdraft damper protects the fan cooler against any reverse flow that might be induced by a LOCA or MSLB. This damper is designed to close quickly (on the order of 70 milliseconds). The backdraft damper is gravity actuated and is normally closed when the fan is not running. For units with filtration sections, accident and bypass dampers are included to direct air flow through the filters or bypass the filters, depending on the operating conditions. In some units, fusible link plates are also used as a type of damper.

Valves: MOVs or AOVs may be used as isolation valves for the cooling water supply and return lines for the cooling coils. These valves can be remotely operated from the control room as required to take fan coolers in or out of service.

Instrumentation: Instrumentation is provided to monitor a number of system operating parameters. Inlet and outlet air temperatures are monitored either locally, in the control room, or on the plant computer. Air flow through the units is monitored by flow switches or differential pressure switches. Humidity detectors are usually provided upstream of each fan cooler. Cooling water flow rate, as well as inlet and outlet temperature are also monitored in the control room. Containment pressure is also monitored by several sensors to detect a pressure rise due to a LOCA or MSLB, and initiate a safety injection signal.

Additional design information on fan cooler units for PWRs and BWRs is included in Appendix B.

2.3 Suppression Pool Cooling System

2.3.1 Suppression Pool Cooling System Description

In BWR plants, a primary means of containment cooling is performed by the suppression pool cooling system. This system, like the containment spray system, is actually an operating mode of the residual heat removal (RHR) system.

The RHR system has been studied in detail under the NPAR program[4], therefore, the aging characteristics of the suppression pool cooling and containment spray modes will not be a focus of this study. The major RHR system components studied previously are common to these modes of operation. However, the containment spray and suppression pool cooling modes of the RHR system will be discussed herein for completeness. To summarize the results of the RHR study, it was found that aging contributed to over 70% of the failures in that system, with the predominant cause of failure being normal service. The components most frequently failed were valves, followed by instrumentation, with the predominant aging mechanism being wear. For valves, the dominant failure mode was leakage, while for instrumentation it was calibration drift.

The RHR system has different configurations among plants, however, there are some basic design characteristics that are common between designs. The RHR system typically has two or three independent trains with each having one to two pumps which operate in parallel. Each train will also have one or two heat exchangers, as well as a number of valves to direct the flow where required. The heat exchangers are typically cooled by the component cooling water or service water system.

In the suppression pool cooling mode, the RHR pumps take suction from the suppression pool through suction strainers and pump the water to the RHR heat exchangers where it is cooled. The cooled water is then delivered back to the suppression pool (Figure 2.5). In the containment spray mode the suction flow path is the same, however, the cooled water is delivered to the containment spray headers located in the dry well or suppression chamber.

2.3.2 Suppression Pool Cooling System Operation

For all BWR RHR systems, the containment cooling modes may be remote manually initiated from the control room. For some BWR designs, the containment spray mode is initiated automatically after a 10 minute delay, if both LOCA and high drywell pressure signals are present concurrently. The RHR system is realigned for containment cooling after the reactor vessel water level has been recovered. An interlock is provided so that the operator does not inadvertently initiate containment cooling before low pressure coolant injection (LPCI), which is another operating mode of RHR, restores reactor vessel water level.

The typical PRA success criteria for containment cooling in BWRs is to have rated flow delivered from any RHR pump/heat exchanger train to the suppression pool for suppression pool cooling, and to the spray headers for containment spray cooling.

2.3.3 Major Suppression Pool Cooling System Components

The suppression pool cooling and containment spray systems use the RHR system pumps, heat exchangers, valves, and piping. Aging of these components has been addressed in Reference 4. Components that are specific to the containment spray and suppression pool cooling modes are the suppression pool, return lines, and spray nozzles. These components are briefly described in the following paragraphs.

<u>Piping</u>: The piping used in the RHR system to support the containment cooling operating modes is typically stainless steel. The joints are welded.

<u>Valves</u>: The valves used in the suction and return lines are conventional gate, globe and check valves designed for nuclear service. The valves may be manually operated, or they may be equipped with motor or air actuated operators for remote operation.

<u>Spray Nozzles</u>: The spray nozzles are similar to those used in the PWR containment spray systems, which are described in Section 2.1.3. The nozzles are located in spray headers, which are supplied by the RHR system.

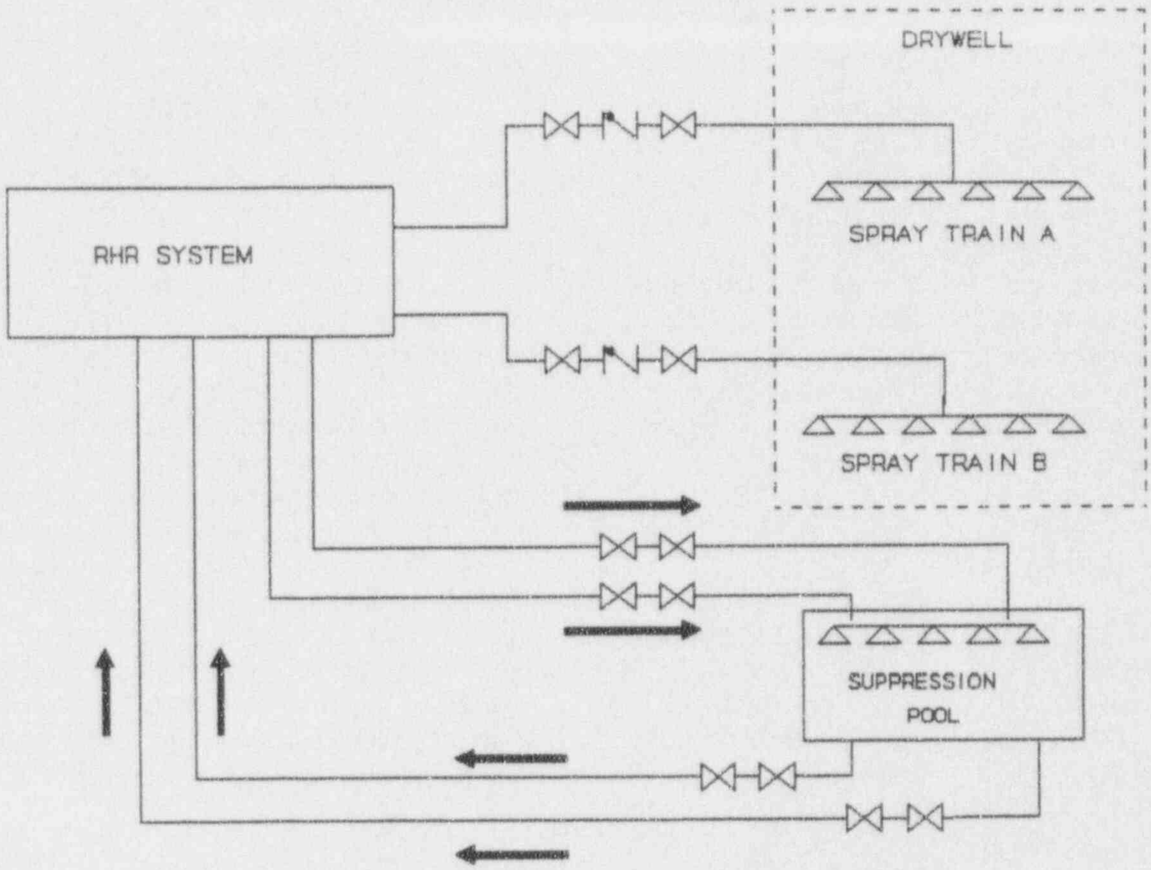


Figure 2.5 BWR suppression pool cooling schematic

3. OPERATIONAL AND ENVIRONMENTAL STRESSES

Aging degradation results when a component is exposed to various aging mechanisms over a period of time. These aging mechanisms are induced by stresses imposed by the operating conditions or environment the component is in. Prolonged exposure to these stresses can result in a decrease in mechanical strength or electrical properties of the various components, and eventually lead to failure. By understanding what the different stresses are and how they are brought about, a better understanding of how to manage the aging process can be obtained.

This section discusses the various operational and environmental stresses containment cooling system components are exposed to. These stresses can be imposed by operation of the components, including both normal operation and testing, along with factors imposed by the surrounding environment. The corresponding aging mechanisms induced by these stresses are also discussed.

3.1 Operational Stresses

As discussed in the previous section, the containment cooling function can be performed by several different plant systems, including the containment spray system and the fan cooler system. Since the containment spray system is predominantly a standby system, the dominant aging mechanisms may be different from a system with similar components that continuously operate. However, this does not mean that aging mechanisms associated with operation will not be important to this system since these mechanisms can be imposed through testing of the components. In some plants, the fan cooler units are operated periodically during normal plant operation, therefore, exposure to normal operating stresses is greater.

For the containment spray system, operation involves the pumping of water from a source (usually the refueling water storage tank, the containment sump, or the suppression pool) to spray nozzles inside containment. The components involved to perform this function are pumps, valves, piping, heat exchangers, and instrumentation/controls. The pumps, valves and piping are typically made of stainless steel and are designed for temperatures as high as 500°F and pressures up to 500 psig, however, actual operating parameters are usually much lower.

The physical processes that are active when the containment spray system operates are water flow through pipes, pumps and valves; internal water pressure; frictional rubbing between moving parts, such as pump seals and wear rings; and vibration. Each of these physical processes imposes one or more stresses on the component that can allow an aging mechanism to become active. For example, components exposed to flowing water are subject to erosion, if the conditions are conducive to this type of degradation. The degree to which erosion leads to degradation of the component depends on several factors, including what material the component is made of, how high the water velocity is, how turbulent the flow is, and how long the component is exposed to this stress.

In good designs, these factors are considered and minimized as much as possible by proper sizing and material selection. However, they can not always be eliminated completely. Trade-offs must usually be made to provide a reliable, as well as cost effective design. Even though the operational stresses are minimized, over long periods of time they can result in degradation severe enough to cause failure of the component. Therefore, it is important to identify all possible aging mechanisms and monitor components for signs of degradation that may be caused by these mechanisms before it results in failure. Each of the physical processes has been reviewed, and the stresses and corresponding aging mechanisms have been identified. These are summarized in Table 3.1 for the components in the containment spray system.

The function of the fan cooler units involves the blowing of air from the containment over cooling coils to extract heat, then returning the cooled air to containment. The cooling coils have water circulating through them to remove the heat from the air. This water is typically supplied by the component cooling water system, which supplies treated water, or the service water system, which supplies untreated water. Cooling coils supplied by the service water system are exposed to a more severe internal environment since service water can use water from nearby lakes, rivers, or oceans, and can be of poor quality.

As previously mentioned, the fan cooler units can be operated during normal plant operation to provide cooling to the containment. Therefore, they are routinely exposed to normal operating stresses. These include water flow through the cooling coils, frictional rubbing of moving parts, such as motor bearings and damper bushings, internal water pressure in the cooling coils, and vibration. The stresses and corresponding aging mechanisms for these operating conditions are summarized in Table 3.2 for the fan cooler units.

3.2 Environmental Stresses

In addition to the operational stresses discussed above, the components are subjected to stresses by the environment in which they are located. This includes high temperatures, which can cause dry out of certain seals and gaskets, humidity, which can lead to corrosion or deterioration of various materials, and radiation, which can cause embrittlement. As for the operational stresses, the degree to which each of these environmental stresses leads to degradation depends on a number of factors, such as the material of construction, the severity of the stress condition, and the time of exposure.

The location of the components plays an important part in determining how severe the environmental stresses are. Since the fan cooler units are located inside containment they are subjected to temperatures as high as 100°F to 130°F during normal plant operation. In addition, they are in a radiation environment, which imposes additional stresses on the components. The containment spray system components are typically located outside of containment, with the exception of the spray rings and nozzles. The external environment is, therefore, less severe than for the fan cooler units.

The environmental stresses acting on the containment cooling systems have been reviewed and the corresponding aging mechanisms have been identified. These are included in Tables 3.1 and 3.2 for the containment spray and fan cooler units, respectively.

To properly manage aging, each of the potential stresses and corresponding aging mechanisms should be addressed by identifying how severe the problem is, and having appropriate inspection, surveillance, and monitoring methods in place to detect and mitigate it. This section has identified what stresses may be present and the aging mechanisms they can result in. The next two sections on data analysis examine the severity of the different aging mechanisms and how they lead to component failures.

Table 3.1 Stresses for Containment Spray System Components

Component	Stress	Aging Mechanism	Probability	Comments
Pumps	- Internal water flow	- Deterioration of gaskets/seals	Medium	
		- Erosion of internals - Corrosion of internals - Cavitation of internals - Pitting of internals	Low Low Low Low	Pumps constructed of stainless steel, which is resistant to these mechanisms.
	- Internal water pressure	- Deformation of internals	Low	Pumps typically do not operate at very high pressures.
		- Fatigue of internals	Low	Cycling of pump can cause fatigue due to pressure increases and decreases.
	- Rotation of shaft, impeller, motor	- Wear of bearings, seals	High	Wear of bearings and seals is a common pump aging problem.
		- Galling/binding of internals	Medium	
		- Vibration induced loosening of internals	Medium	
		- Distortion of internals due to centrifugal forces	Low	
	- Exposure to external environment	- Deterioration of gaskets and seals	Medium	
		- Dirt/dust intrusion	Medium	
Valves	- Internal water flow	- Erosion of internals - Corrosion of internals	Low Low	Valves are made of stainless steel which is resistant to these mechanisms.
		- Deterioration of gaskets and seals	Medium	
	- Stroking of the valve	- Wear of packing	High	Wear of valve packing is a common aging problem.
		- Wear of internals	Medium	
		- Adjustment drift of switches/linkages	Medium	
		- Galling/binding of internals	Low	
		- Distortion/fatigue of internals	Low	
		- Short/burnout of motor operator	Low	

Table 3.1 Stresses for Containment Spray System Components (Cont'd)

Component	Stress	Aging Mechanism	Probability	Comments
Valves (Cont'd)	- Exposure to external environment	- Deterioration of gaskets and seals	Medium	
		- Deterioration of MOV motor insulation/ electrical connections	Medium	High temperatures and humidity can cause breakdown of insulation and corrosion of electrical connections.
Instruments Controls	- Normal operation	- Calibration drift	High	Calibration drift is a common aging problem.
		- Deterioration of electrical components	Medium	
		- Wear of internals	Low	
	- Exposure to external environment	- Deterioration of electrical connections	Medium	High temperatures and humidity can cause breakdown of insulation and corrosion of electrical connections.
Circuit Breakers	- Breaker cycling	- Wear/fatigue of internals	High	Fatigue of pole shaft welds has been a problem.
		- Misalignment of internals	Medium	
		- Deterioration of electrical contacts	Medium	Arcing of contacts can cause pitting.
	- Exposure to external environment	- Deterioration of electrical connections	Low	
		- Dirt/dust intrusion	Low	
Heat Exchangers	- Internal water flow	- Fouling/blockage	High	Fouling/plugging of tubes is a common aging problem.
		- Corrosion of internals	Medium	Most tubes are made of copper or nickel alloys, which have good corrosion resistance.
		- Deterioration of gaskets and seals	Medium	
		- Erosion of internals	Low	
		- Tube vibration	Low	
	- Internal water pressure	- Fatigue/deformation of internals	Low	

4. ANALYSIS OF NATIONAL DATABASE OPERATING EXPERIENCE

To characterize the effects of aging on the containment cooling system, several sources of data were analyzed. These include the Nuclear Plant Reliability Data System (NPRDS) and Licensee Event Reports (LERs), which are national databases. In addition, plant specific data were obtained to supplement and validate the national database findings. This section presents the results of the national database analyses. The results of the plant specific data analyses are presented in Section 5.

4.1 Data Analyzed

A search of the NPRDS database was performed covering the five and one-half year period from January 1986 to June 1991. This search produced approximately 2500 records related to failures of the containment cooling system. In this analysis, any event which required the component to be taken out of service for corrective maintenance was considered to be a failure. In some cases, the component may still have been able to perform its design function, such as a valve with excessive packing leakage. These events were classified as failures since the component was removed from service and was unavailable, which may be significant to system reliability. In addition, the component condition could worsen, if left uncorrected, and result in catastrophic failure at a later date.

The failure records were divided into two categories, corresponding to the systems performing the containment cooling function, and a separate analysis was performed on each. These categories are the containment spray system (approximately 1400 records), and the containment fan coolers (approximately 800 records). Records related to suppression pool cooling (approximately 300) were not analyzed, as discussed previously. The analyses performed involved a detailed review of each record to determine whether the failure was related to aging, and, if so, to identify the aging characteristics. This information was then coded and entered into a computerized database for analysis.

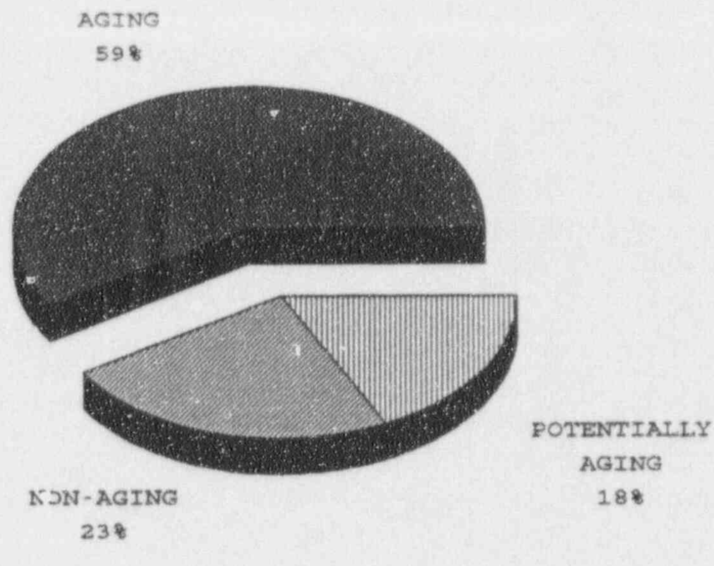
A similar approach was taken for the LER search, however, due to the relatively small number of records, the data were not computerized. The LER search covered the six and one-half year period from January 1985 to June 1991 and yielded approximately 100 events related to containment cooling systems. The analysis results are discussed in the following subsections according to the aforementioned categories.

4.2 Containment Spray System Findings

4.2.1 Fraction of Failures Related to Aging

An important question which must be answered as part of this aging analysis is whether aging degradation is a significant contributor to system failures. To provide some insight into the answer, the data were reviewed and a determination was made as to whether each failure was age related. To make this determination, the NPAR definition of aging, as described in NUREG-1144[1], was applied. By this definition, a failure is considered age related if it is the result of cumulative changes with the passage of time which, if unchecked, may result in loss of function or impairment of safety. Factors causing aging include natural internal chemical or physical processes during operation, external stresses caused by storage or operating environment, service wear, and excessive testing. Improper installation, application, or maintenance can also lead to aging degradation under certain conditions, if the degradation occurs over a period of time.

The NPRDS data indicate that aging degradation plays a major role in containment spray system failures, with 59% of the failures being age related (Figure 4.1). Typical exam-



SOURCE: NPRDS 1/86 TO 6/91

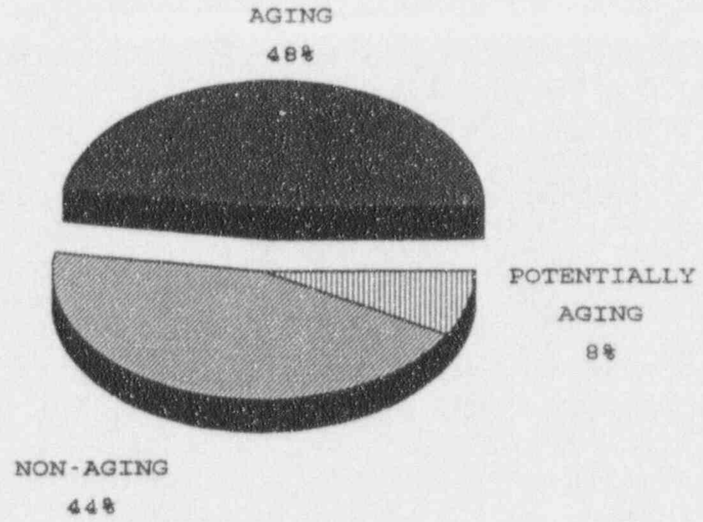
Figure 4.1 Fraction of containment spray system failures reported to NPRDS related to aging

ples of age related failures are leakage of containment spray pump shaft seals due to normal wear, or incorrect instrumentation readings due to calibration drift over a period of time. An example of a failure which would not be considered age related is failure of an isolation valve to open due to an incorrect torque switch setting. In some cases, insufficient information was available to determine whether or not the failure was related to aging. These were classified as "potentially age related" since they could have resulted from aging degradation.

The LER data show a similarly high aging contribution to failure, with 48% of the reported events being age related (Figure 4.2). The percentage of failures related to aging for the LER data is lower than that for the NPRDS data due to the large number of human error events reportable as an LER. These include administrative problems, such as failure to have certain procedures available, or failure to perform surveillance tests required by Technical Specifications. These events are reportable as LERs, however, they are not reportable to the NPRDS and are clearly not age related.

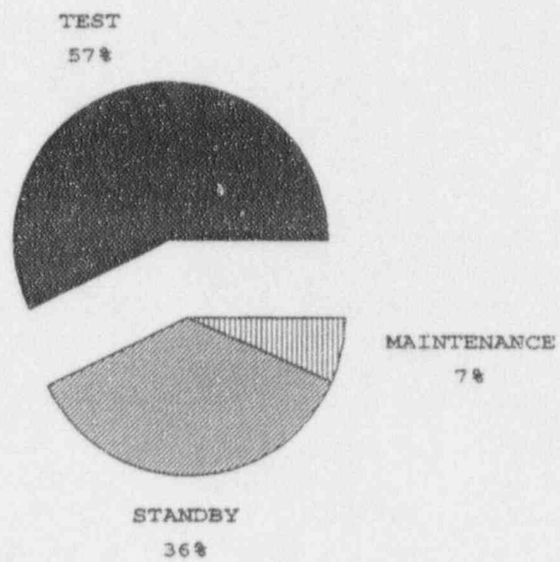
4.2.2 Failure Detection Methods

During normal plant operation the containment spray system is maintained in a standby condition, which is the condition this system spends most of its time in. Surveillance tests and maintenance, which are performed periodically, account for the remaining time. Using these three categories, the data were sorted to determine what the status of the system is when most failures are detected. The results show that most failures are detected while the system is being tested (Figure 4.3). Approximately one-third of the failures are detected while the system is in standby, and less than 10% are detected during mainte-



SOURCE: LERs 1/85 TO 6/91

Figure 4.2 Fraction of containment spray system events reported as LERs related to aging



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.3 Status of the containment spray system during failure detection nance. This shows the importance of performing surveillance tests for this predominantly standby system. Failures which may be present while the system is in standby awaiting an accident initiation signal may not be detected until the system is called into operation and it fails to perform its function.

Since the predominant number of failures are detected while the system is being tested, it is expected that the test results are the most common means of detecting failures for the containment spray system. This is confirmed by the data, which show a correspondingly high percentage of failures detected by test results (Figure 4.4). The data also show that the failure detection method most useful while the system is in standby is inspections, which includes system walkdowns. This includes planned inspections, which are performed on a routine basis, as well as unplanned inspections or casual observations. This shows the importance of having trained personnel available to monitor equipment and determine whether they are operating properly using only visual or audible information. Detection methods used to a lesser degree are maintenance actions, alarms, and operational abnormalities.

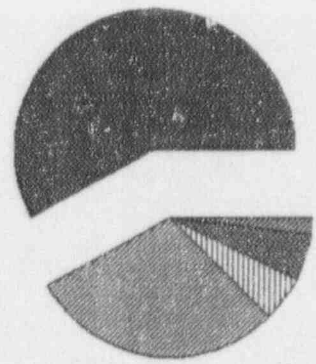
The LER data support the results of the NPRDS data showing the largest percentage of failures are detected using test results (Figure 4.5). This is followed by inspections and, an additional detection method found only in the LER data, engineering analysis. Analysis can detect potential failures, for example, when a review is performed to determine if the system design is sufficient to meet criteria assumed in the safety analysis. On occasion, design inadequacies are found which would prevent the system from performing its function. For example, a design review discovered that the logic circuitry design for the system would have prevented the containment spray system from operating in the recirculation mode if the reactor water level were too low. This is considered a failure since the system would not have operated according to design. However, it is not considered age related.

4.2.3 Failure Causes

To address failure causes at the system level, the data were sorted into three broad categories; namely, normal service, human error, and other. Normal service includes exposure to any stresses the component would normally be expected to see during the course of everyday operation. This could include, for example, wear of pump shaft seals due to pump operation, or corrosion of valve internals due to exposure to poor quality water. Failures caused by normal service are typically age related. Failures caused by human error include improper or lack of maintenance, installation errors, and operational errors. Failures classified as "other" include those caused by failures of other components or systems, manufacturing and design errors, or failures for which the cause could not be determined.

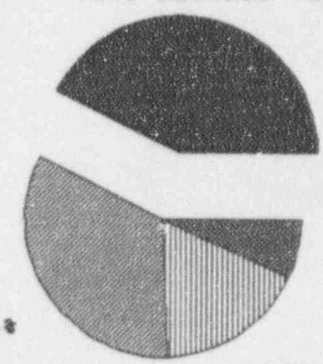
The data indicate that normal service is the predominant failure cause, accounting for 74% of the failures (Figure 4.6). This supports the high aging fraction discussed previously. Human error contributes to approximately 19% of the failures. The breakdown of human error failures presented in Figure 4.6 shows that most human errors are in the area of maintenance. This includes maintenance which was not performed properly and subsequently resulted in component failure, or maintenance which was not performed when required. These findings indicate that failures due to human error can be reduced by focusing on improvements in current maintenance practices.

The LER data analysis shows that normal service is also the predominant cause of failure (Figure 4.7) This supports the



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.4 Detection methods for containment spray system failures reported to NPRDS



SOURCE: LERs 1/85 TO 6/91

Figure 4.5 Detection methods for containment spray events reported as LERs

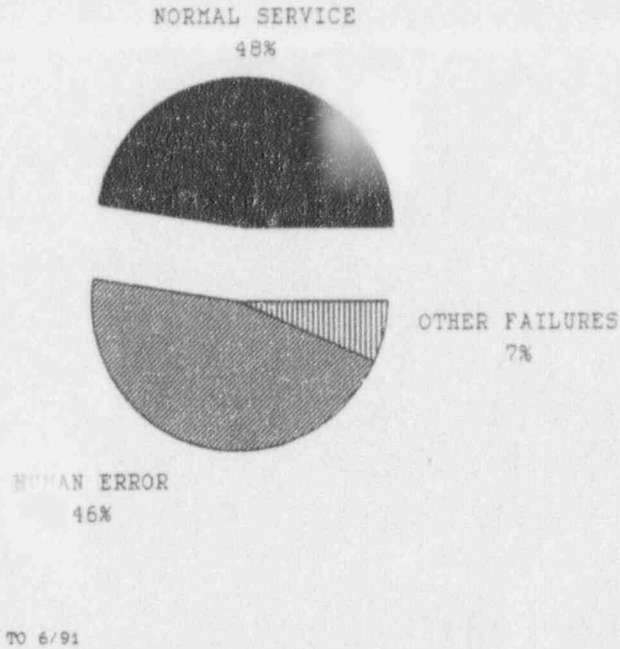


Figure 4.6 Causes of containment spray system events reported as LERs

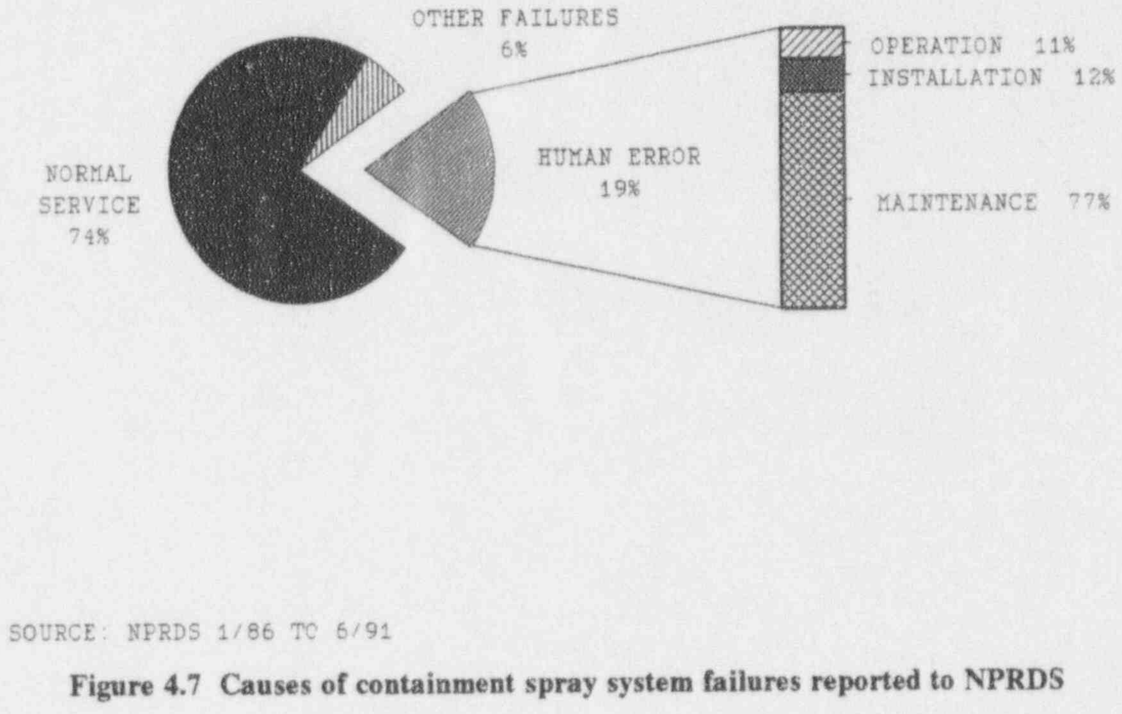


Figure 4.7 Causes of containment spray system failures reported to NPRDS

results of the NPRDS data analysis. Again, the percentage of failures attributed to human error is higher than that observed in the NPRDS data due to the types of events reportable as LERs.

4.2.4 Effect of Failures on System Performance

The effect of the failures on system performance was identified by sorting the data into three distinct categories. Degraded operation implies that the system could still perform its function although its performance was degraded. This would apply to failures such as pump seal leaks which were not severe enough to cause the pump to fail to run. The pump is still considered operable, however, some corrective action would have to be taken or the failure would worsen and eventually lead to complete loss of operation of the component. Loss of redundancy implies that one train of the system was unavailable to perform its function. Since the systems have redundant trains, the system function would still be available. The third category is for failures which had no effect on system performance. In the data analyzed (1986 to 1991), there were no failures found in which the containment spray system function was totally unavailable.

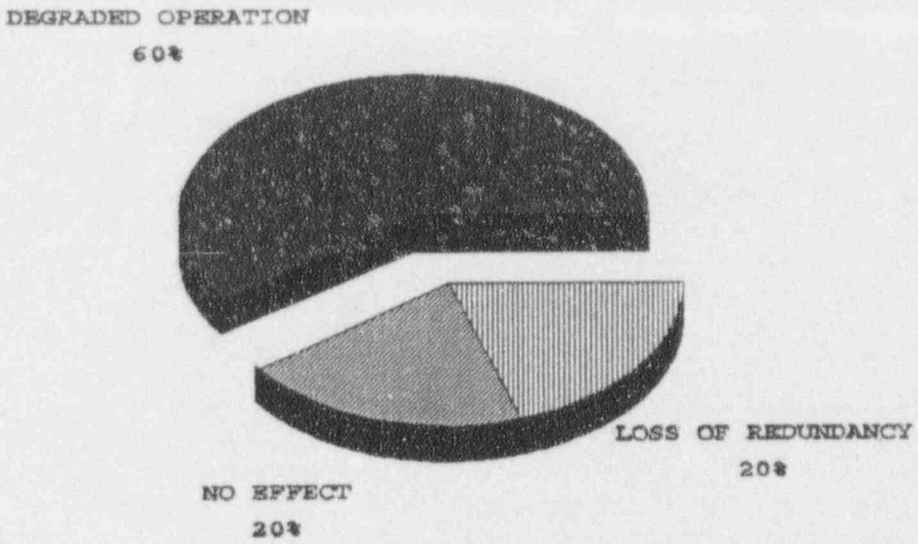
The data show that the predominant number of failures result in degraded operation of the system (Figure 4.8). The remaining failures either have no effect on system performance (20%), or result in a loss of redundancy (20%). These findings indicate that the failures occurring in the containment spray system typically are not severe enough to cause a complete loss of system function. However, they can affect the availability and reliability of the system. In particular, failures resulting in a loss of redundancy have a direct effect on system reliability since a single failure can result in loss of system function if one of two trains is already failed.

To provide more insight into the consequence of the failures, the data were further sorted to identify the system function that was affected by each failure. To do this, the containment spray system was broken down into five main functional groups. These are delivery, which includes the function of piping, nozzles, and valves to deliver cooling water to the proper location; monitoring, which involves the proper functioning of instrumentation; pumping, which requires proper operation of pumps and motors; chemical addition, which is performed by the chemical injection system; and cooling, which involves proper operation of heat exchangers and cooling water supplies. As shown in Figure 4.9, delivery of cooling water was the system function most often affected by component failures.

4.2.5 Containment Spray Components Affected by Aging

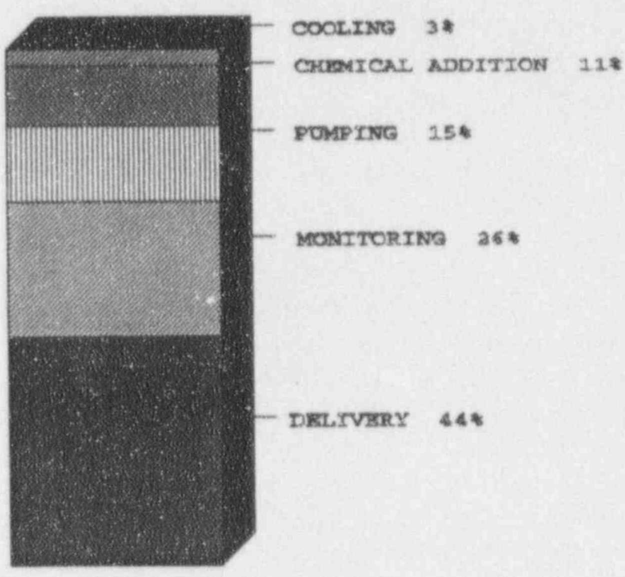
To provide a better understanding of how aging degradation affects the containment spray system, the NPRDS data were analyzed to identify the components most frequently failed. The results show that valves account for the predominant number of failures in the system (Figure 4.10). This is believed to be primarily due to the large population of these components. These data were not normalized to account for population effects since the intent of this analysis is to identify areas where additional effort is needed to control aging degradation, and not to calculate failure rates. Instrumentation and controls are the second most frequently failed components, followed by circuit breakers, pumps, and heat exchangers.

As a comparison with the NPRDS findings, the LER data were also sorted based on components. The findings showed valves to be the predominant contributor to LERs (Figure 4.11). This is consistent with the NPRDS findings and confirms the fact that



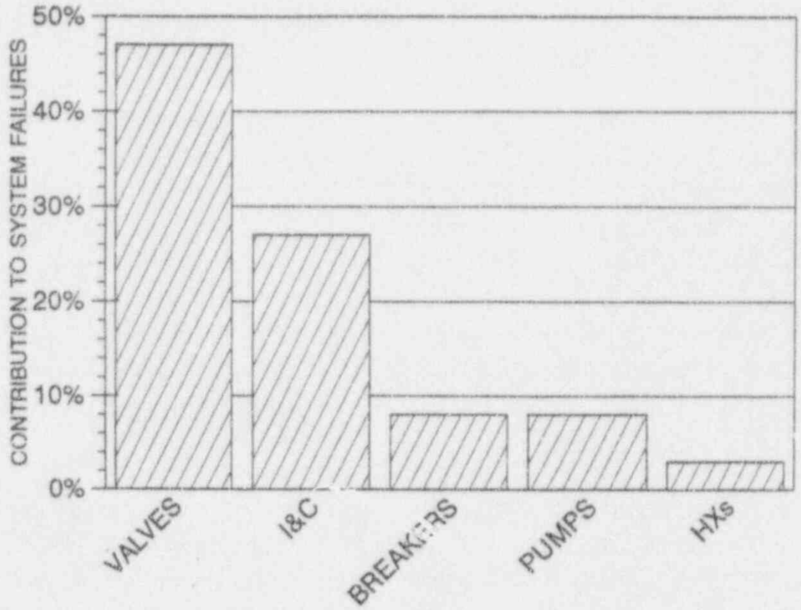
SOURCE: NPRDS 1/86 TO 6/91

Figure 4.8 Effect of containment spray system failures reported to NPRDS



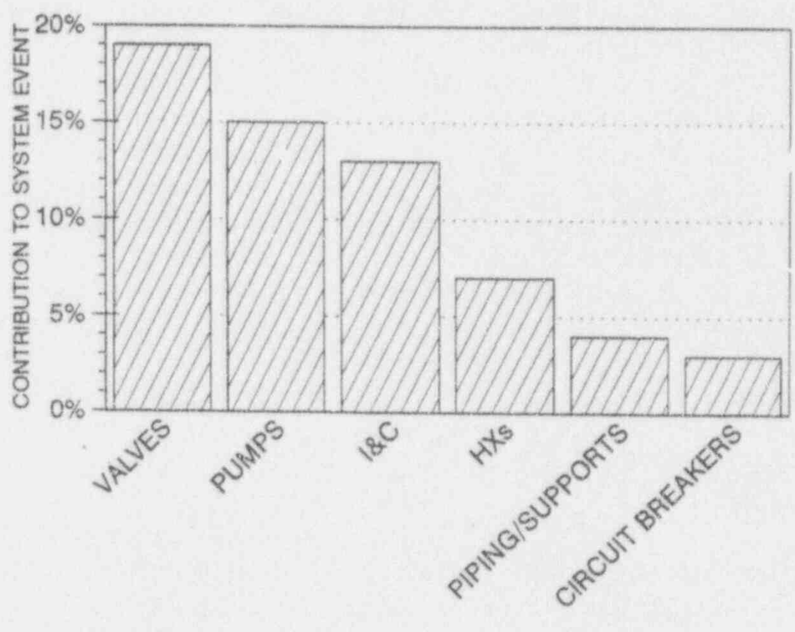
SOURCE: NPRDS 1/86 TO 6/91

Figure 4.9 Functions of containment spray systems affected by failures



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.10 Most frequently failed containment spray system components reported to NPRDS



SOURCE: LERs 1/85 TO 6/91

Figure 4.11 Containment spray components most frequently involved in LERs

valves are involved in a large percentage of occurrences related to improper operation of the system. The LERs show pumps to be the second most frequently reported component. This is due to the relatively large number of events related to design or operational errors involving the pumps. Some examples are inability of a pump to deliver design flow due to an incorrectly personnel turning the wrong switch. These types of events are not reportable to NPRDS and are not considered age related events.

Since valves are the most frequently failed component, the data were further analyzed to identify the types of valves most often failed. As shown in Figure 4.12, motor operated valves (MOVs) are involved in the most failures. This can be attributed to the complexity of the component since it includes the valve and an operator, which itself includes a motor, gears, and switches. MOVs have also been found to be the predominant valve type involved in failures in other systems studied[3,4]. The MOVs are followed by manual valves, check valves, and air operated valves (AOVs). It should be noted that these results are not normalized, therefore, population effects contribute to the relative number of failures experienced by each valve type.

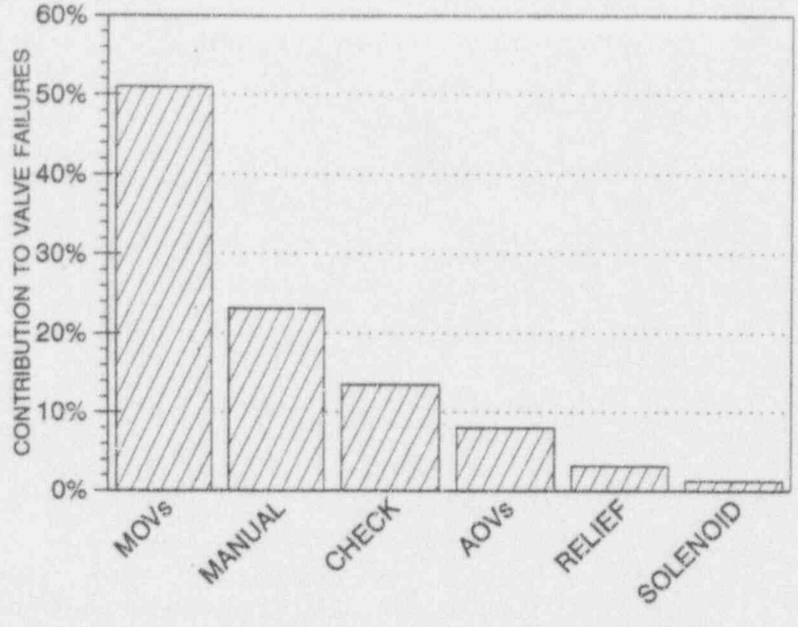
The instrumentation and control (I&C) data were also sorted to identify the types of components most frequently failed. The results show that transmitters are the predominant I&C component failed, followed by indicators/recorders, and integrators/computators (Figure 4.13). As with valves, the relative number of failures are believed to be due to population effects.

4.2.6 Aging Mechanisms and Failure Modes for Containment Spray Components

To help in understanding and evaluating ways of detecting and mitigating aging, the aging mechanisms and failure modes for the most frequently failed components were identified. This information is important since it forms a basis for determining how well current inspection, testing, and maintenance practices are able to detect aging degradation and incipient failures. In general it was found that each component has one predominant aging mechanism and failure mode. However, there are typically several others which also need to be addressed to completely control the aging process. The aging mechanisms and failure modes for each component are discussed in the following paragraphs.

As discussed previously, valves are the most frequently failed component in the containment spray system. The predominant aging mechanism for valves was found to be wear, which is a time-dependent process resulting from normal operation of the component (Figure 4.14). As an example of a typical valve failure attributed to wear, one plant reported seat leakage of a containment spray header isolation control valve (air operated butterfly valve). Investigation found the valve liner was worn out and the valve disc-to-shaft taper pin holes were elongated to the point where the disc would wobble on the shaft. This was attributed to normal wear, and the valve was repaired by replacing the liner bushings, o-rings, disc, disc pins, and valve stem. As another example of valve failure due to wear, one plant reported that a containment spray pump recirculation check valve would not seat. Investigation found the valve seat and hinge degraded due to normal wear causing the clapper to stick in the midstroke position. The valve was subsequently replaced. Additional check valve aging characteristics are reported in Reference 18.

Other common aging mechanisms leading to valve failures are adjustment drift, galling/binding, and dirt/dust intrusion (Figure 4.14). Adjustment drift failures typically involve MOVs or AOVs which fail to operate due to torque or limit switches being out of adjustment. Galling/binding typically involves damage to the valve stem or corrosion of the



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.12 Types of containment spray valves most frequently failed

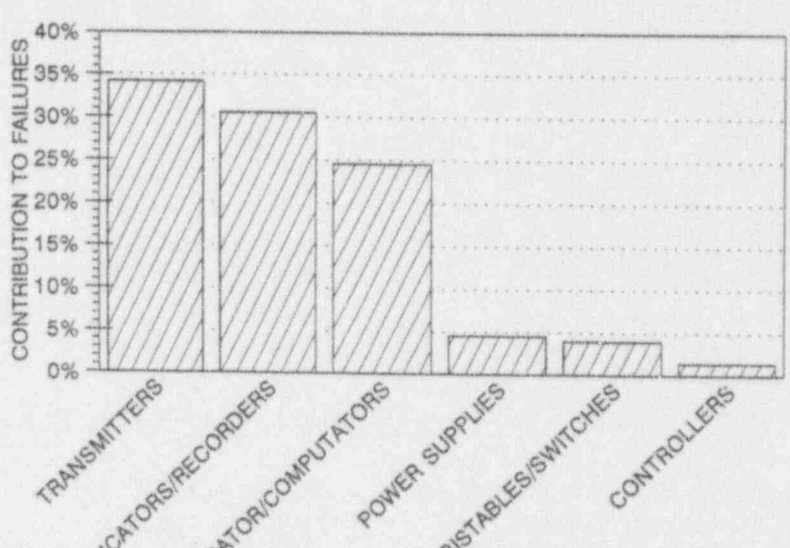


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Figure 4.13 Types of containment spray I&C most frequently failed

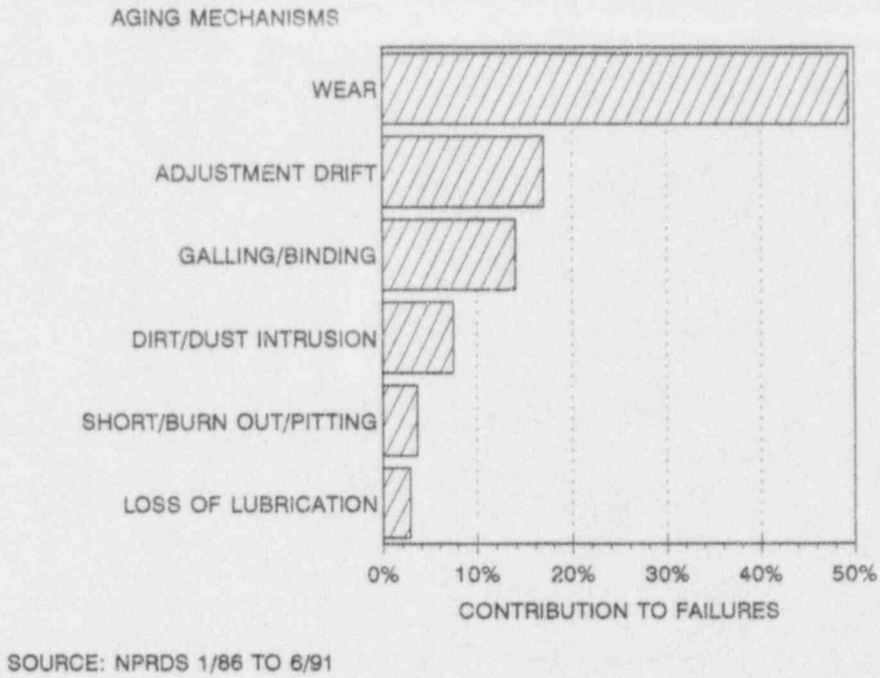
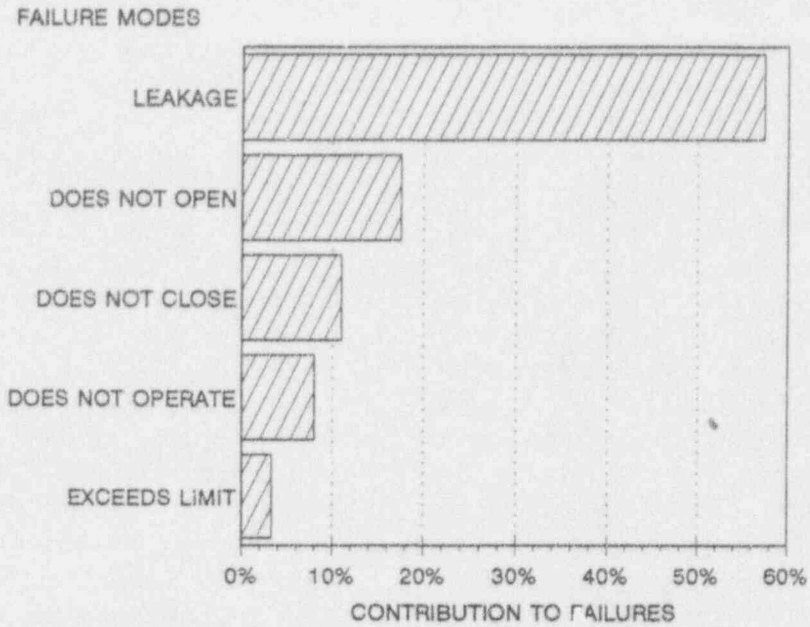


Figure 4.14 Aging mechanisms for containment spray valves

valve internals which causes the valve to bind. Dirt/dust intrusion typically involves debris being introduced into the valve which can build up between the disc and seat causing seat leakage, or can foul electrical contacts in the valve operator causing the valve to malfunction. Other less common aging mechanisms are shorting/burnout of MOV motors, and lubrication problems.

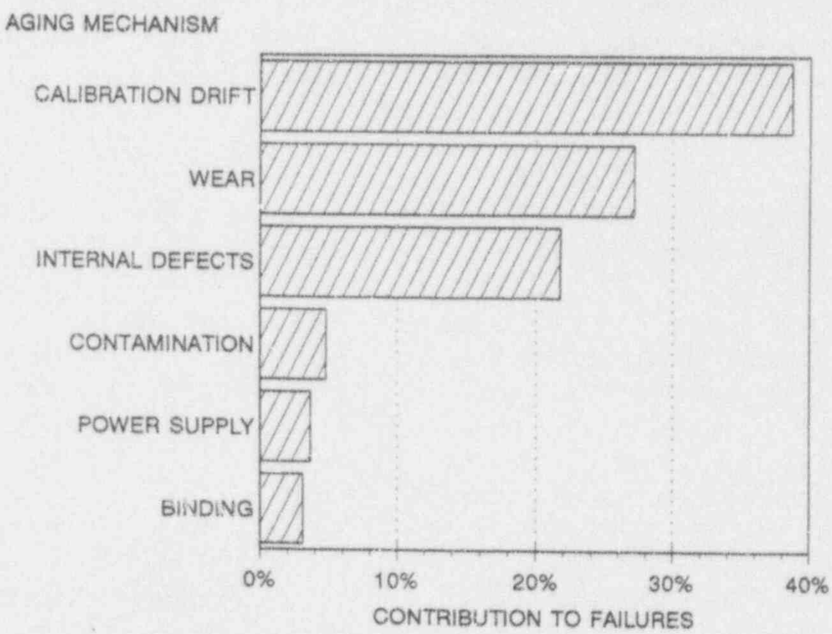
The predominant failure mode associated with valves is leakage (Figure 4.15). This includes internal leakage through the valve seat, as well as external leakage through packings or gaskets. Valve seat leakage is typically detected by tests, while external valve leakage is typically detected by visual inspections. Other common valve failure modes are failure to open, failure to close, and failure to operate (open or close). An additional failure mode applicable to relief valves is "exceeds limit", where the valve fails to open at its design set-pressure.

The predominant aging mechanism for instrumentation and controls is calibration drift (Figure 4.16). This is considered an aging mechanism since it is a process which occurs over a period of time while the component is in normal service. Calibration drift can be detected by tests or by observation of the instrument reading. It is usually corrected by recalibrating the instrumentation, however, in severe cases the instrument may need to be replaced due to extreme wear of internal parts. Other common aging mechanisms for I&C components are wear and internal defects. These can be due to cycling of the component, or exposure to heat and/or moisture which deteriorates the internal electrical components. Some of the less common aging mechanisms found are contamination from dirt or dust, problems with the power supplies, and binding of internal components. The most common failure modes for I&C components are incorrect signal and loss of function.



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.15 Failure modes for containment spray valves



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.16 Aging mechanisms for containment spray I&C components

Circuit breakers are the third most frequently failed component in the containment spray system, and the predominant aging mechanism is adjustment drift (Figure 4.17). As an example, one plant reported that during surveillance testing the circuit breaker for a spray pump failed to close on demand. Investigation found the reason to be a latch adjustment screw which was set too sensitive due to setpoint drift through normal usage. This was corrected by readjusting the screw. In another example, a plant reported a spray pump circuit breaker failed to close during testing due to a switch being out of adjustment. The switch was readjusted and the circuit breaker was returned to service. Other common aging mechanisms for circuit breakers are galling/binding, shorting/burnout/pitting, and wear. Additional aging insights are presented in References 16 and 17.

The most common failure mode for circuit breakers is failure to close, which accounted for nearly 60% of all breaker failures (Figure 4.18). The closed position is designated to be when the breaker contacts are closed allowing power to be supplied to the component. When the breaker opens, contact is broken and the power supply to the component is terminated. Other failure modes for the circuit breaker are failure to open and failure to operate.

For the containment spray pumps the most significant aging mechanism is wear (Figure 4.19). A very common failure attributed to wear is seal leaks. As an example, one plant reported that one of the containment spray pumps was found to have a seal leak during a routine inspection. This was attributed to normal wear and was corrected by replacing the seal. In another case, a plant reported that during a surveillance test a containment spray pump bearing temperature exceeded 140 °F, and there was a metallic rubbing noise coming from the pedestal bearing during coast down of the pump. Investigation found the pump to be rubbing on damaged inner wear rings. In addition, the pump shaft was out of tolerance and the impeller was out of round. This was attributed to wear due to normal pump service. The problem was corrected by rebuilding the pump. Although wear is the dominant aging mechanism for pumps, there are several others which can lead to pump failure, such as galling/binding and adjustment drift, as shown in Figure 4.19. To completely control aging degradation each of these mechanisms must be addressed.

The predominant failure mode for pumps is leakage, which is usually the result of a seal failure (Figure 4.20). The remaining pump failures typically result in failure of the pump to run, or failure of the pump to start. It should be noted that the contribution to failures shown in Figure 4.20 where the pump failed to start does not include those failures attributed to circuit breaker or motor problems. This explains why pump failure to start is lower than pump failure to run.

Although cooling coils or heat exchangers are not included in all containment spray system designs, they are susceptible to aging and can lead to system failures. Therefore, the aging mechanisms and failure modes for this component were also identified. The predominant aging mechanism is blockage/-fouling by debris (Figure 4.21). This usually involves some foreign substance, such as mussels or clams being drawn into the heat exchanger and plugging the tubes. This is typically a problem for heat exchangers cooled by service water systems which use local oceans, lakes, or rivers for cooling water. Other heat exchanger aging mechanisms are corrosion, wear, and vibration.

The predominant failure mode for the heat exchangers is plugging, which is consistent with the high percentage of failures attributed to contamination by foreign substances (Figure 4.22). The remaining heat exchanger failures manifest themselves in the form of leakage or fouling.

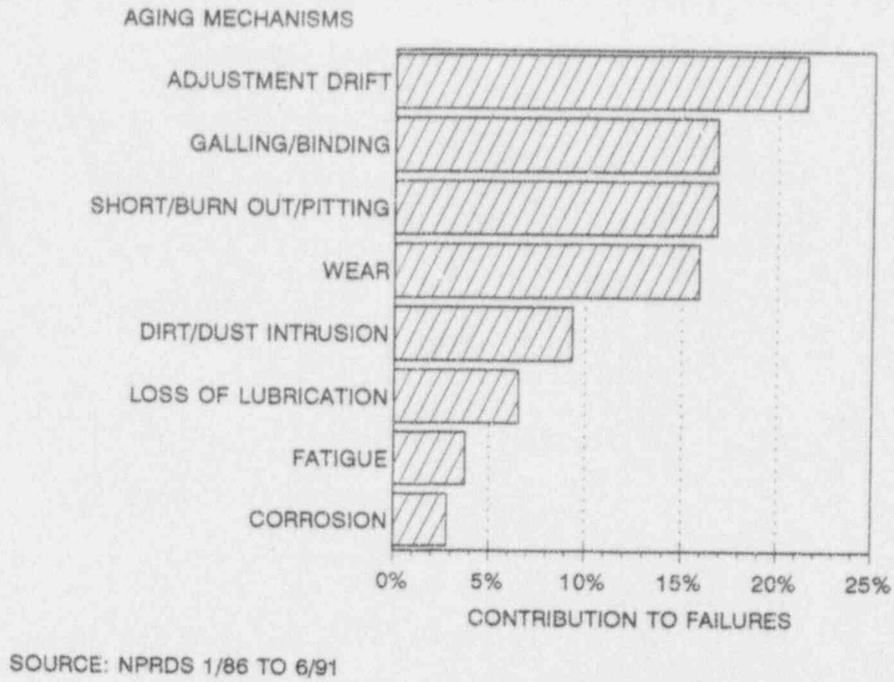


Figure 4.17 Aging mechanisms for containment spray circuit breakers

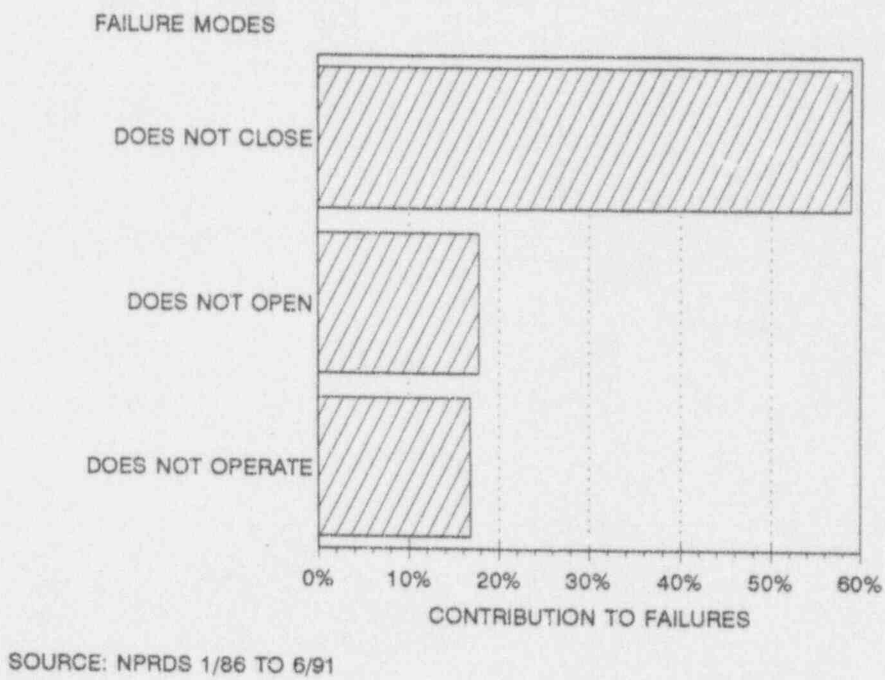


Figure 4.18 Failure modes for containment spray circuit breakers

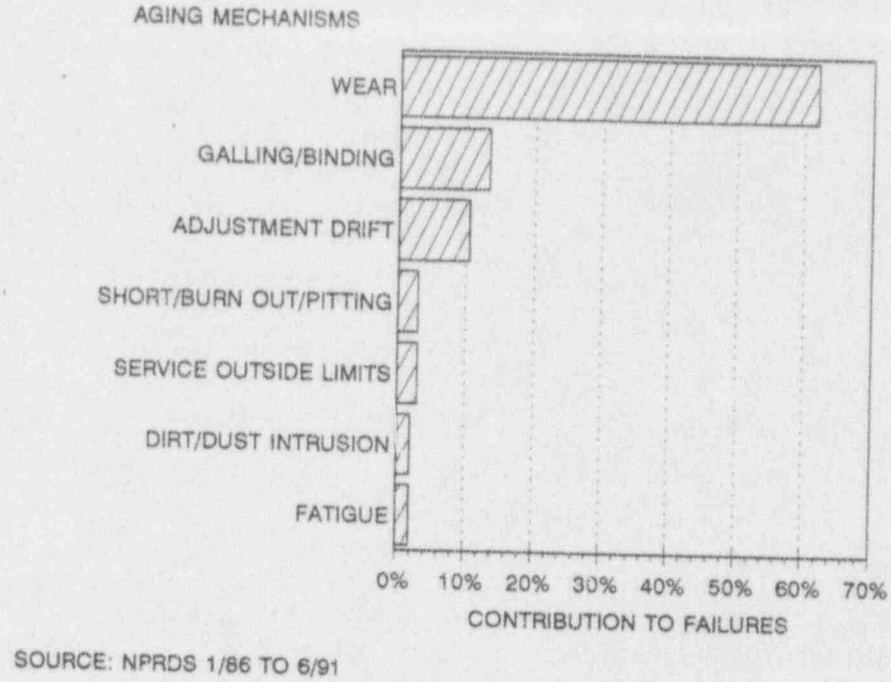


Figure 4.19 Aging mechanisms for containment spray pumps

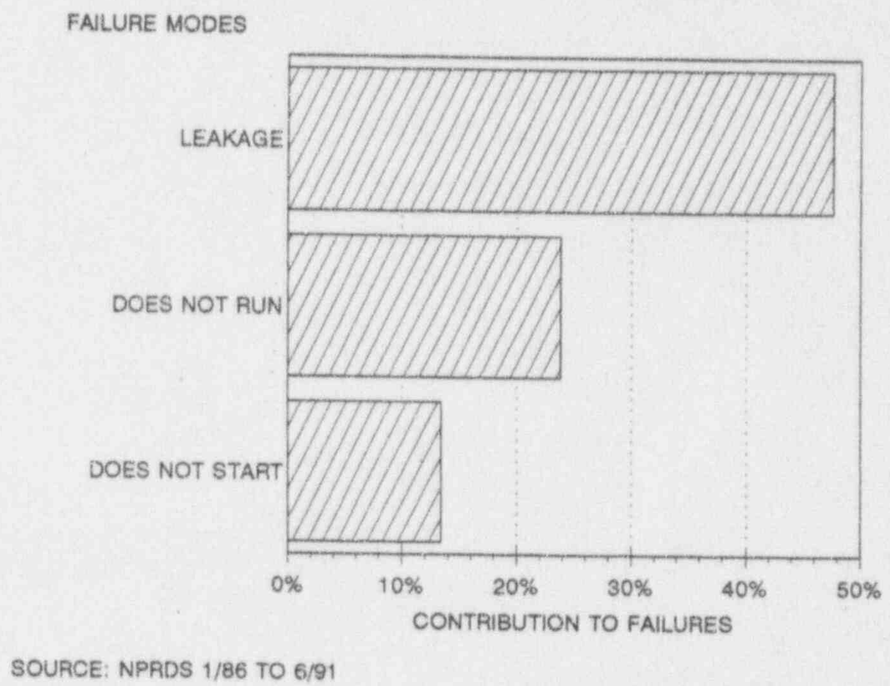
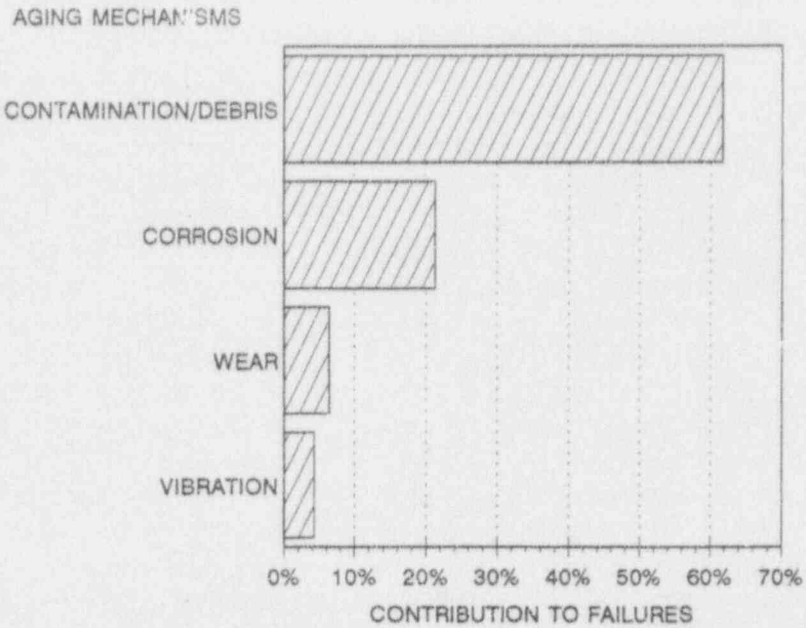
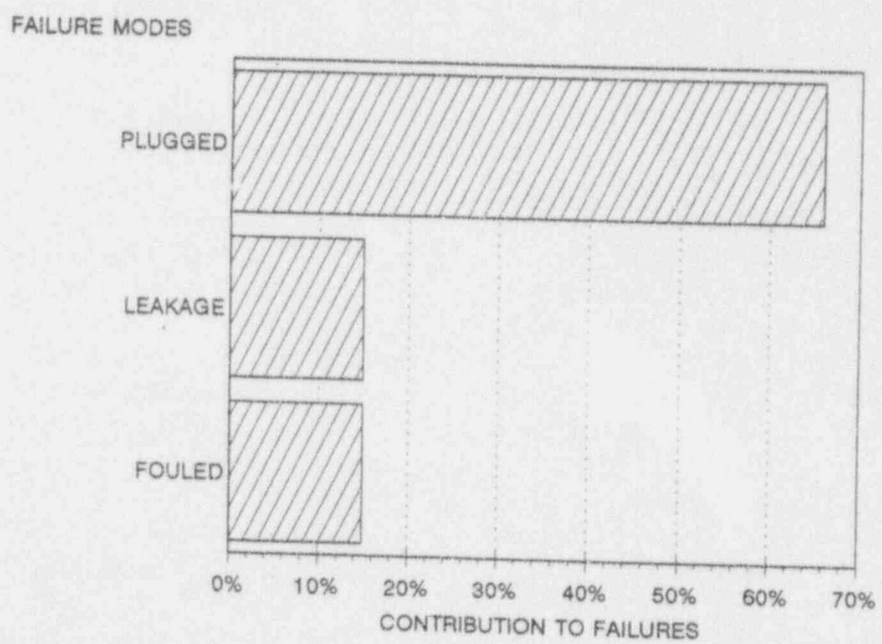


Figure 4.20 Failure modes for containment spray pumps



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.21 Aging mechanisms for containment spray heat exchangers



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.22 Failure modes for containment spray heat exchangers

4.3 Fan Cooler System Findings

4.3.1 Fraction of Failures Related to Aging

As was done for the containment spray system, the fan cooler data were sorted to identify the fraction of failures related to aging. The results indicate that aging degradation is also an important contributor to failures of the fan cooler units with over 50% of the failures related to aging (Figure 4.23). As an example of an age related fan cooler unit failure, one plant reported that low flow and high temperature alarms were received for one of the containment cooling units. Investigation found that the alarms were caused by reduced air flow through the cooling coils due to the accumulation of dirt and dust on the coils. This was corrected by cleaning the coils. In another case a plant reported that a fan motor circuit breaker failed its functional test. The breaker failed to recharge and could not close. Investigation found that the drive pawl, ratchet assembly, and pawl pivot were worn due to normal wear. These parts were subsequently replaced. These results are similar to those found in the NPAR aging study of circuit breakers.

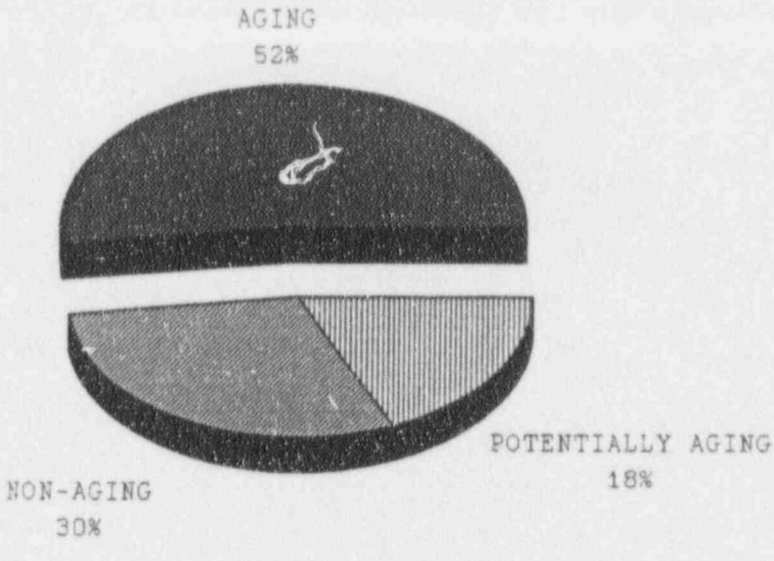
The LER data also showed a high percentage of events related to aging, however, the predominant number of events reported were found to be non-age related (Figure 4.24). As discussed in relation to the containment spray system LERs (Section 4.2.1), the large number of non-age related events can be attributed to the types of events reportable as LERs. Many of the LERs are related to administrative or procedural events which are not reportable to NPRDS. These incidents are typically not age related problems, therefore, this results in a higher percentage of LERs being classified as non-aging.

4.3.2 Failure Detection Methods

During normal plant operation the fan cooler units are used to maintain the containment temperature within acceptable limits. The number of fan cooler units in operation depends on the reactor power level. At full power operation all units may be used to provide cooling, while at shutdown conditions only one unit may be required. The fan cooler units spend the predominant amount of time either in operation or in standby. Periodically the units are removed from service for maintenance or testing.

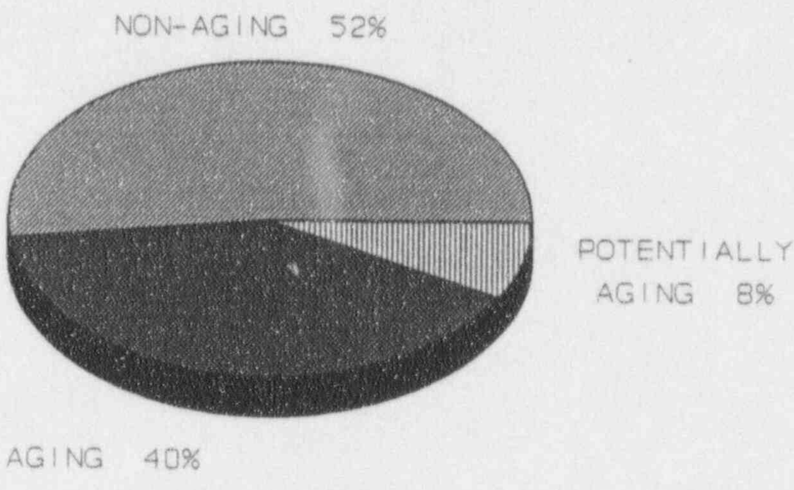
The failure data were analyzed to determine what mode the fan coolers are in when most failures are detected. The results show that most failures are detected while the units are in service (Figure 4.25). The category "in service" includes the time when the unit is actually operating, as well as the time the unit is in standby waiting for a start signal. The remainder of the failures are detected while the unit is being tested or is out for maintenance.

The methods used to detect the failures were also identified from the data. While the units are in service, operating abnormalities and inspections are the predominant methods used to detect failures (Figure 4.26). Alarms account for approximately 8% of the failures detected. While this percentage is low, it does not indicate that the system is inadequately instrumented since many of the more common failures (e.g., leaks) do not require instruments to detect. The remaining failures are detected by test results and maintenance, which is consistent with the findings for the status of the units during failure detection.



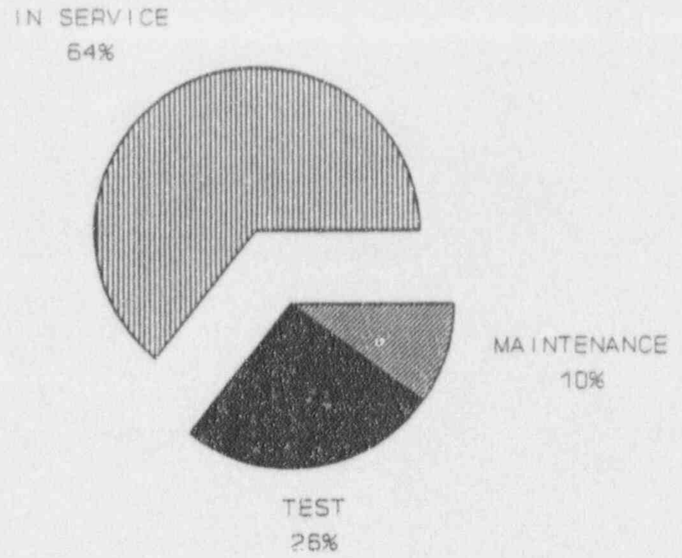
SOURCE NPRDS 1/86 TO 6/91

Figure 4.23 Fraction of failures reported to NPRDS related to aging



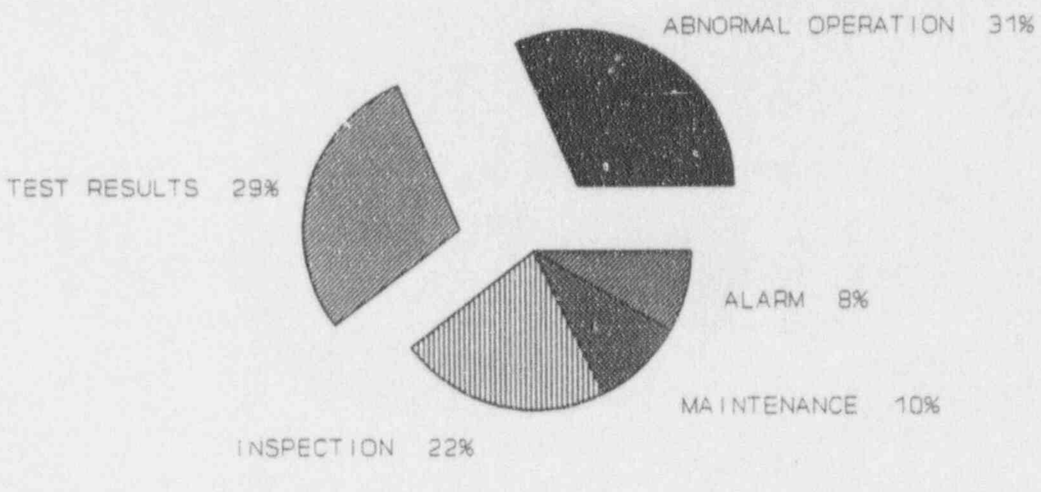
SOURCE LERs 1/85 TO 6/91

Figure 4.24 Fraction of fan cooler events reported as LERs related to aging



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.25 Status of fan coolers during failure detection



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.26 Detection methods for fan cooler failures reported to NPRDS

The LER data were also analyzed to identify the detection methods used. The results show that inspections account for the predominant number of events reported, followed by test results (Figure 4.27). As for the containment spray system, analysis is a method commonly found in the LER data base for identifying problems. This is not found in the NPRDS data base since the problems identified are typically design errors or procedural deficiencies which could potentially lead to a failure.

4.3.3 Causes of Fan Cooler Failures

The fan cooler data were sorted into the same three failure cause categories discussed previously for the containment spray system (see Section 4.2.3). The results indicate that normal service is also the predominant failure cause for fan coolers (Figure 4.28). This is consistent with the high percentage of failures related to aging, and indicates that aging management is important for fan coolers. Human errors account for approximately 23% of the failures, and these are dominated by maintenance related errors.

The LER data also show normal service to be a significant cause of failures for fan coolers, however, human error is the predominant cause in the events reported (Figure 4.29). This again is attributable to the types of events reportable as LERs. The human errors found in the LERs are related to design errors, where, for example, a component is sized incorrectly or a circuit logic would not allow a component to perform its intended function. They also include procedural errors, where, for example, required procedures are not available or they were not performed at the required frequency.

4.3.4 Effect of failures on fan cooler performance

As previously discussed, plants typically have three or more fan coolers inside containment to provide redundancy. In the event one unit fails, another available unit can be put into operation to make up for the failed unit. In cases such as this, the effect of the failure would be classified as a loss of redundancy. The containment cooling function would not be affected. In other cases, the failure may not be severe enough to cause the fan cooler unit to be inoperable. However, some corrective action is required or the condition would worsen and eventually lead to a complete failure of the unit. In these cases the failure would be classified as degraded component operation.

The data were sorted based on the aforementioned classifications to identify the effect of the failures on fan cooler performance. The predominant failure effect was found to be a loss of redundancy (Figure 4.30). This indicates that most failures are severe enough to cause a loss of function of the fan cooler unit. From this finding the importance of redundancy becomes apparent. The remainder of the failures are equally divided between causing degraded component operation and having no effect on fan cooler performance.

4.3.5 Fan Cooler Components Affected by Aging

There are a number of different components which must function properly in order for a fan cooler unit to operate. Each component can be affected by aging to a different degree. To illustrate this, the data were sorted to identify which components are most affected by aging degradation. The results show that circuit breakers supplying power to the fan cooler units are the most frequently failed component, accounting for approximately one-third of all fan cooler failures (Figure 4.31). Typical circuit breaker problems include blown fuses, worn trip units, burned contacts, worn springs, defective overload relays, and trip settings out of calibration. In addition to circuit breakers, other commonly

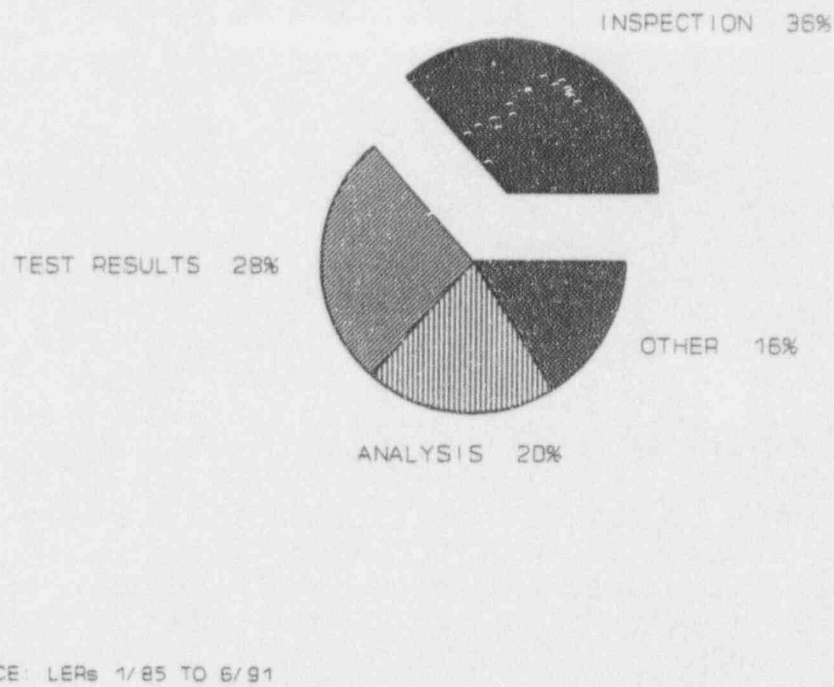


Figure 4.27 Detection methods for fan cooler events reported as LERs

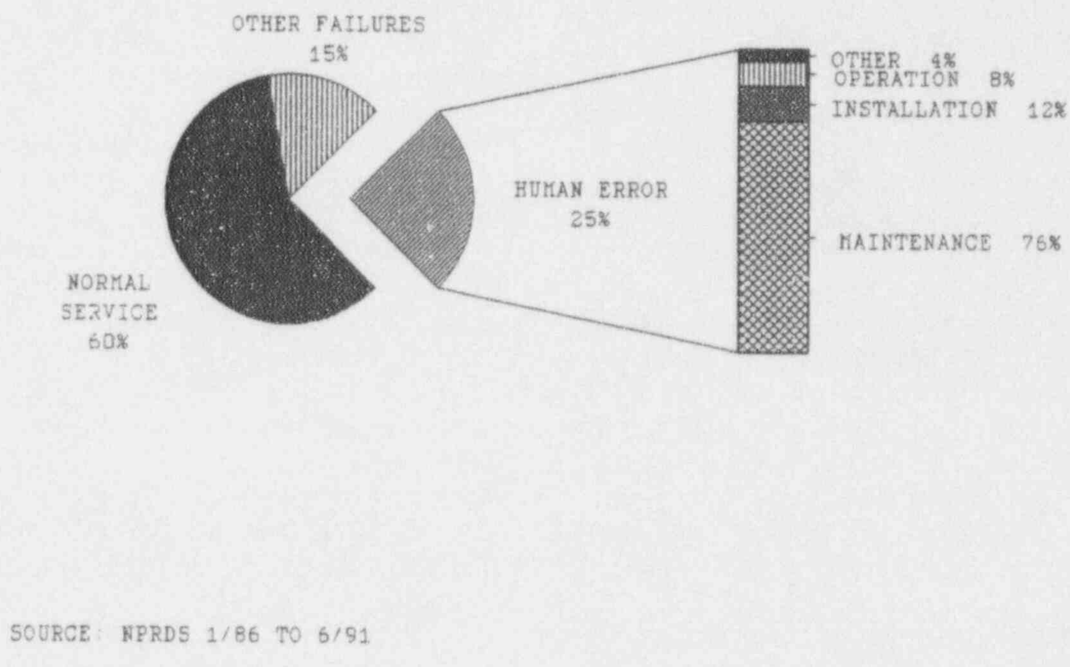


Figure 4.28 Causes of fan cooler failures reported to NPRDS

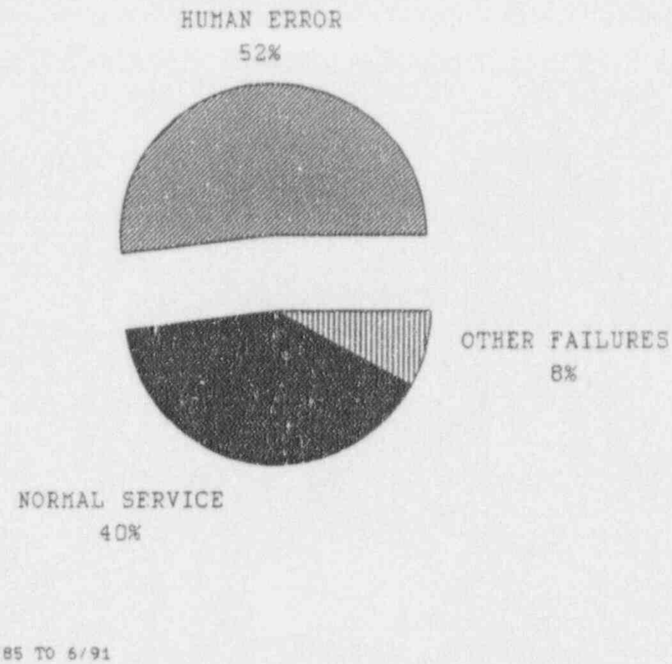


Figure 4.29 Causes of fan cooler events reported as LERs

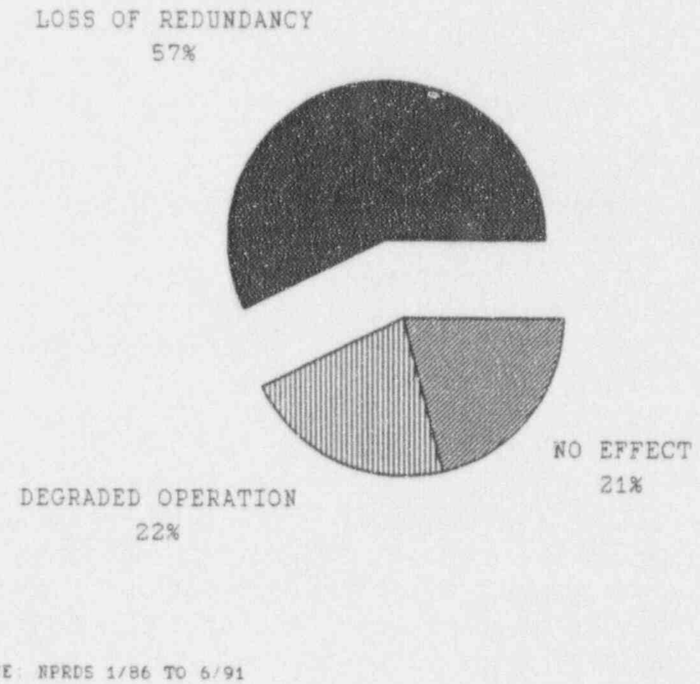
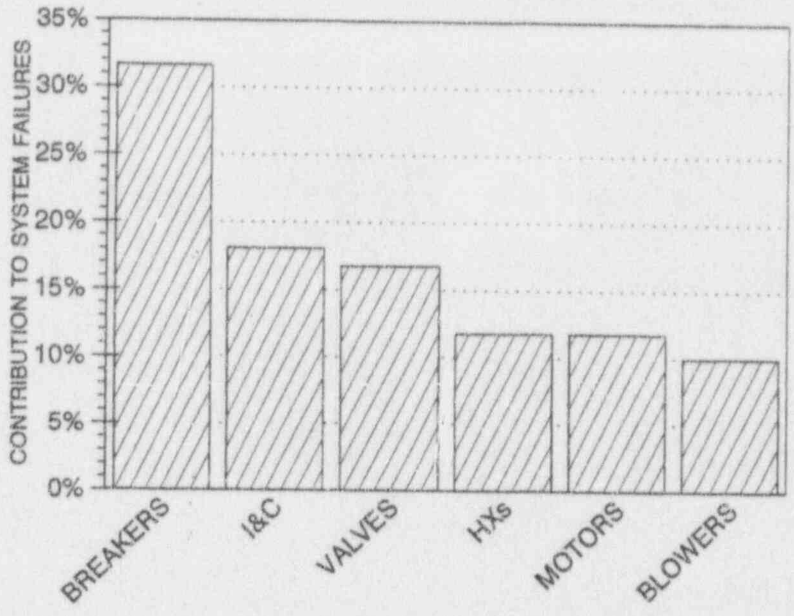


Figure 4.30 Effect of fan cooler failures reported to NPRDS



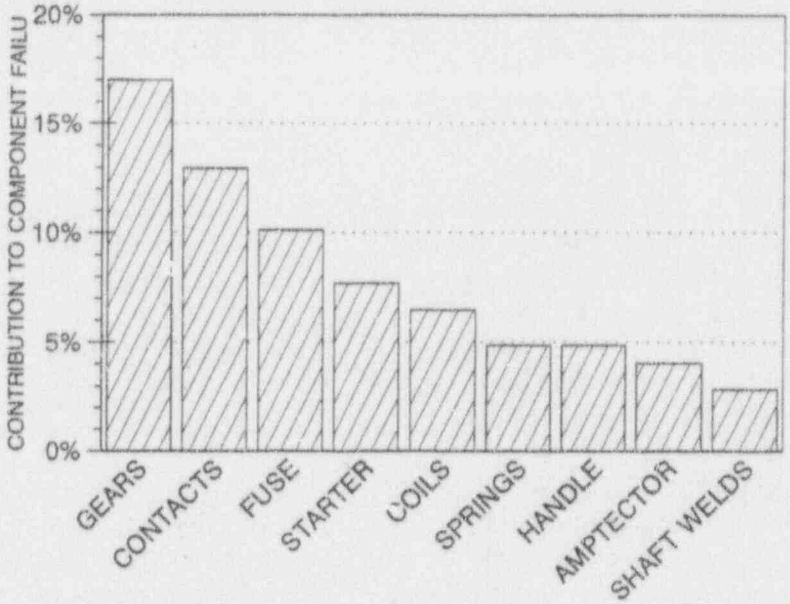
SOURCE: NPRDS 1/86 TO 6/91

Figure 4.31 Most frequently failed fan cooler components reported to NPRDS

failed components are instrumentation and controls, valves, heat exchangers (i.e., cooling coils), fan motors, and blowers.

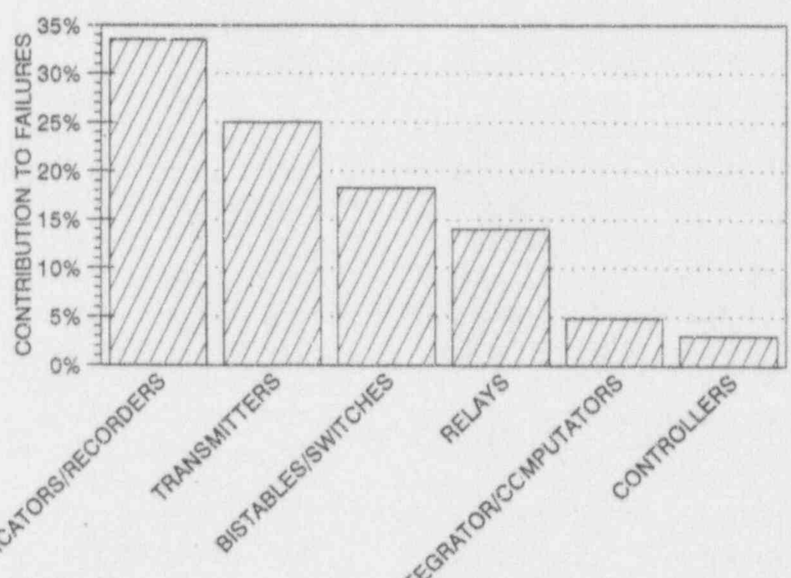
Since circuit breakers accounted for a relatively large number of fan cooler failures, an analysis was performed to identify the subcomponents in the circuit breaker which were the most problematic. The data indicate that gears/linkage were involved in the largest number of circuit breaker failures (Figure 4.32). As an example of a typical failure, one plant reported that during surveillance testing, the breaker for a containment cooler could not be charged. Investigation found that the charging motor would not charge the breaker due to ratchet wheel tooth damage. This is believed to be caused by misalignment of the holding fork. The failure was corrected by replacing the ratchet pawl assembly and associated parts. In another case, a plant reported that during surveillance testing of a fan cooler, the breaker would not close. It was subsequently found that the stationary racking pawl was riding at an angle on the spring charging gear, which caused the charging gear to move back and forth without advancing. This failure was corrected by realigning the racking pawl and tightening the retaining clip on the racking pawl. Other common circuit breaker failures involved burned or pitted contacts, degraded fuses, and defective starters.

A similar analysis was performed to identify the types of instrumentation and controls most frequently failed. Indicators and recorders account for the predominant amount, followed by transmitters, bistables/-switches, and relays (Figure 4.33). As an example of a typical indicator failure, one plant reported that a cooling coil temperature indicator operated very sluggishly. It was subsequently found that the indicator's motor bearings were bound, causing the motor to



SOURCE: NPRDS 1/86 TO 6/9ı

Figure 4.32 Most frequently failed fan cooler circuit breaker subcomponents



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.33 Types of fan cooler I&C most frequently failed

operate at less than rated speed. This was attributed to natural wear of the bearings. The failure was corrected by replacing the bearings. In another case, a plant reported that a drywell temperature recorder was printing all points erratically. Examination of the recorder found that the servo amplifier had failed. This was attributed to its natural end of life. The failure was corrected by replacing the servo amplifier. Other common I&C failures include calibration drift, short circuits, and burned contacts.

4.3.6 Aging Mechanisms and Failure Modes for Fan Cooler Components

The aging mechanisms and failure modes for the most frequently failed fan cooler components were investigated by analyzing the failure data. For some of the components it was found that one aging mechanism was predominant, while other components are equally affected by several different mechanisms. The results for each component are discussed in the following paragraphs.

The predominant aging mechanisms for circuit breakers are shorting, burnout, and pitting (Figure 4.34). These mechanisms are grouped together since they represent deterioration of electrical components. They affect several different circuit breaker components, including contacts, fuses, starters, and coils. There are also several other aging mechanisms which lead to degradation of circuit breakers. These are wear, adjustment drift, galling/binding, fatigue/cracking, and dirt/dust intrusion.

The failure modes for the circuit breakers are grouped into three categories; namely, fail to close, fail to open, and fail to operate. As shown in Figure 4.35, the predominant failure mode is fail to close, which accounted for nearly 70% of the circuit breaker failures. As a typical example of this type of failure, one plant reported that during a refueling outage operators attempted to start a containment cooling fan, however, the starter contactor was binding. This prevented the electrical contacts from closing and the fan from operating. The cause of the failure was attributed to wear out of the moving magnetic armature assembly in the starter contactor. The starter was removed and the worn armature assembly was replaced.

For the fan cooler instrumentation and controls, there were four main aging mechanisms identified in the data. These are calibration drift, wear, shorting/burnout, and contamination (Figure 4.36). Each contributes to a significant number of failures with no one mechanism being dominant. Binding is another mechanism which also leads to failures, but to a lesser degree. The dominant failure modes for I&C are incorrect readings and loss of function.

The data showed the dominant aging mechanism for the valves/dampers used in the fan cooler systems to be wear (Figure 4.37). As an example of a typical damper failure, one plant reported that upon starting a containment cooling fan the associated damper failed to operate. Investigation found that the damper motor had failed due to wear out of the damper linkages. The damper motor was subsequently replaced. The data also showed that galling/binding is a significant contributor to valve/damper failures, along with adjustment drift and fatigue/cracking. Binding typically results from misalignment or damage to the damper linkage. As an example, one plant reported that during a special inspection, a back draft damper was found stuck in the 50% open position and would not fully open or close during fan cooler operation. Investigation found that the damper blade linkages were misaligned. The failure was corrected by realigning the linkages and adding additional counter weights to assist closing.

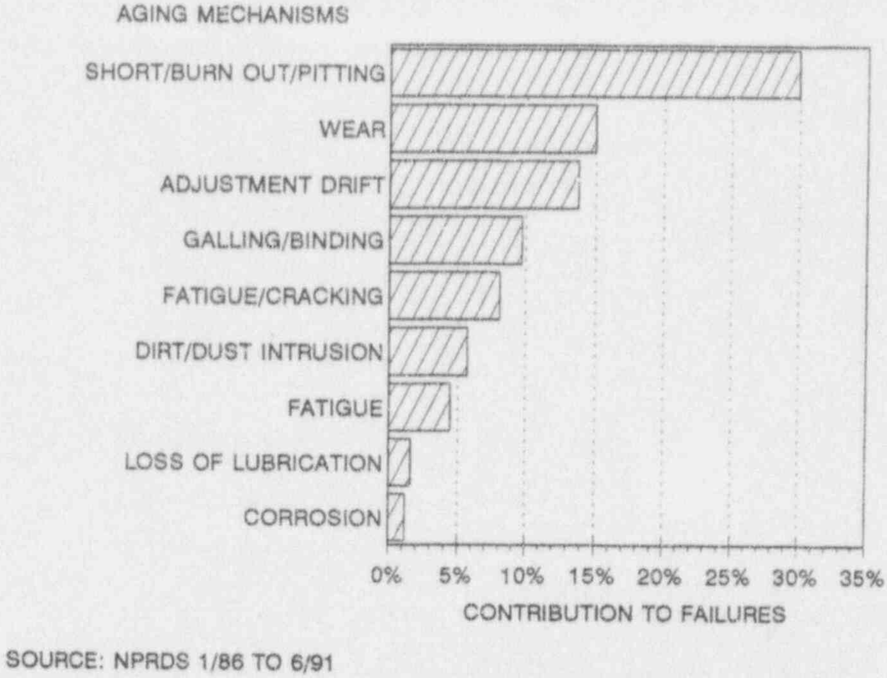


Figure 4.34 Aging mechanisms for fan cooler circuit breakers

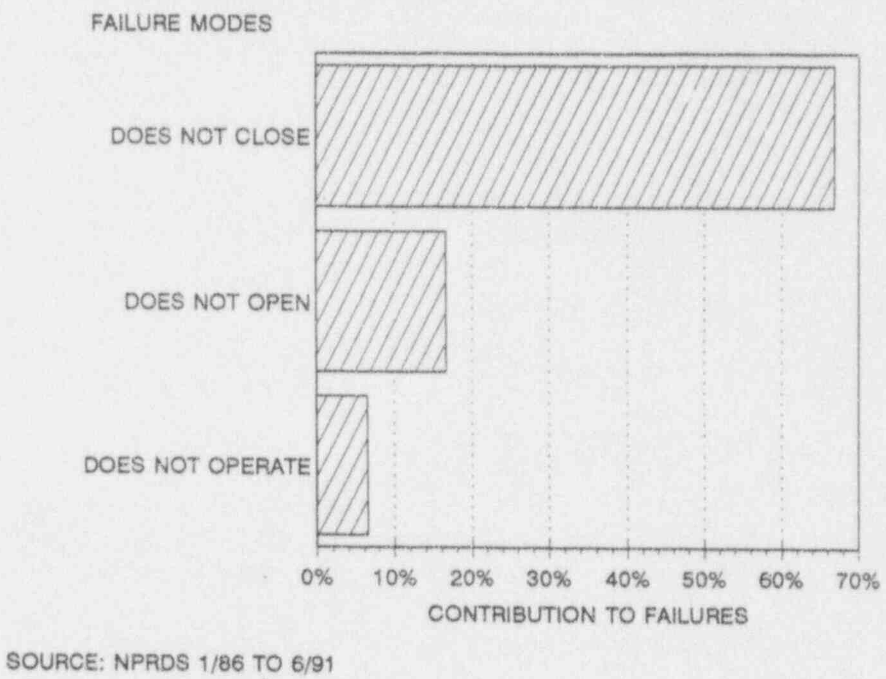
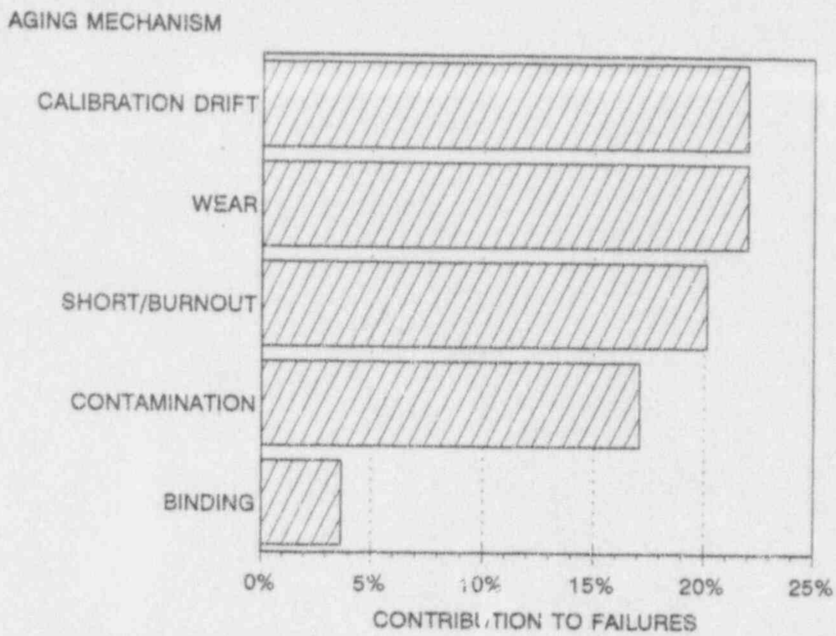
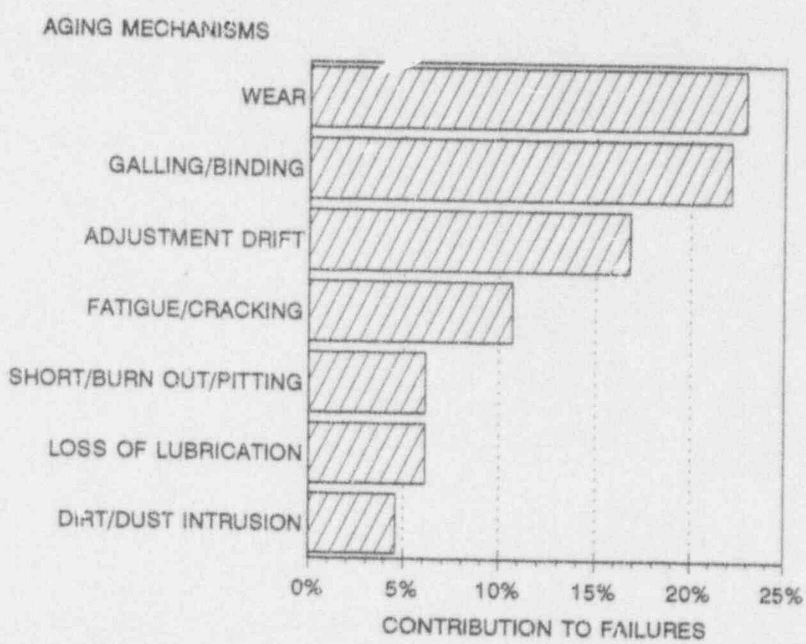


Figure 4.35 Failure modes for fan cooler circuit breakers



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.36 Aging mechanisms for fan cooler I&C components



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.37 Aging mechanisms for fan cooler dampers and valves

Another problem worth noting that was found in the data involves pneumatically operated dampers. One plant reported that with the unit shutdown for refueling, a containment inservice purge supply damper would not move from the closed position when the control board switch was activated. Investigation found that the shuttle valve supplying air to the damper actuator was leaking, which prevented station air from pressurizing the actuator. These shuttle valves have experienced accelerated aging at this plant in the containment environment, and periodic replacement is routine. A modification was subsequently initiated to replace these shuttle valves with solenoid valves in this plant. In light of this experience all plants using these shuttle valves on pneumatically operated dampers inside containment should monitor them for signs of air leakage. If accelerated aging is noted, the valve should be repaired or replaced.

The predominant failure mode for the fan cooler valves and dampers is failure to close (Figure 4.38). This failure mode is typically associated with the back draft dampers used on the fan cooler discharge. The back draft damper must close when the fan is shut down to prevent back flow through the unit, which can cause reverse rotation of the fan. The majority of these failures are due to misalignment or damage to the linkage. Other common failure modes for the dampers are failure to operate, failure to open, and leakage.

The failure data for fan cooler motors indicates that the most common aging mechanism is deterioration of electrical components. This includes shorting, grounding, and burnout of insulation and motor internals (Figure 4.39). The second most frequent aging mechanism is wear, which primarily affects the noise and vibration, and can cause motor are also subject to failure from aging mechanisms. The most common aging mechanism is contamination due to foreign material or debris entering the system (Figure 4.40). This results in plugging or fouling of the coils. Other common aging mechanisms are corrosion and vibration, which can lead to damage of the coil material and leakage. As mentioned in Section 1.5, one incident involving corrosion of cooling coils resulted in leakage of service water, and flooding of the reactor cavity.

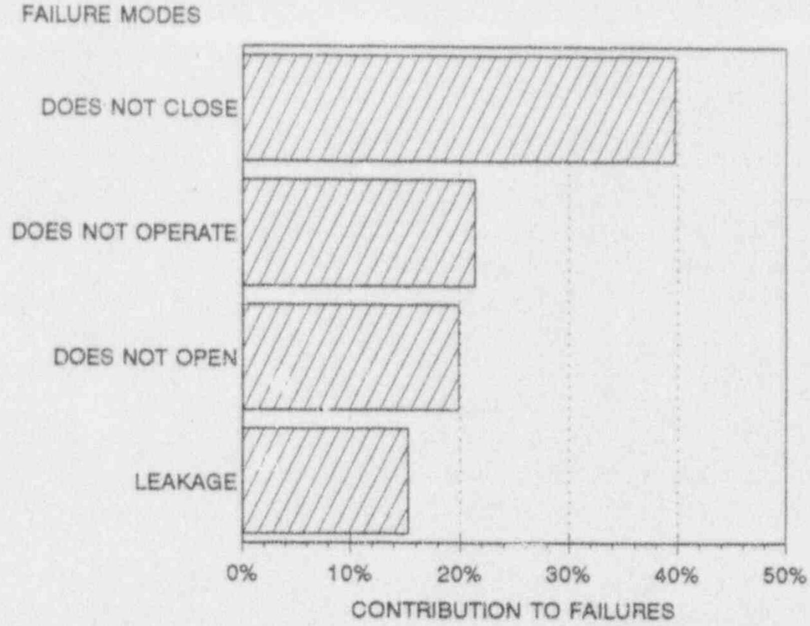
The most common aging mechanism for the fan cooler blowers is wear (Figure 4.41). This is followed by vibration and fracture/crack growth. The most common failure mode for the blowers is failure to run.

4.4 Summary of Aging Characteristics

The analyses of the national database data have identified the major aging characteristics for the containment cooling system components. This information is necessary for understanding the aging process so that it can be properly monitored and managed. The following tables summarize the findings from the data analyses.

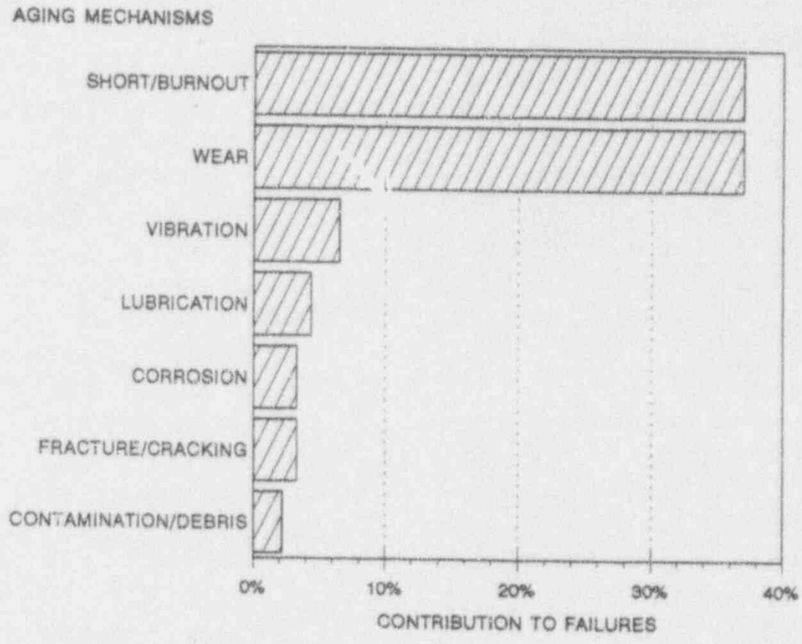
Table 4.1 presents the aging characteristics for the most frequently failed components in the containment spray system. The component relative failure frequency represents the relative frequency at which that component fails as compared to other components in the system. Similarly, the subcomponent relative failure frequency represents the relative frequency at which that subcomponent fails as compared to other subcomponents in that specific component. The relative failure mode frequency represents the frequency at which that failure mode occurs when that subcomponent fails as compared to other possible failure modes for that subcomponent.

The frequency ratings of low, medium, and high are based on the percentage of total occurrences found in the data analyzed. A frequency was judged to be high if it accounted for 50% or more of the total number of



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.38 Failure modes for fan cooler dampers and valves



SOURCE: NPRDS 1/86 TO 6/91

Figure 4.39 Aging mechanisms for fan cooler motors

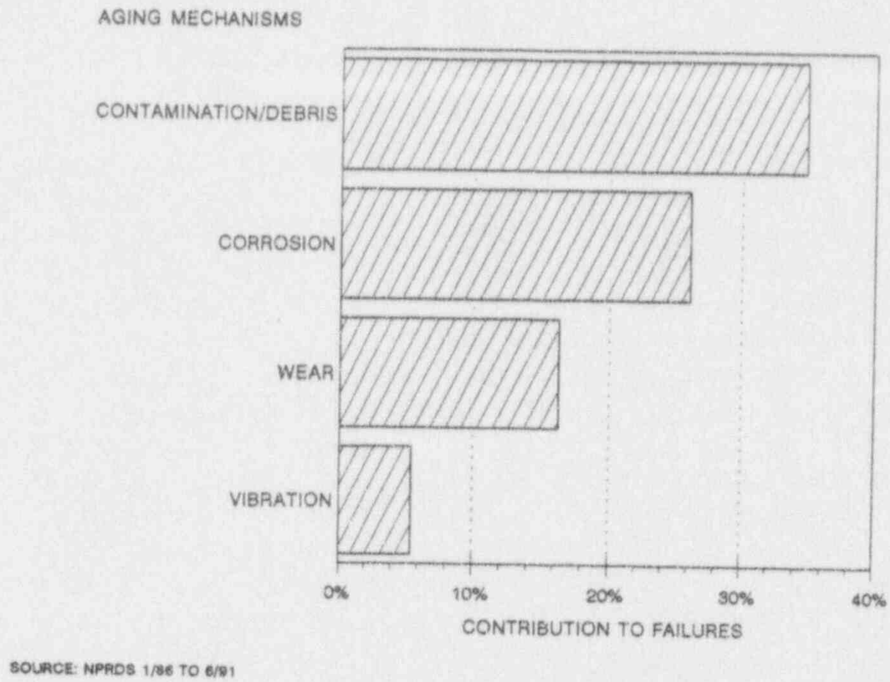


Figure 4.40 Aging mechanisms for fan cooler cooling coils

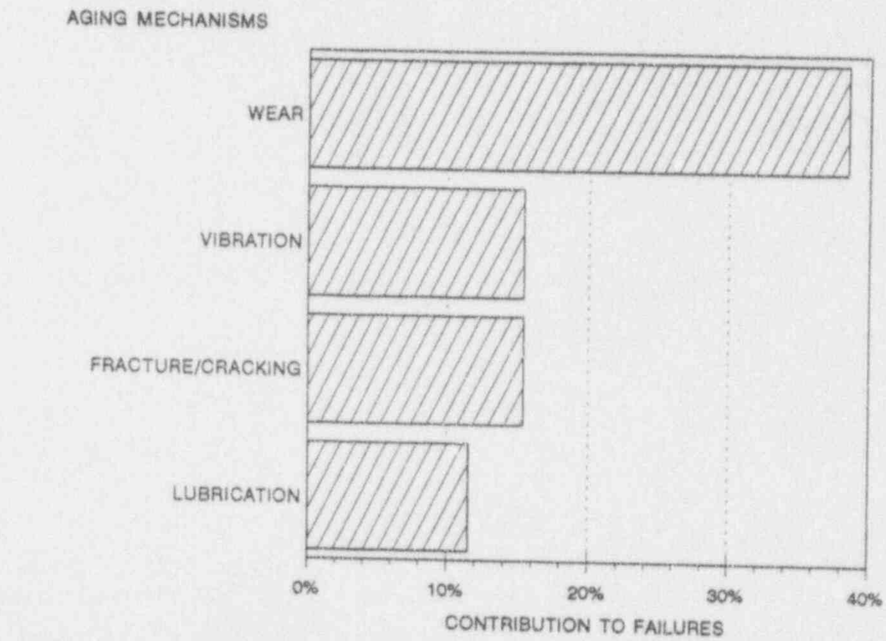


Figure 4.41 Aging mechanisms for fan cooler blowers

occurrences. A frequency was judged to be medium if it accounted for 25% to 50% of the total number of occurrences, and low if it represented less than 25% of the total. It should be noted that these ratings may not be representative of any specific plant since there are many factors which can influence these results. These findings should be considered as industry averages which can be used as a baseline for reviewing existing aging management techniques.

As an example of the interpretation of these tables, referring to Table 4.1, the first entry is for valves in the containment spray system. Their relative failure frequency is medium, which indicates that if a failure occurs in the containment spray system there is a good chance it will involve a valve. Further, if the failure does involve a valve, there is a very good chance that the failure will involve the valve packing, and a very good chance this packing problem will manifest itself in the form of external leakage. The predominant aging mechanism leading to this type of failure is wear of the packing, and it can be detected by a visual inspection. The table also shows that, instead of leakage, there is a chance that the valve packing problem will manifest itself by causing the valve not to open or close, however, the probability of this failure mode is low. This could be caused by binding or distortion of the packing, and can be detected by a valve stroke test. Entries for other components can be interpreted in the same manner.

Table 4.1 Aging Characteristics for Containment Spray System Components

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Valves	Medium	Seals/Packing	High	External Leakage	High	- Wear	- Visual inspection
				Does Not Open/Close	Low	- Binding - Distortion	- Valve stroke test
		Seats	Medium	Internal Leakage	High	- Wear - Corrosion - Erosion - Dirt/Crud Buildup	- Valve leakage test
				Does not open/close	Low	- Binding - Dirt/crud buildup	- Valve stroke test
		Stem/linkage	Low	Does not open/close	High	- Wear - Binding - Poor lubrication	- Stroke test
				External leakage	Medium	- Galling - Nicking	- Visual inspection
Valve Operator	Medium	Torque switch	Medium	Does not open/close	High	- Setpoint drift - Short/ground - Wear - Dirt/dust intrusion	- Valve stroke test - Valve leakage test
		Gears	Low	Does not open/close	High	- Wear - Poor lubrication - Fatigue - Fracture/cracking	- Valve stroke test - Visual inspection
		Motors	Low	Does not open/close	High	- Short/burnout - Wear - Dirt/dust intrusion - Deterioration of insulation	- Valve stroke test - Motor current signature analysis - Motor insulation resistance test

Table 4.1 Aging Characteristics for Containment Spray System Components (Cont'd.)

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Valve Operator (cont.)		Limit switch	Low	Does not open/close	High	- Wear - Out of adjustment - Dirt dust intrusion - Short/ground	- Valve stroke test
		Solenoid	Low	Does Not Open/Close	High	- Binding - Dirt/dust intrusion - Short/burnout	- Valve stroke test
		Diaphragms	Low	Does not open/close	High	- Wear - Deterioration	- Valve stroke test
Instrumentation/ Controls	Medium	Transmitter	Medium	Incorrect signal	High	- Calibration drift - Short/ground - Deterioration - Dirt/dust intrusion	- Visual inspection - Functional test
		Indicator/ Recorder	Medium	Incorrect signal	High	- Calibration drift - Short/ground - Deterioration - Dirt/dust intrusion	- Visual inspection - Functional test
		Integrator/ Computator	Medium	Incorrect signal	High	- Calibration drift - Short/ground - Deterioration - Dirt/dust intrusion	- Functional test
		Relays/ Bistables/ Switches	Low	Loss of function	High	- Wear - Deterioration - Dirt/dust intrusion - Short/ground	- Functional test
		Power Supply	Low	Loss of function	High	- Short/burnout - Wear - Dirt/dust intrusion - Deterioration	- Functional test

Table 4.1 Aging Characteristics for Containment Spray System Components (Cont'd.)

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Circuit Breakers	Medium	Contacts	Medium	Does not open/close	High	- Wear - Out of adjustment - Dirt dust intrusion - Binding - Corrosion - Burnout/pitting	- Visual inspection - Functional test
		Gears	Low	Does Not Open/Close	High	- Binding - Out of adjustment - Fatigue - Fracture/crack - Wear	- Visual inspection - Functional test
		Overload Relays	Low	Breaker Trip	High	- Wear - Deterioration - Fatigue - Dirt/dust intrusion	- Visual inspection - Functional test
		Delay Timer	Low	Failure to trip when required	High	- Calibration drift - Short/ground - Deterioration - Dirt/dust intrusion - Wear	- Visual inspection - Functional test
		Handle/ Control Switch	Low	Does not open/close	High	- Wear - Fatigue/cracking - Binding - Deterioration - Poor lubrication - Short/burnout	- Visual inspection - Functional test

Table 4.1 Aging Characteristics for Containment Spray System Components (Cont'd.)

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Pumps	Low	Shaft Seals	Medium	Leakage	High	- Wear - Dirt dust intrusion - Deterioration	- Visual inspection - Functional test
				Does Not Run	Low	- Binding - Out of adjustment - Distortion - Wear	- Visual inspection - Functional test - Shaft torque measurement
		Gaskets	Low	Leakage	High	- Wear - Deterioration	- Visual inspection - Functional test
		Bearings	Low	Does not run	Medium	- Deterioration - Dirt/dust intrusion - Wear - Poor lubrication - Binding	- Visual inspection - Functional test - Vibration measurements - Excessive noise - Lube oil analysis
				Leakage	Low	- Wear - Deterioration - Poor lubrication	- Visual inspection - Functional test

Table 4.2 Aging Characteristics for Fan Cooler Unit Components

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Valves/Dampers	Low	Stem/linkage	High	Does not open/close	High	- Wear - Binding - Poor lubrication	- Valve stroke test - Visual inspection
		Seats	Low	Internal Leakage	High	- Wear - Corrosion - Erosion - Dirt/Crud Buildup	- Valve leakage test
		Bolts/ Fasteners	Low	Does not open/close	High	- Vibration - Fatigue - Fracture/cracking	- Visual inspection
		Louvers	Low	Does not open/close	High	- Fatigue - Wear - Fracture/cracking	- Visual inspection - Functional test
		Seals	Low	External leakage	High	- Wear - Deterioration	- Visual inspection - Functional test
Valve Operator	Low	Diaphragm	Medium	Does not open/close	High	- Deterioration - Wear	- Valve stroke test - Valve leakage test
		Solenoids	Medium	Does not open/close	High	- Wear - Deterioration - Short/ground	- Valve stroke test
		Motors	Low	Does not open/close	High	- Short/burnout - Wear - Dirt/dust intrusion - Deterioration of insulation	- Valve stroke test - Motor current signature analysis - Motor insulation resistance test

Table 4.2 Aging Characteristics for Fan Cooler Unit Components (Cont'd.)

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Instrumentation/ Controls	Low	Transmitter	Medium	Incorrect signal	High	- Calibration drift - Short/ground - Deterioration - Dirt/dust intrusion	- Visual inspection - Functional test
		Indicator/ Recorder	High	Incorrect signal	High	- Calibration drift - Short/ground - Deterioration - Dirt/dust intrusion	- Visual inspection - Functional test
		Integrator/ Computator	Low	Incorrect signal	High	- Calibration drift - Short/ground - Deterioration - Dirt/dust intrusion	- Functional test
		Controllers	Low	Loss of function	High	- Wear - Deterioration - Dirt/dust intrusion - Short/ground	- Functional test
Cooling Coils	Low	Tubes	High	External leakage	High	- Wear - Fracture/cracking	- Visual inspection - Eddy current testing
				Fouling/ Plugging	Medium	- Dirt/crud buildup	- Visual inspection - Functional test - Differential pressure/temperature
		Gaskets	Low	External leakage	High	- Wear - Deterioration	- Visual inspection

Table 4.2 Aging Characteristics for Fan Cooler Unit Components (Cont'd.)

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Circuit Breakers	Medium	Contacts	Low	Does not open/close	High	- Out of adjustment - Corrosion - Burnout/pitting	- Visual inspection - Functional test
		Gears	Low	Does Not Open/Close	High	- Binding - Out of adjustment - Fracture/crack - Wear	- Visual inspection - Functional test
		Overload Relays	Low	Breaker Trip	High	- Wear - Deterioration - Fatigue	- Visual inspection - Functional test
		Fuses	Low	Loss of function	High	- Short/ground - Deterioration - Fatigue	- Visual inspection - Functional test
		Coils	Low	Loss of function	High	- Out of adjustment - Short/burnout - Deterioration	- Functional test
		Starters	Low	Loss of function	High	- Wear - Short/burnout	- Functional test
		Springs	Low	Loss of function	High	- Wear - Fatigue - Binding - Distortion	- Functional test - Visual inspection
		Handle/ Control Switch	Low	Does not open/close	High	- Wear - Fatigue/cracking - Binding - Deterioration - Poor lubrication - Short/burnout	- Visual inspection - Functional test

Table 4.2 Aging Characteristics for Fan Cooler Unit Components (Cont'd.)

COMPONENT	COMPONENT RELATIVE FAILURE FREQUENCY	SUBCOMPONENT	SUBCOMPONENT RELATIVE FAILURE FREQUENCY	COMPONENT FAILURE MODE	RELATIVE FAILURE MODE FREQUENCY	AGING MECHANISMS	DETECTION METHODS
Blowers	Low	Bearings	Medium	Does not run	High	- Deterioration - Dirt/dust intrusion - Wear - Poor lubrication - Binding	- Visual inspection - Functional test - Vibration measurements - Excessive noise
		Shaft	Low	Loss of function	High	- Wear - Fatigue - Fracture/cracking	- Functional test - Disassembly inspection
		Rotors/ Blades	Low	Loss of Function	High	- Wear - Fatigue - Fracture/ cracking - Vibration	- Visual inspection - Functional test - Disassembly inspection
		Belts	Low	Loss of function	High	- Wear - Deterioration	- Visual inspection - Functional test
Motors	Low	Bearings	Medium	Does not start	High	- Wear - Dirt/dust intrusion - Poor lubrication	- Functional test - Vibration measurement
		Leads/ Connectors	Low	Does not start	High	- Dirt/dust intrusion - Vibration	- Visual inspection - Functional test
		Insulation	Low	Does not start	High	- Wear - Deterioration	- Disassembly inspection - Functional test - Resistance measurement

5. ANALYSIS OF PLANT OPERATING EXPERIENCE

To supplement the data from the national databases, plant specific data were obtained and analyzed. One operating plant was visited and containment cooling system data were collected, including maintenance work requests, surveillance testing practices, and inspection activities. The purpose of this effort was to validate the findings of the national databases, and to provide some insight into current inspection, surveillance, and monitoring practices. This section presents the results of these analyses.

5.1 Design Descriptions

The plant visited is a 16 year old PWR unit. This plant uses a number of independently controlled systems to serve the function of controlling the containment atmosphere. These systems are:

- containment fan cooling system
- containment spray system
- containment iodine removal system
- containment combustible gas removal system
- co[illegible]ment purge system
- [illegible] cuum relief system

The two systems of interest for this study are the containment fan cooling system and the containment spray system (i.e., safety-related systems). The fan cooling system is an engineered safeguard system that is designed to operate during normal power generation, as well as during a design basis loss-of-coolant-accident, with or without a loss of off-site power. The containment spray system provides a redundant means of post-accident heat removal. Any of the following combinations of containment spray and fan cooler equipment trains will provide sufficient heat removal to maintain the post-accident containment pressure below the design value, assuming that core residual heat is released to the containment as steam:

- All five containment fan coolers
- Both trains of containment spray
- Three of five containment fan coolers and one train of containment spray.

5.1.1 Containment Spray System Design

The containment spray system consists of two separate, 100 percent capacity trains. Each train consists of one containment spray pump, which delivers borated, pH-adjusted cooling water to a spray header located in the upper dome of the containment structure. Borated water drawn from the refueling water storage tank is blended with sodium hydroxide from the common spray additive tank to raise the pH level for more efficient fission product removal. Only one containment spray pump is needed to operate for effective iodine removal.

The principal components of the containment spray system are two pumps, one spray additive tank, two eductors, four spray ring headers and associated nozzles, and the necessary piping and valves. The containment spray pumps and the spray additive tank are located in the auxiliary building and the spray pump suctions are normally lined up to the RWST. Following an accident, the containment spray pumps are utilized until the water in the RWST is depleted. During the recirculation phase, the system utilizes the two RHR pumps, two residual heat exchangers and associated valves and piping of the safety injection system.

When the spray pumps draw from the RWST, a small portion of the spray flow is diverted from the pump discharge line through the eductor and back to the pump suction. The liquid from the spray additive tank then mixes with the liquid entering the suction of the pumps. When the RWST water is depleted, the spray flow is discontinued and containment pressure control is maintained with the RHR system functioning in the containment spray mode.

All associated components, piping, structures, and power supplies of the containment spray system are designed to Class I (seismic) criteria. The two containment spray pumps are of the horizontal, centrifugal type, driven by 400 hp electric motors, which can be supplied with power from the standby ac power supply. The materials of construction are stainless steel or equivalent corrosion-resistant material. The pumps have a design pressure of 250 psig, a design temperature of 150 °F, and a rated flow of 2600 gpm.

The containment spray header piping and nozzle orientation is designed to provide maximum spray coverage of the containment. The arrangement consists of four 360 degree ring headers at different elevations, with alternate headers connected. The spray headers are stainless steel with a hollow-cone pressure nozzle design, and a 3/8 inch diameter orifice. The nozzles have no internal parts which could be subject to clogging. During the recirculation mode, the water is screened through a 1/4 inch mesh before leaving the containment sump.

5.1.2 Containment Fan Cooler System Design

The containment fan cooling system is designed to recirculate and cool the containment atmosphere in the event of a LOCA and thereby ensure that the containment pressure will not exceed its design value of 47 psig at 271 °F. Although the water in the core after a postulated LOCA is designed to be quickly subcooled by the safety injection system, the containment fan cooling system is designed on the conservative assumption that the core residual heat is released to the containment as steam.

The containment ventilation system, which includes the fan cooling system, is designed to remove the normal heat loss from equipment and piping in the reactor containment during plant operation. It must also remove sufficient heat from the reactor containment, following the initial LOCA containment pressure transient, to keep the containment pressure from exceeding the design pressure. The fan cooler units continue to remove heat after the LOCA and reduce the containment pressure to close to atmospheric within the first 24 hours.

The containment fan cooling system consists of five air handling units. Each unit includes a motor, fan, motor heat exchanger, cooling coils, roughing filters, dampers, duct distribution system, instrumentation, and controls. The units are located on the operating floor, between the containment wall and the polar crane wall. Each of the five fan cooler units is capable of transferring heat at the rate of 81×10^6 BTU/hr from the containment atmosphere. The cooling coils are supplied by the service (river) water system. The fans are designed to supply 110,000 cfm during normal operation, and 47,000 cfm during accident operation.

Duct work distributes the cooled air to the various containment compartments and areas. During normal operation, the flow sequence through each air handling unit is as follows: inlet dampers, roughing filters, cooling coils, fan, discharge header. During post-accident operation, air is drawn through a moisture separator, a post-accident high-efficiency particulate air (HEPA) filter section and cooling coils. Tight closing dampers isolate the post-accident filter section from the normally operating components.

The roughing filters are designed to remove the larger particles of suspended dust and dirt from the containment atmosphere during normal power operation, normal reactor shutdown, and loss of offsite power conditions. Removal of the particles also prevents buildup on the cooling coils, thus avoiding a reduction in heat transfer. The filters are arranged in two banks, each consisting of a structural steel frame and removable filter cells. Each filter cell contains a fiberglass media, which is capable of removing 90% of visible dust particles.

The HEPA filters in each fan cooler are provided to remove any particulate matter from the containment atmosphere. They are arranged in a structural steel frame and are individually removable. The filter media is fiberglass with asbestos separators, and is capable of collecting 99% of particles 0.3 micron and larger in size.

The five containment cooling fans are of the centrifugal, non-overloading, direct drive type. They are driven by two-speed motors, which are totally enclosed, water cooled, 300 hp, induction type. The motor insulation is Westinghouse Thermalastic, which is impregnated and coated to give a homogeneous insulation system that is highly impervious to moisture. The motors are cooled by an air-to-water heat exchanger, which is connected to the motor to form an entirely enclosed cooling system. Cooling water is supplied by the service water system.

The cooling coils are fabricated of AL-6X tubing, which is high nickel, chrome, molybdenum content alloy with good corrosion resistance. The design internal pressure of each coil is 200 psig and the coils can withstand an external pressure of 47 psig at a temperature of 271 °F without damage. Each unit consists of 12 coil units mounted in two banks of 6 coils high. These banks are located one behind the other for horizontal series air flow, and the tubes of the coil are horizontal with vertical fans.

A moisture separator in each fan cooler removes the larger droplets of suspended moisture from the containment atmosphere in the event of a LOCA. This prevents any significant water deluge over the face of the HEPA filters, which would result in a reduction in filter effectiveness. The separator consists of a structural steel frame with removable separator elements. Each element is capable of removing 95% of water droplets 10 microns and larger in size. The coils are provided with drain pans and piping, which drain to the sump, to prevent flooding during accident conditions.

The ducts are of welded and flanged construction. All longitudinal seams are welded. Where flanged joints are used, gaskets are provided suitable for temperatures up to 300 °F. The ducts are constructed of galvanized sheet steel.

The air control dampers are designed to Class I seismic criteria. Each damper is constructed of specially painted steel, with multiple blades that operate in unison, and an edge seal to minimize air leakage. A backdraft damper is provided at the discharge of each fan cooler, which opens automatically when the fan starts. This damper prevents pressure surges from damaging the fan-motor assembly. Two-position shut-off dampers are provided at each fan cooler to divert air flow through the HEPA filters and moisture separators during any LOCA, or through the roughing filters during normal operation. Each damper is provided with redundant pneumatic operators that can provide 150% of the design operating torque. The fan coolers are also equipped with pressure relief dampers in the filter enclosures.

5.2 Data Analysis Results

5.2.1 Containment Spray System

Corrective maintenance records were collected for the containment spray system for the five year period from 1987 to 1991. A total of 99 records were obtained. Each event was reviewed in a manner similar to the national database records to identify the predominant aging characteristics for this plant system. In general, the maintenance records were not as comprehensive as the NPRDS records, however, useful information was obtained.

The events were first reviewed to determine whether the required maintenance was the result of aging degradation. As for the national database records, the NUREG-1144 definition of aging was applied. The results showed that approximately 68% of the corrective maintenance was due to failures related to aging (Figure 5.1). This is consistent with the national database findings, which also showed a relatively high aging fraction of 59% (Figure 4.1).

The data were also reviewed to identify the failure causes. Again the results were consistent with the national database findings, showing the predominant cause of failure to be normal service (Figure 5.2). It should be noted that normal service implies that the degradation mechanism is the result of exposure to one or more stresses the component is expected to see during its normal service life. Even though the containment spray system is a standby system, there are aging mechanisms that can be active while the components are idle (see Section 3). Therefore, normal service does not necessarily mean that the component is operating.

The components most frequently failed in the containment spray system were found to be valves (Figure 5.3), which is the same as the finding from the national databases (Figure 4.10). This was followed by instrumentation/controls, motors, pipes/tanks, and pumps (Figure 5.3). As discussed previously, the dominance of valves is believed to be due primarily to the large population of these components as compared to the other components in the system. As in the NPRDS and LER data analysis, these data were not normalized to account for population effects since the intent of this analysis is to identify areas where additional effort is needed to control aging degradation, and not to calculate failure rates.

The valve failures typically involved leakage from the packing, along with leakage of flange and bonnet gaskets. Therefore, leakage is the predominant failure mode for the valves. Similarly for pumps and piping, leakage of seals and flange gaskets was the predominant failure mode. The instrumentation and control failures involved a number of calibration problems, such as switches being out of specification and recorders being out of calibration. The motor failures most often involved overheating of the torque and limit switches on motor operated valves.

5.2.2 Containment Fan Cooling System

Fan cooler data were also collected for the five year period from 1987 to 1991. These data were analyzed separately to identify aging characteristics specific to the fan cooler components. The aging fraction for these failures was consistent with national database findings showing approximately 66% of the failures being related to aging degradation (Figure 5.4). This confirms the previous findings that aging degradation is present in the fan cooler system and that it contributes to component failures.

The causes of failure were also examined for the plant data. As in the national database analysis (Figure 4.28), normal service was found to be the predominant failure cause in the plant data (Figure 5.5). This is expected since the fan coolers are used during normal operation, as well as accident conditions.

The components most frequently failed in the fan cooler system are instrumentation and controls (Figure 5.6). Typical failures involved incorrect signals from the component

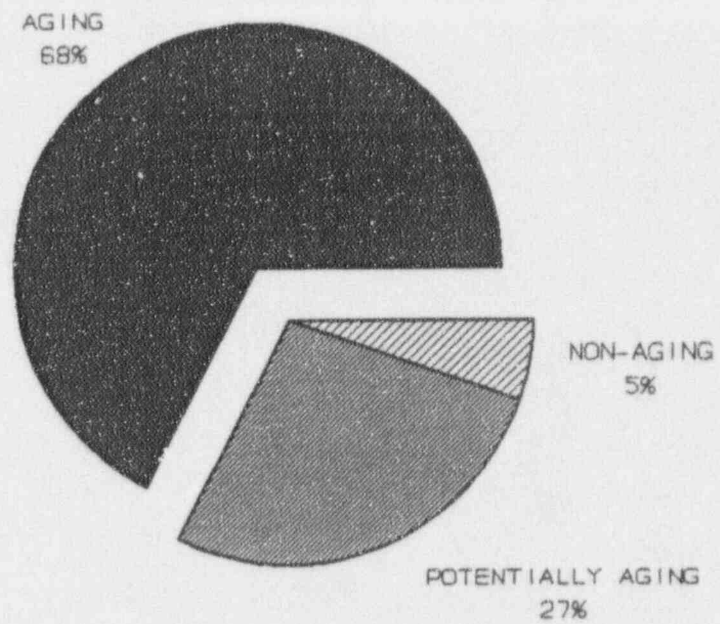


Figure 5.1 Aging fraction for plant specific containment spray data

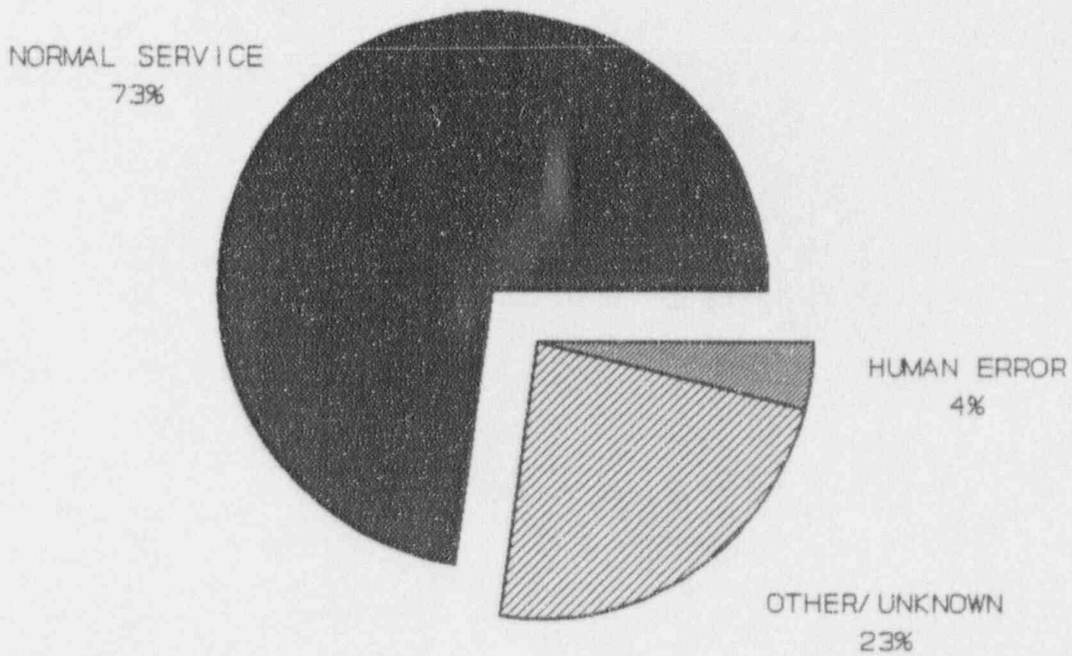


Figure 5.2 Failure causes for plant specific containment spray data

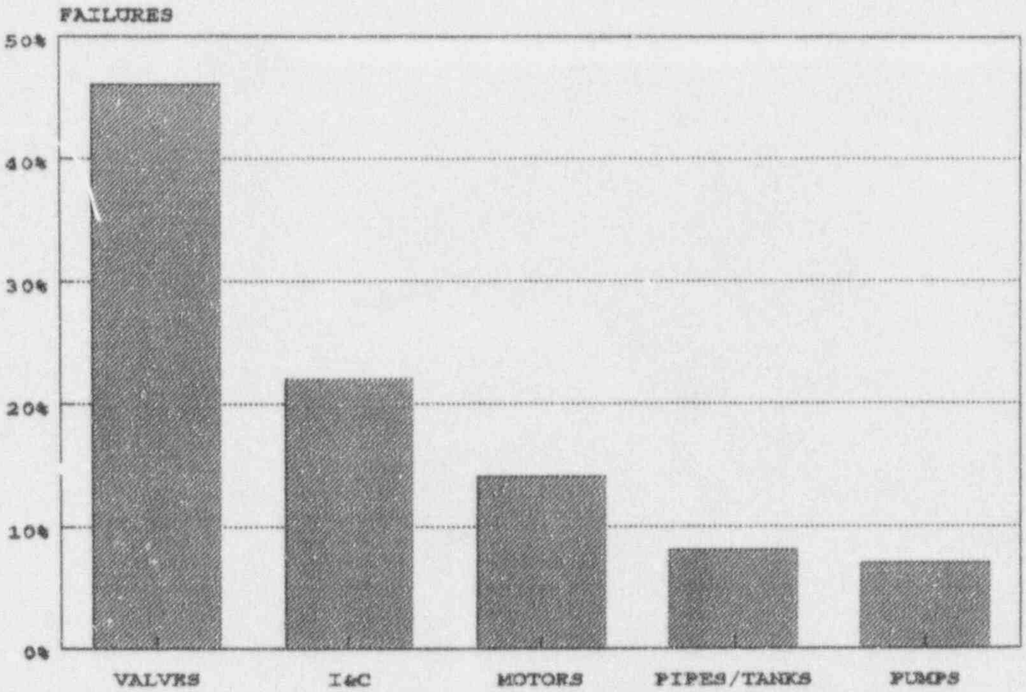


Figure 5.3 Containment spray components most frequently failed (1987 - 1991 plant specific data)

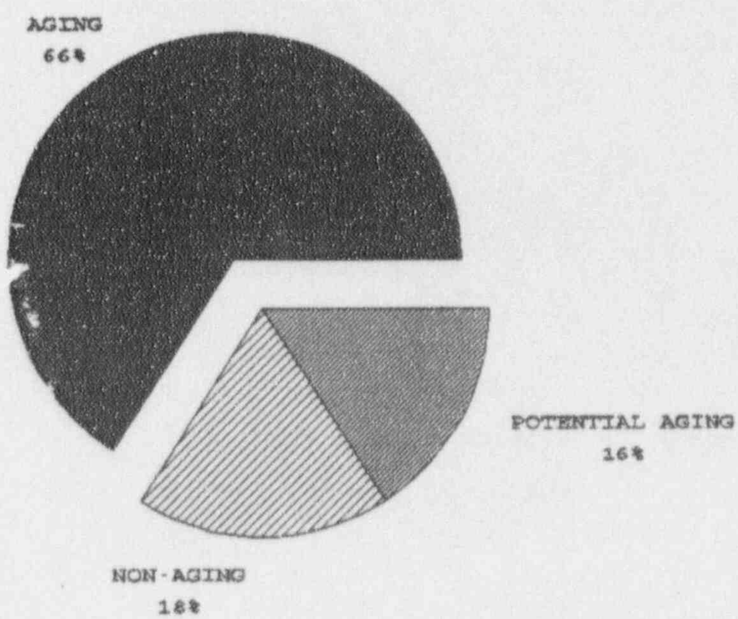


Figure 5.4 Aging fraction for plant specific fan cooler data

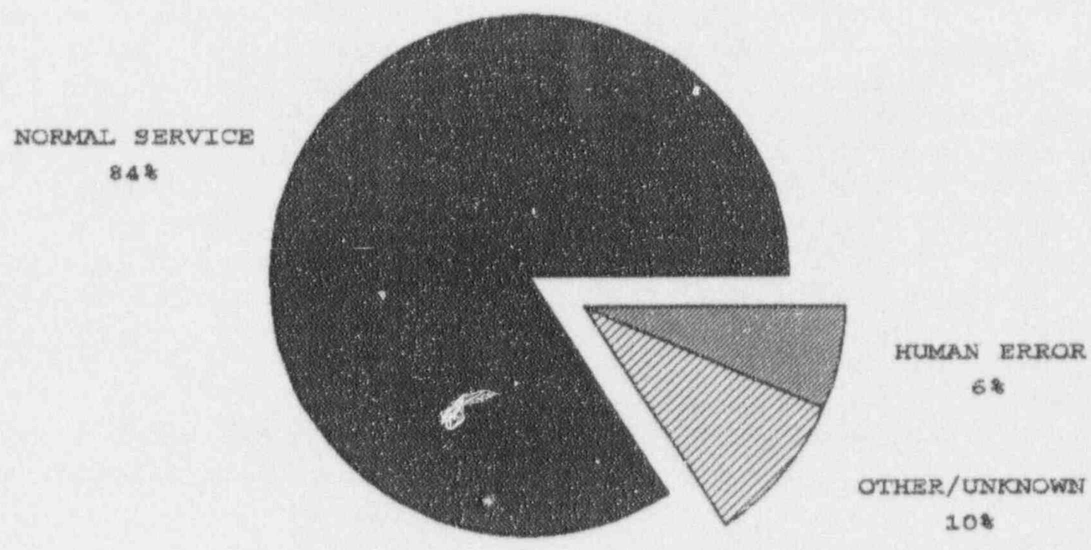


Figure 5.5 Failure causes for plant specific fan cooler data

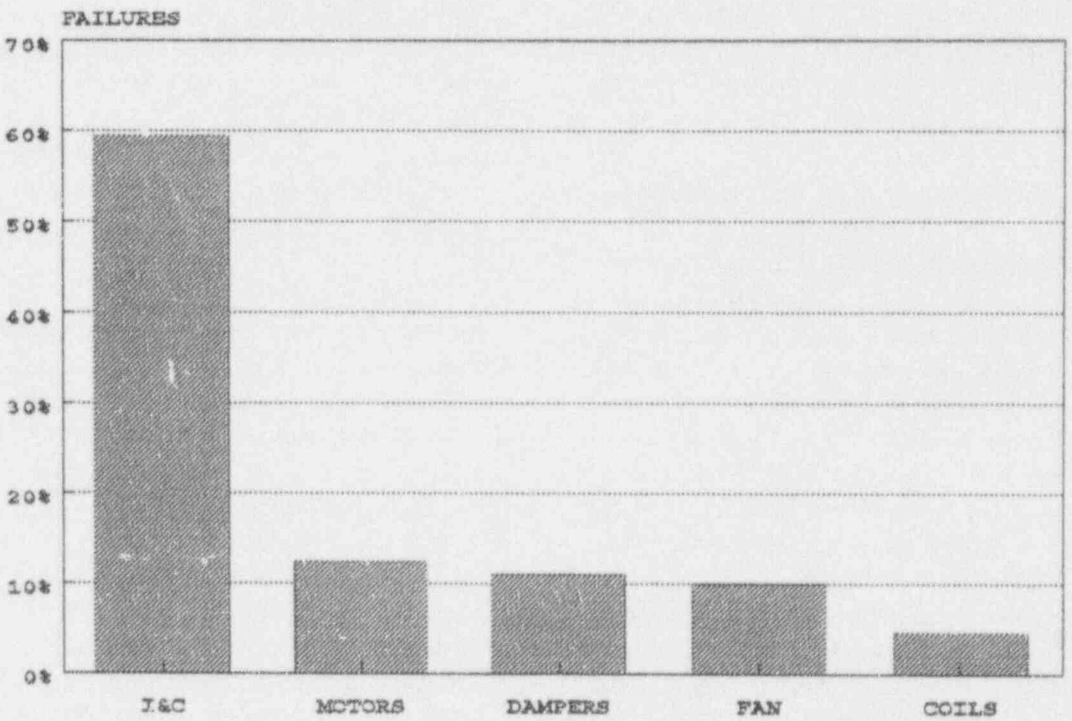


Figure 5.6 Fan cooler system components most frequently failed from plant specific data

or loss of function. The corrective actions taken required rebuilding or replacing of subcomponents or recalibration. The types of I&C most often failed were thermocouples and switches. Following I&C, motors, dampers, and fans were the next most frequently failed components. In comparison with the national database results (Figure 4.31), circuit breakers were not found to be a frequently failed component. This could be due to the plant using a type of breaker that is not as prone to failure, or differences in reporting, where the plant associated the breaker failure with the component it services. However, neither of these reasons could be verified.

5.3 Inspection, Surveillance and Monitoring (IS&M) Practices

The plant data collected also provided information on the inspection, surveillance, and monitoring methods used for the containment cooling systems. These practices were reviewed to provide a preliminary look at what is being done to detect and mitigate aging degradation in containment cooling systems.

5.3.1 Containment Spray System IS&M

Active components of the containment spray system are tested periodically to ensure their operational readiness. The spray pumps must be tested in accordance with ASME Section XI, which requires quarterly measurements of pump flow, vibration, and head. The pumps are tested individually by opening the valves in the miniflow line and starting the pump to establish flow. The performance parameters are then measured and compared to reference values. The spray injection valves must also be tested in accordance with ASME Section XI. This requires stroke testing the valves quarterly, or during shutdown if quarterly testing is impractical. During these tests, the equipment is visually inspected for leaks.

Valves and pumps are operated and inspected after any maintenance to ensure proper operation. Permanent test lines for all spray loops are located so that the system, up to and including the isolation valves at the spray header, can be tested. The isolation valves are tested separately. Test lines for checking the spray nozzles with air connect downstream of the isolation valves. Tests with air or smoke flow through the nozzles are performed every 5 years as required by the Technical Specifications, to verify the nozzles are unobstructed.

The tests and inspections performed for the containment spray system are summarized in Table 5.1.

5.3.2 Fan Cooler System IS&M

The containment fan cooling system is designed such that the components can be tested periodically, and after any component maintenance, for operability and functional performance. Four of the five fan cooling units are typically in use during normal plant operation. The fifth unit can be started from the control room to verify operational readiness. The dampers directing flow through the post-accident filter section can be tested when the fan is running on low speed.

The functional test of the emergency core cooling system includes testing for proper transfer of the fan units in the event of a loss-of-power. A test signal is used to initiate damper motion and fan starting. This test verifies proper functioning of the air flow switch provided for each fan.

Access is provided for visual inspection of the containment fan cooler components, including the fans, cooling coils, dampers, and duct work. Visual inspections are performed periodically or when an operational abnormality exists. The inspection, surveillance, and monitoring practices for the fan cooler system are summarized in Table 5.2.

Table 5.1 Inspection, Surveillance and Monitoring Practices for the Containment Spray System

Component	IS&M Practice	Frequency
Valves	Verify correct position[2]	31 days
	Verify stroke time[2]	Quarterly/cold shutdown
	Verify full stroke (check valves)[1]	Cold shutdown/refueling[4]
	Verify valve seat leakage[1,3]	2 years
	Verify relief valve set pressure[1]	5 years
	Verify automatic valves actuate on high-high containment pressure signal[2]	18 months
Pumps	Verify pump develops adequate discharge pressure in recirculation mode[2]	31 days
	Verify pump starts on containment high-high pressure signal[2]	18 months
	Verify pump head within limits[1]	Quarterly
	Verify pump flow within limits[1]	Quarterly
	Verify pump vibration within limits[1]	Quarterly
Nozzles	Verify nozzles unobstructed using air or smoke[2]	5 years
Piping	Verify no system external leakage[1]	3 years
	Hydrostatically test system[1]	10 years
Spray Additive System	Verify solution level in tank within limits[2]	6 months
	Verify NaOH concentration in tank within limits	6 months
	Verify NaOH flow rate through sample valve[2]	5 years
	Verify eductor flow to containment spray system within limits[2]	5 years

1. ASME Section XI[21] requirement
2. Technical Specification requirement
3. 10CFR Part 50, Appendix J[20] requirement
4. Relief from ASME Section XI[21] requested

Table 5.2 Inspection, Surveillance, and Monitoring Practices for the Fan Cooler System

Component	IS&M Practice	Frequency
Fans	Manual start test[1]	31 days
	Operate for 15 minutes[1]	31 days
	Verify cooling water flow[1]	31 days
	Verify automatic start on high-high containment pressure signal[1]	18 months
Dampers and Valves	Verify automatic operation for power operated components[1]	18 months
Cooling Coils	Verify cooling water flow within limits[1]	18 months
	Verify no external system leakage[2]	3 years
	Hydrostatically test the system[2]	10 years

1. Technical Specification requirement
2. ASME Section XI[21] requirement

5.4 Summary of Findings

The results of the plant data analysis have confirmed the findings from the national databases. Both data sources show that the majority of failures are related to aging degradation, with normal service being the dominant failure cause. In the containment spray system, both data sources show valves are the component that fails most frequently. For fan coolers, the national data bases show circuit breakers to be the most frequently failed component followed by instrumentation/controls. The plant data show instrumentation/controls to be the most frequently failed component. Circuit breakers did not show up as a frequently failed component in the plant data, possibly due to the type of breaker used, or due to plant reporting practices.

From these findings it is seen that aging degradation is present in containment cooling systems and contributes to component failures. The inspection, surveillance, and monitoring practices currently used are able to detect and mitigate some of the aging mechanisms, however, they do not detect all of them. This is evidenced by the high fraction of failures related to aging. Additional attention should be given to improving aging management for these systems.

6. SAFETY SIGNIFICANCE AND TIME-DEPENDENT UNAVAILABILITY IMPACT

One of the primary reasons for understanding and managing aging of nuclear power plants is that as components and systems age there may be an increase in failure rate due to unchecked aging degradation. If this occurs, it could result in a decrease in system availability. To understand the significance of decreased containment cooling system availability on plant safety, several existing probabilistic risk assessments (PRAs) were reviewed to better define the role of this system. A system unavailability analysis was then performed to simulate the effects of unmitigated aging on the availability of common containment spray system and fan cooler system designs. This section discusses the results of this work.

6.1 Safety Significance of the Containment Cooling System

During normal plant operation the majority of the heat generated in the reactor is removed by the power conversion system. The remainder is transferred to the containment atmosphere and the structures within it. One function of the containment cooling system is to remove this waste heat during normal operation and maintain the containment atmosphere within specified temperature limits. This is necessary for proper operation of the components and structures within containment, and to prolong their life. A loss of containment cooling during normal operation may result in a reactor scram. For example, in BWRs, loss of drywell coolers will result in a containment temperature increase, and corresponding pressure increase, which can result in a scram at approximately 2 psig in containment. This is especially true in BWRs with small containments, such as Mark Is and Mark IIs.

Under accident conditions, decay heat remaining in the reactor after shutdown, and stored energy in the primary cooling system can be significant. If the accident involves a pipe break, this decay heat can be released directly into containment. There are several safety-related methods for removing decay heat from containment. For BWRs this function can be performed by the residual heat removal system operating in the suppression pool cooling mode, the shutdown cooling mode, or containment spray mode. In early BWRs isolation condensers are used. As a last resort, decay heat can also be removed by venting the primary containment.

In PWRs, safety-related methods of removing containment heat include the auxiliary feedwater system, the containment spray system, containment fan coolers, ice condensers, the residual heat removal system in the shutdown cooling mode, feed and bleed cooling, and high/low pressure recirculation with heat exchangers.

There are other non-typical system alignments that can be utilized when decay heat is low, such as using the spent fuel pool cooling heat exchangers, reactor water cleanup non-regenerative heat exchangers, suppression pool letdown, and high pressure coolant injection (HPCI) and reactor core injection cooling (RCIC) in the condensate storage tank recirculation test mode. However, these systems are not credited in the Safety Analysis Report (SAR) and are not generally modeled in PRAs.

A number of boiling water reactor PRAs, including the Reactor Safety Study WASH-1400[5] and the Browns Ferry Interim Reliability Evaluation Program (IREP)[6], have postulated a significant percentage of the degraded core frequency to be caused by a transient with the loss of containment heat removal. This represents the probability that a core will be damaged due to the loss of systems such as shutdown cooling, suppression pool cooling, containment sprays, power conversion, and containment venting systems. If these systems are not available during accident conditions, this could cause the suppression pool temperature to increase, containment to over-pressurize and fail, loss of makeup water to the core, and, subsequently, core damage. Early PRAs, such as WASH-1400[5], conservatively assume no recovery of the power conversion system, and a loss of all core injection following containment failure. Additionally, no credit for venting is given since most plants did not have venting procedures for this at the time the PRAs were performed.

In the Peach Bottom NUREG-1150 PRA[7], which is a more recent study, credit is given for venting from the wetwell to prevent containment overpressurization failure, and continued core injection after containment failure. In this analysis, transients with a loss of containment heat removal sequences account for less than 1% of the core damage frequency. In contrast, in the WASH-1400 analyses of Peach Bottom, transients with a loss of containment heat removal account for 53% of the core damage frequency, while in the Browns Ferry IREP analyses they account for 55%. Therefore, in the PRA analyses the contribution of loss of containment heat removal to core damage frequency is a strong function of the availability of alternative containment heat removal systems (i.e., venting), as well as the assumptions made regarding power conversion system recovery and reactor pressure vessel injection. However, the PRAs do show that the containment cooling function can play a significant role in mitigating core damage.

In addition to its contribution to core damage, PRAs also evaluate the use of containment heat removal systems to mitigate severe accidents once core damage has occurred. These systems, which are the subject of this study, may delay or prevent containment venting or failure, and decrease the quantity of fission products released.

The containment spray system is utilized to condense the steam released into the containment following an accident, thereby lowering containment pressure and reducing stress to the containment structure. It can also be used to mitigate the effects of molten core on the drywell floor by preventing contact with the drywell shell, and can decontaminate the containment atmosphere, thereby reducing the severity of any accidental releases. In BWRs, the suppression pool cooling system helps to reduce containment pressure following an accident by maintaining the suppression pool water in a subcooled state as steam is condensed in it. This also reduces the potential for pool flashing should the containment fail or be vented, or should core debris be deposited into the pool. In addition, the suppression pool cooling system helps prevent emergency core cooling system pump failures due to inadequate net positive suction head (NPSH) or seal failures due to overtemperature, since these pumps take suction from the suppression pool.

From the preceding discussion it is seen that the containment cooling system is important to plant safety during both normal and accident conditions. It is, therefore, important to understand the effects of aging on the performance of its various components, and to ensure that aging degradation is properly managed. In the following subsection the effects of uncontrolled aging degradation are examined using a fault tree methodology.

6.2 Unavailability Analysis of the Containment Spray System

As the basis of this analysis, an existing utility PRA was obtained which included a common design for a containment spray system, with sodium hydroxide injection. A system fault tree model was developed, and several system components that could be affected by aging were identified. A base case unavailability was calculated using the failure rates specified in the utility PRA or generic databases. A parametric study was then performed in which the failure rate for selected components was increased by factors of two, five, and ten to simulate the effect of increasing failure rates due to aging. The system unavailability was recalculated for each case.

The containment spray system, as analyzed, consists of two trains; each with one normally closed motor operated valve, one check valve, and one motor driven pump. Also included in each train are several manual valves, which are used for test and maintenance purposes, along with piping, instrumentation, and spray nozzles. The success criterion for the containment spray system is for one out of two trains to inject into the containment when signaled. For this simplified analysis, only the injection phase of containment spray was modeled. A detailed system description and the system fault tree are included in Appendix C.

6.2.1 Base Case Analysis

The base case unavailability for the containment spray system was calculated to be 4.1×10^{-3} per demand. The top 15 cutsets, which account for over 99% of the system unavailability, are presented in Table 6.1. These cutsets show that the failure to correctly reposition manual valves after surveillance testing (events CSMNV-CS0037-HEP and CSMNV-CS0040-HEP) are the dominant events leading to system unavailability. These human errors (HEP) appear in 11 of the top 15 cutsets.

For the components that can be affected by aging, Table 6.1 shows that failure of the pumps to start (events CSPMP-A-FTS and CSPMP-B-FTS), including common cause failures (event CSPMPAB-CCF-FTS), appear in five of the top 15 cutsets contributing to system unavailability. MOV failure to open (events CSMOV-CS0002-FTO and CSMOV-CS0004-FTO) also appears in five of the top 15 cutsets. Maintenance unavailability (events CSA-MAINT-UNAVAI and CSB-MAINT-UNAVAI), test unavailability (events CSA-TEST-UNAVAIL and CSB-TEST-UNAVAI-L), and nozzle plugging (events CSNOZAPL-UGGED and CSNOZBPLUGGED) are seen to be much smaller contributors.

Examination of Table 6.1 shows that the sum of the cutset frequencies for all cutsets with a human error event is 85% of the total for all 15 cutsets. Similarly, the sum for pump events is 21%, and for MOV events the sum is 15%. This indicates that human error is the most significant contributor to system unavailability for this particular design. This is followed by events involving pumps and MOVs, which are both subject to aging degradation.

6.2.2 Parametric Study for Increasing Failure Rates

Using the base case model of the containment spray system, a parametric study was performed to determine the potential influence of aging on the system unavailability. Basic events that could be affected by aging were identified and analyzed. The failure rates for these events were multiplied by factors of two, five, and ten, and a new system unavailability was calculated. The events analyzed for the containment spray system are pump failure to start, MOV failure to open, check valve failure to open, nozzle plugging, and maintenance unavailability. Maintenance unavailability was included since aging degradation can lead to an increase in downtime for maintenance.

The parametric study results show that an increase in pump failure rate can influence total system unavailability (Table 6.2 and Figure 6.1). If the pump failure rate were to

Table 6.1 Containment Spray System Base Case Top 15 PRA Cutsets

CUTSET NUMBER	CUMULATIVE UNAVAILABILITY	CUTSET CONTRIBUTION	CUTSET FREQUENCY	CUTSET DESCRIPTION
1	60.7%	60.7%	2.5×10^{-3}	CSMNV-CS0037-HEP, CSMNV-CS0040-HEP
2	73.0%	12.3%	5.1×10^{-4}	CSPMPAB-BETA-FTS, CSPMPAB-CCF-FTS
3	80.0%	6.9%	2.8×10^{-4}	CSMNV-CS0040-HEP, CSMOV-CS0002-FTO
4	86.9%	6.9%	2.8×10^{-4}	CSMNV-CS0037-HEP, CSMOV-CS0004-FTO
5	90.6%	3.7%	1.5×10^{-4}	CSMNV-CS0040-HEP, CSPMP-A-FTS
6	94.4%	3.7%	1.5×10^{-4}	CSMNV-CS0037-HEP, CSPMP-B-FTS
7	95.2%	0.7%	3.2×10^{-5}	CSMOV-CS0002-FTO, CSMOV-CS0004-FTO
8	95.9%	0.7%	2.9×10^{-5}	CSMNV-CS0037-HEP, CSB-MAINT-UNAVAI
9	96.6%	0.7%	2.9×10^{-5}	CSMNV-CS0040-HEP, CSA-MAINT-UNAVAI
10	97.2%	0.5%	2.3×10^{-5}	CSMNV-CS0037-HEP, CSB-TEST-UNAVAIL
11	97.7%	0.5%	2.3×10^{-5}	CSMNV-CS0040-HEP, CSA-TEST-UNAVAIL
12	98.2%	0.4%	1.7×10^{-5}	CSPMP-B-FTS, CSMOV-CS0002-FTO
13	98.6%	0.4%	1.7×10^{-5}	CSPMP-A-FTS, CSMOV-CS0004-FTO
14	98.9%	0.2%	1.2×10^{-5}	CSMNV-CS0037-HEP, CSNOZBPLUGGED
15	99.2%	0.2%	1.2×10^{-5}	CSNOZAPLUGGED, CSMNV-CS0040-HEP

Table 6.2 Parametric Study of Containment Spray System Unavailability

BASIC EVENT DESCRIPTION	BASIC EVENT FAILURE RATE	SYSTEM UNAVAILABILITY			
		BASIC EVENT FAILURE RATE MULTIPLICATION FACTOR			
		BASE CASE	X 2	X 5	X 10
Pump failure to start failure to run	3.1×10^{-3} 3.0×10^{-5}	4.1×10^{-3}	5.0×10^{-3}	7.6×10^{-3}	1.2×10^{-2}
MOVs failure to open	5.7×10^{-3}	4.1×10^{-3}	4.8×10^{-3}	7.4×10^{-3}	1.3×10^{-2}
Maintenance unavailability	5.9×10^{-4}	4.1×10^{-3}	4.2×10^{-3}	4.4×10^{-3}	4.7×10^{-3}
Spray nozzle plugging	2.4×10^{-4}	4.1×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.4×10^{-3}
Check valve failure to open	4.3×10^{-5}	4.1×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.2×10^{-3}
All of the above	--	4.1×10^{-3}	5.9×10^{-3}	1.2×10^{-2}	2.6×10^{-2}

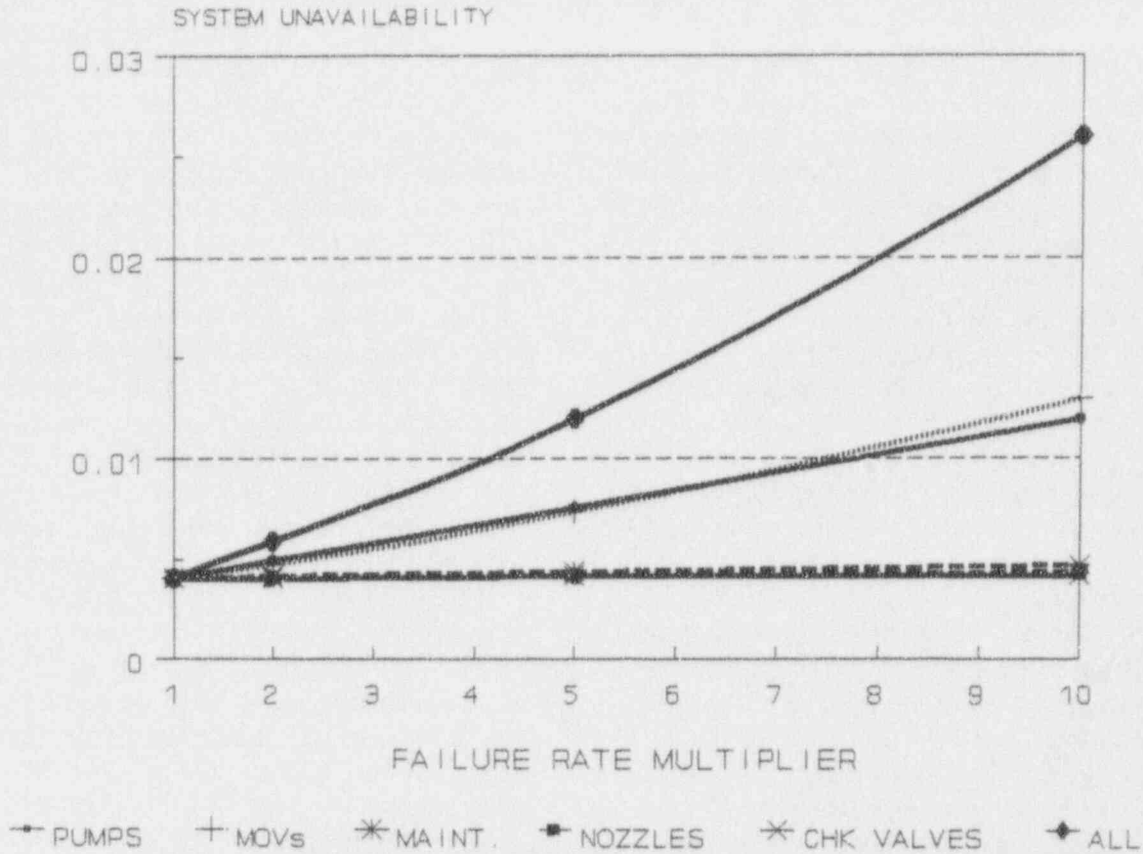


Figure 6.1 Containment spray system unavailability versus component failure rate

increase by a factor of five, its contribution to system unavailability becomes approximately equal to that of the human error related to repositioning the manual valves. At ten times the base case failure rate, the total system unavailability increases by a factor of three, and the pump contribution (72%) exceeds that of the human error (53%). These results show that if pump aging degradation is not properly controlled, and failure rates increase over time, pump failures can become an important contributor, and lead to an increase in containment spray system unavailability.

The parametric results for MOVs also show a similar influence on system unavailability when failure rates increase (Table 6.2 and Figure 6.1). For the case where MOV failure rate experiences a ten fold increase, the contribution of MOVs to system unavailability also exceeds the human error related to repositioning of manual valves, and system unavailability is seen to increase by a factor of approximately three. This indicates that MOVs can also become important contributors to system unavailability if aging degradation is not properly controlled.

Maintenance unavailability, nozzle plugging, and check valve failures have less of an influence on overall system unavailability. Even with a ten fold increase in the base case failure rate, the impact is seen to be minor. This is due to the relatively small base case failure rate associated with these events, as shown in Table 6.2. These results show that the system unavailability is dominated by those basic events which have the largest failure rate, and that it is important to properly manage aging degradation for these basic events to avoid an increase in unavailability with age. As a limiting case, the failure rates for all of the basic events were increased simultaneously. This resulted in a six fold increase in system unavailability for the case where failure rates were multiplied by a factor of ten (Table 6.2 and Figure 6.1).

6.3 Unavailability Analysis of Fan Cooler Units

To perform this analysis, fault trees were developed that modeled the individual fan cooler subcomponents that could be subject to aging degradation. The subcomponents modeled are the fan motors, cooling coils, circuit breakers, and dampers. As for the containment spray system, maintenance unavailability was also included in the model.

The plant design chosen as the basis for this analysis is from a PWR using five fan cooler units inside containment. The units are normally operating, as required, to maintain the containment temperature within specified limits. On an accident signal, the operating fan coolers switch to a slower speed and the standby units start. Three units are sufficient to maintain the containment pressure within design limits for the design basis accident. A detailed description of the fan cooler system and the fault tree are presented in Appendix C.

6.3.1 Base Case Analysis

The base case containment fan cooler system unavailability was calculated to be 5.3 x 10^{-5} per demand. This is based on a success criteria of three of five fan cooler units operating, thus the system fails when three fan cooler units fail. As a result, most cutsets have three elements. The top ten cutsets are shown in Table 6.3. Unlike the containment spray system, there are no dominant failure contributors. The top cutset is the common mode failure of the fan motors, which itself contributes 11% to the system unavailability. The remaining 807 cutsets generated from the analysis contribute less than 1% each. As shown for cutsets two through ten in Table 6.3, there are three event cutsets involving fan coolers being unavailable due to maintenance (FCX-MAINT-UNAVAI) and failure of other components, such as failure of a back flow damper to open (FCBKFLWDMPRX-FTO).

Based on a cumulative contribution from all cutsets in which it appears, the PRA results show maintenance unavailability to be the leading contributor to system unavailability at 79%. This is followed by dampers failing to open, which contributes 65%, circuit breaker malfunction, which contributes 50%, and the common cause failure of the fan motors, which contributes 11%. Cooling coil failures do not significantly contribute to system unavailability.

6.3.2 Parametric Study for Increasing Failure Rates

A parametric study similar to that done for the containment spray system was performed for the fan cooler system. The basic events analyzed, along with their base case failure rate, are presented in Table 6.4. For each event the base case failure rate was multiplied by factors of two, five, and ten to simulate the effects of aging degradation where no provisions are made to properly manage it.

As shown in Table 6.4 and Figure 6.2, an increase in fan damper failure rate has the greatest influence on system unavailability. When the failure rate is doubled, the system unavailability increases by a factor of approximately two. For a ten fold increase in failure rate, system unavailability increases by a factor

Table 6.3 Fan Cooler System Base Case Top 10 PRA Cutsets

CUTSET NUMBER	CUMULATIVE UNAVAILABILITY	CUTSET CONTRIBUTION	CUTSET FREQUENCY	CUTSET DESCRIPTION
1	11.1%	11.1%	6.0×10^{-6}	FCMTR-BETA-CCF, FCMTR-CCF-FAIL
2	11.4%	0.3%	1.7×10^{-7}	FC1-MAINT-UNAVAI, FC2-MAINT-UNAVAI, FCBKFLWDMPR4-FTO
3	11.7%	0.3%	1.7×10^{-7}	FC2-MAINT-UNAVAI, FC4-MAINT-UNAVAI, FCINTDMPR5-FTO
4	12.1%	0.3%	1.7×10^{-7}	FC1-MAINT-UNAVAI, FC2-MAINT-UNAVAI, FCINTDMPR4-FTO
5	12.4%	0.3%	1.7×10^{-7}	FC2-MAINT-UNAVAI, FC4-MAINT-UNAVAI, FCBKFLWDMPR5-FTO
6	12.7%	0.3%	1.7×10^{-7}	FC3-MAINT-UNAVAI, FC4-MAINT-UNAVAI, FCINTDMPR1-FTO
7	13.0%	0.3%	1.7×10^{-7}	FC2-MAINT-UNAVAI, FC5-MAINT-UNAVAI, FCBKFLWDMPR1-FTO
8	13.3%	0.3%	1.7×10^{-7}	FC2-MAINT-UNAVAI, FC5-MAINT-UNAVAI, FCBKFLWDMPR4-FTO
9	13.7%	0.3%	1.7×10^{-7}	FC1-MAINT-UNAVAI, FC4-MAINT-UNAVAI, FCBKFLWDMPR2-FTO
10	14.0%	0.3%	1.7×10^{-7}	FC1-MAINT-UNAVAI, FC3-MAINT-UNAVAI, FCINTDMPR5-FTO

Table 6.4 Parametric Study of Fan Cooler System Unavailability

BASIC EVENT DESCRIPTION	BASIC EVENT FAILURE RATE	SYSTEM UNAVAILABILITY			
		BASIC EVENT FAILURE RATE MULTIPLICATION FACTOR			
		BASE CASE	X 2	X 5	X 10
Dampers failure to open	3.0×10^{-3}	5.3×10^{-5}	1.2×10^{-4}	6.7×10^{-4}	3.5×10^{-3}
Maintenance unavailability	7.6×10^{-3}	5.3×10^{-5}	1.3×10^{-4}	5.8×10^{-4}	2.0×10^{-3}
Circuit breaker failure to open failure to close	1.9×10^{-3} 2.4×10^{-3}	5.3×10^{-5}	8.9×10^{-5}	2.5×10^{-4}	6.9×10^{-4}
Fan motor failure to start	6.1×10^{-5}	5.3×10^{-5}	5.9×10^{-5}	7.7×10^{-5}	1.1×10^{-4}
Cooling coil plugging	1.4×10^{-4}	5.3×10^{-5}	5.3×10^{-5}	5.3×10^{-5}	5.3×10^{-5}
All of the above	--	5.3×10^{-5}	3.9×10^{-4}	5.9×10^{-3}	4.6×10^{-2}

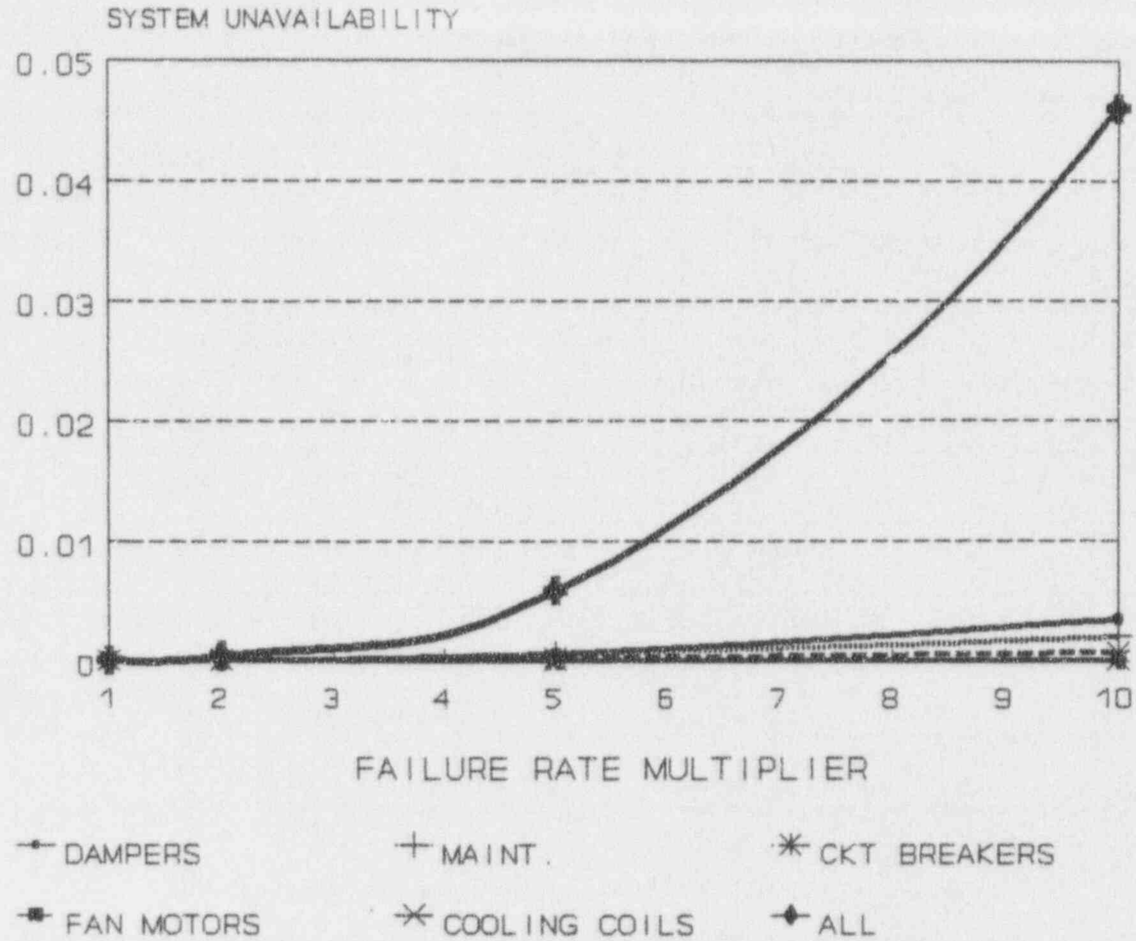


Figure 6.2 Fan cooler system unavailability versus component failure rates

of approximately 66. These results indicate that aging of dampers should be properly controlled since an increase in failure rate could result in a significant increase in system unavailability.

Maintenance unavailability has the next largest influence on system unavailability. When the maintenance unavailability is increased by a factor of ten, the system unavailability increases by a factor of approximately 38. This shows that as the components age, if increasing amounts of maintenance are required to maintain the components in an operational condition, system unavailability could increase significantly.

Circuit breaker failures also show an influence on system unavailability when the failure rate increases. When circuit breaker failure rate is increased by a factor of ten, system unavailability increases by a factor of approximately 13. Therefore, proper aging management is also important for this component.

Increases in fan motor failures and cooling coil failures show little or no influence on system unavailability. For a ten fold increase in fan motor failure rate, system unavailability approximately doubles. Increases in cooling coil failure rate show no effect on system unavailability. This is due to the relatively small initial failure rate for these components as compared to the other components (Table 6.4).

6.4 Time-Dependent Failure Trend Analysis

The system unavailability analysis has shown that certain components can affect system unavailability if their failure rate increases with age. For the particular containment spray system design analyzed, the important components are pumps and MOVs. For the fan cooler system design analyzed, the important components are dampers, circuit breakers, and, due to its contribution in the base case, fan motors. To examine the potential for increases in the failure rates for these components, the data were analyzed to identify any time-dependent trends. For each of the aforementioned components, the failure data were categorized based on failure mode, then sorted into five year age groups. Within each group, the number of failures of the component were counted and normalized based on the number of plants reporting during that period. A linear regression analysis was then used to determine if there is any trend with age.

It should be noted that the purpose of this analysis is not to calculate component failure rates, but only to identify potential trends in the failure rate as a function of time. For this purpose, the use of five year age groupings for the failure data was chosen to provide a sample size that was large enough to provide meaningful information. As part of the linear regression analysis, the standard error in the trend slope was calculated, along with the correlation coefficient for the data (Note: a correlation coefficient of -1 or +1 indicates perfect linear correlation, while a coefficient of 0 indicates no correlation). These parameters were used to determine if the linear regression provided meaningful results for the data analyzed, and to provide an estimate of the uncertainty in the calculations. This analysis methodology is believed to be an acceptable approach for identifying trends in the data. A more sophisticated analysis would be required to accurately calculate failure rates.

The first set of data analyzed were for the containment spray pump. The data for the failure to run failure mode show an increasing trend with age in the number of failures, with a fairly good correlation coefficient of 0.64 for the linear regression (Figure 6.3). For this failure mode, an increase of 18% $\pm$ 15% of the initial value per year was calculated for the trend. With this rate of increase, the failure rate would more than triple by the time the component is 20 years old (Table 6.5).

The pump failure to start failure mode was also analyzed, however, a poor linear regression correlation of 0.16 was obtained. This indicates that the data are not well represented by a linear equation, and no meaningful trend can be obtained from the data (Figure 6.4).

The data for MOVs show a decreasing trend with age for the failure to open failure mode, with a correlation coefficient of -0.49 (Figure 6.5). This could be due to additional attention being given to MOVs in light of an increasing industry awareness of MOV problems. It could also be due to inconsistencies in the data. However, it should be noted that other aging studies have found an increasing trend in MOV failure rate with age (Refs. 3,4). Therefore, the possibility of MOV failure rates increasing with age should not be ruled out by these findings.

Table 6.5 Failure Rate Increase Versus Age for Containment Cooling Components

COMPONENT	FAILURE MODE	YEARLY RATE OF INCREASE[1]	MULTIPLICATION FACTOR FOR AVERAGE FAILURE RATE			
			AGE GROUP (YEARS)			
			1 TO 5	6 TO 10	11 TO 15	> 15
PUMP	Failure to run	18% ± 15%	1.0	1.8	2.6	3.4
DAMPERS	Failure to open	22% ± 15%	1.0	2.2	3.2	4.4
CIRCUIT BREAKERS	Failure to open	8% ± 8%	1.0	1.4	1.8	2.1

1. Percent of value for age group 1 to 5 years old.

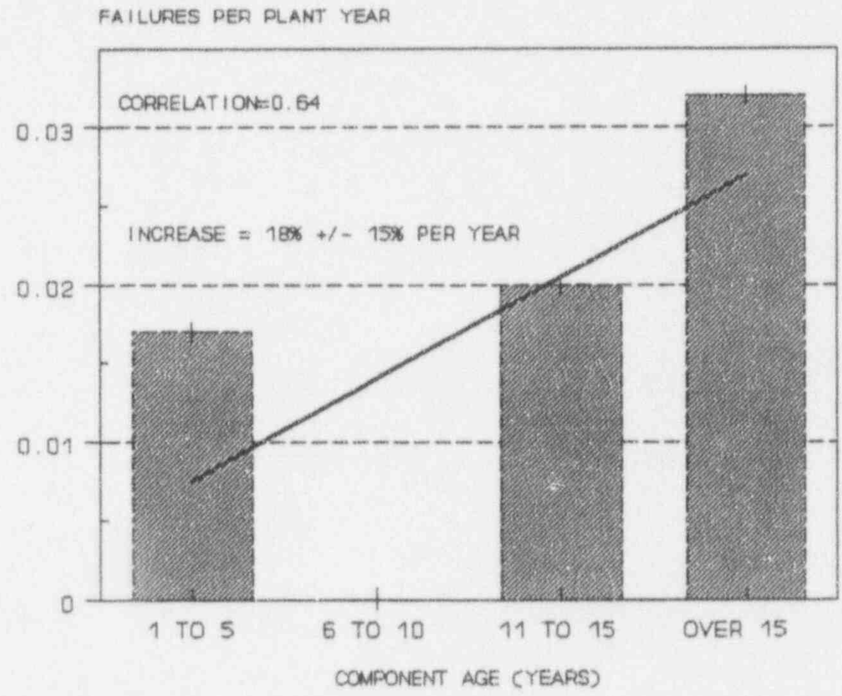


Figure 6.3 Failure trend versus age for containment spray pump failure to run

Of the fan cooler components examined, dampers were found to have the highest increase in failures with age. For dampers failing to open, an increasing trend of 22% ± 15% per year was found, with a correlation coefficient of 0.74 (Figure 6.6). If the failure rate were to increase at this rate, it would reach approximately 4.4 times its original value in 20 years. This is based on zero failures in the first five years of service, as found in the data analyzed. It is possible that there could be a step change in failure rate after five years. This was also analyzed, however the linear regression correlation coefficient of 0.09 was obtained, indicating that the data are not well represented and no meaningful trend can be obtained from the data.

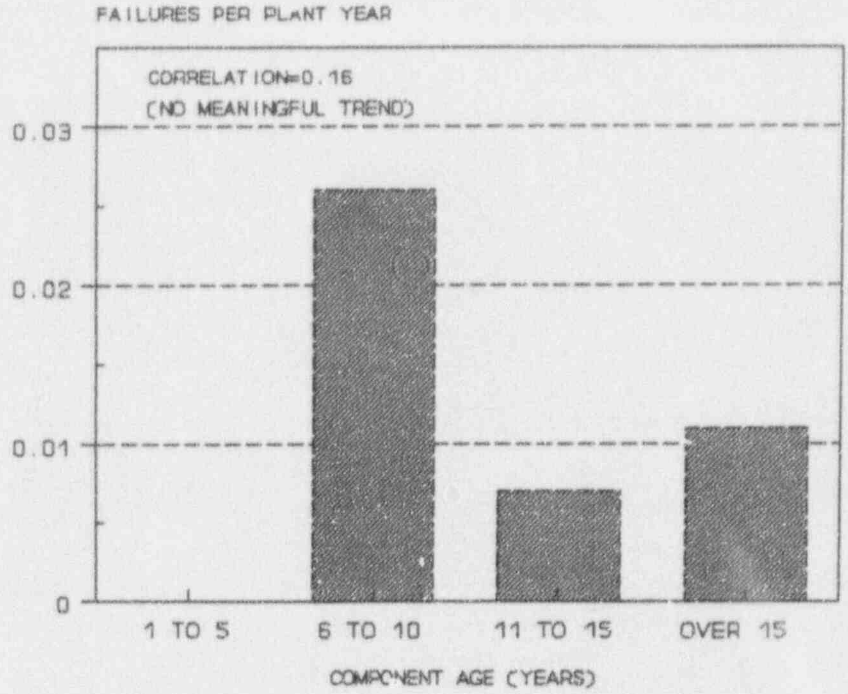


Figure 6.4 Failure trend versus age for pump failure to start

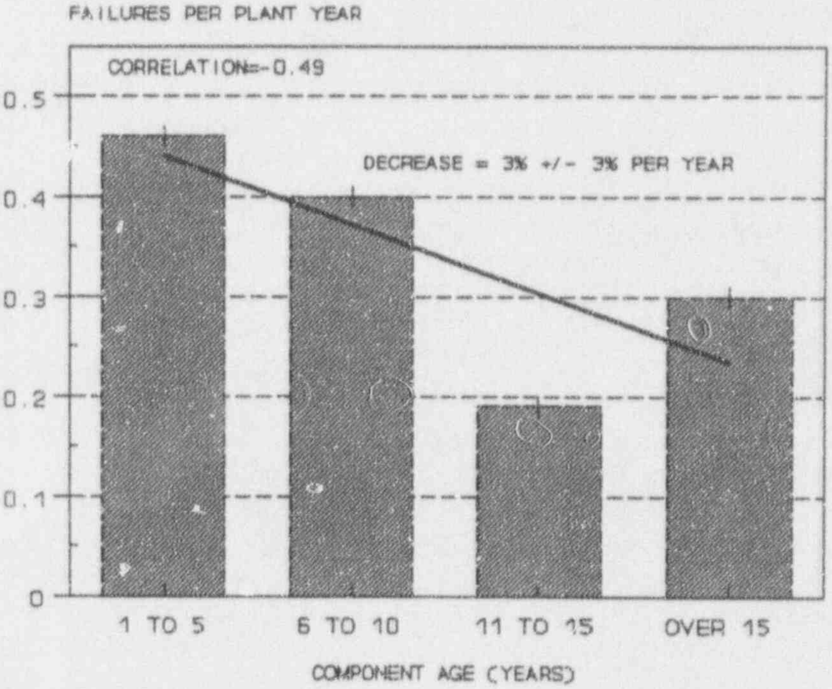


Figure 6.5 Failure trend versus age for MOV failure to open

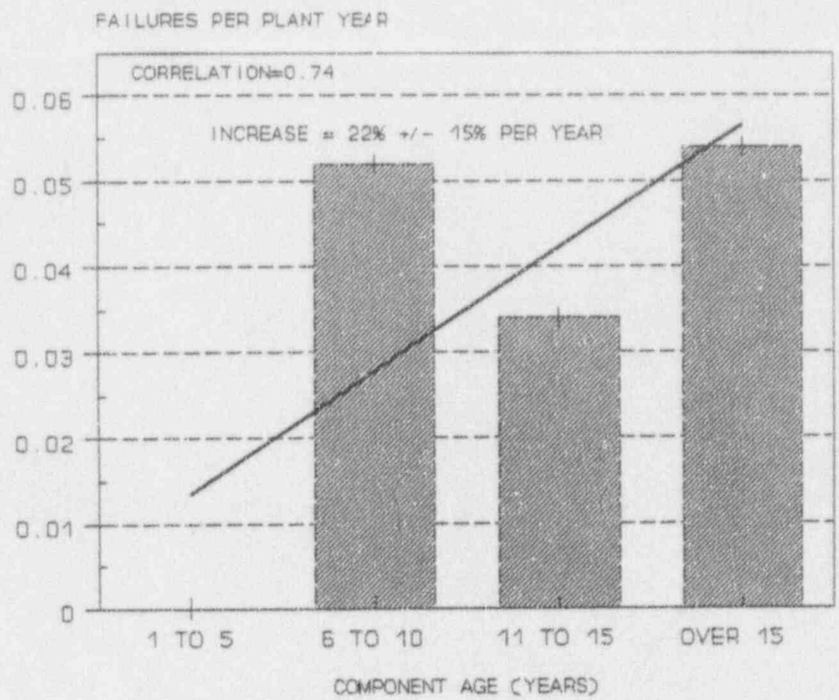


Figure 6.6 Failure trend versus age for fan cooler dampers

Circuit breakers showed the next largest trend, with an increase of 8% ± 8% per year for breakers failing to open (Figure 6.7). The correlation coefficient was calculated to be 0.61 for this data. This rate of increase would cause the breaker failure rate to approximately double in 20 years (Table 6.5).

Analysis of the fan motor data resulted in a poor correlation coefficient of 0.09, indicating that no meaningful trend could be obtained from the data (Figure 6.8).

The failure trend analysis shows that there is a trend toward increasing numbers of failures with age for most of the important components. If these trends are allowed to continue, they could impact system unavailability. To demonstrate this, system unavailability was calculated as a function of age assuming the components aged according to the trends observed in the above analysis. For the containment spray system it was assumed that pump failure rates increased at a rate of 18% per year, while all other component failure rates remained constant. This resulted in system unavailability increasing at a rate of approximately 2.6% per year. This is shown in Figure 6.9 in which system unavailability is normalized to equal one in the first year, and plotted as a function of age. Similarly, for fan coolers it was assumed that damper failure rates increased at a rate of 22% per year. This resulted in a 47% increase in fan cooler system unavailability per year (Figure 6.10).

It should be noted that these results are based on data from a national database, which can only be viewed as industry averages. These results can not be assumed to be representative of any specific plant since actual plant failure rates will differ based on plant specific factors, such as maintenance programs, component manufacturers, and person-

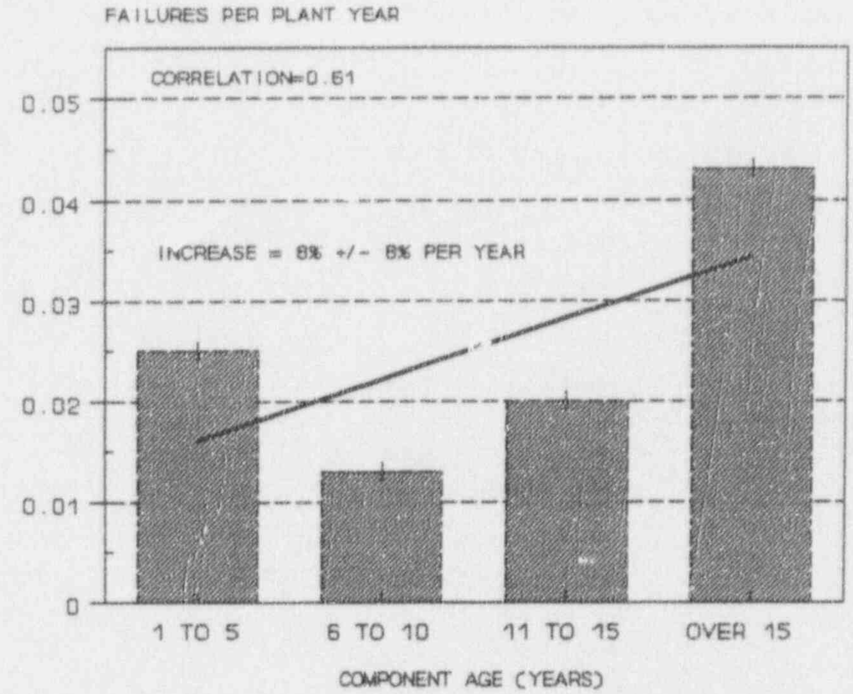


Figure 6.7 Failure trend versus age for fan cooler circuit breakers

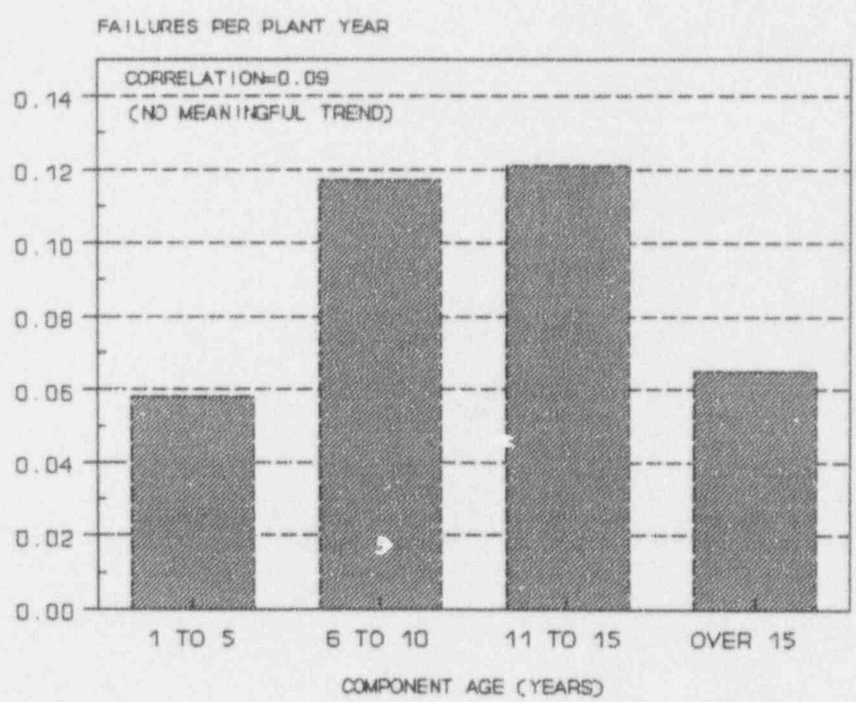


Figure 6.8 Failure trend versus age for fan cooler motors

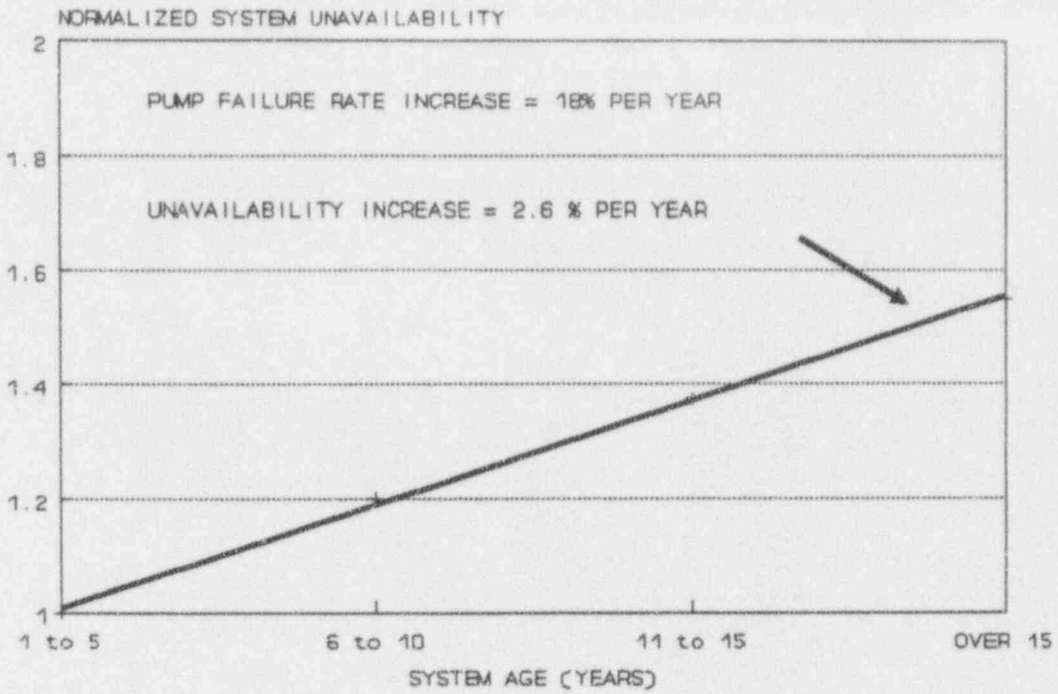


Figure 6.9 Containment spray system unavailability versus age

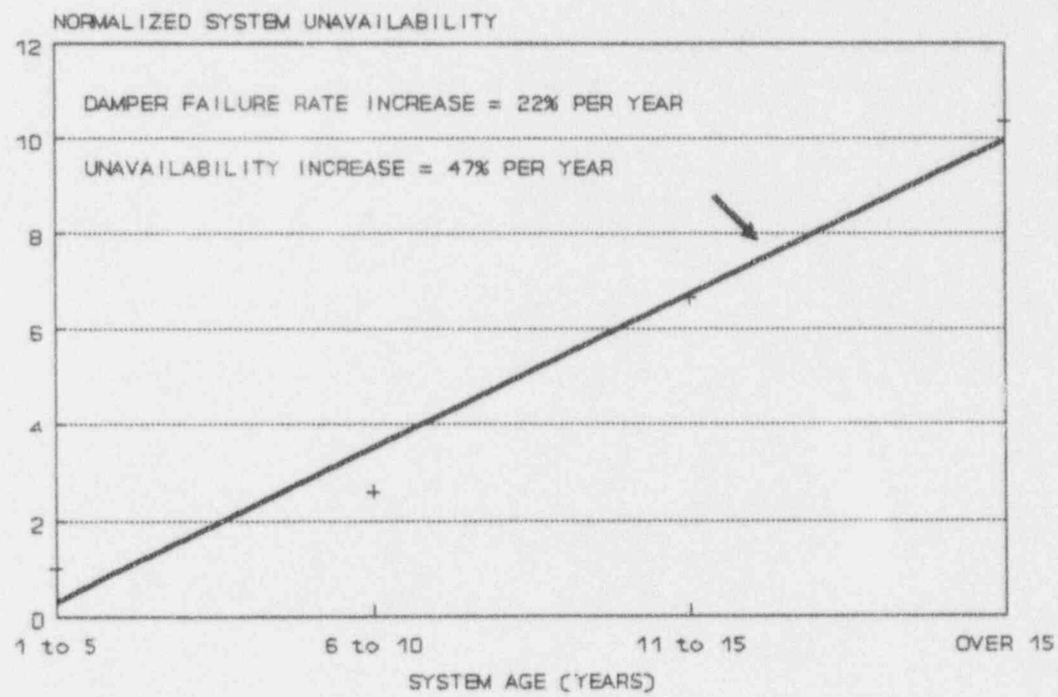


Figure 6.10 Fan cooler system unavailability versus age

nel attentiveness to component and system performance. Some individual plant component failure rates will be lower and some higher. The findings discussed here are only presented to show the potential effects of aging degradation, and to demonstrate how certain components can be more important than others in relation to their contribution to system unavailability.

7. RESULTS

This study has examined a number of different areas related to the containment cooling system to provide an understanding of the aging process in this system. This section discusses the results obtained.

7.1 FSAR Reviews

The review of FSARs provided insights into the various systems used to provide the containment cooling function and how they operate. Those systems used to mitigate the consequences of an accident were the focus of this study. In PWRs, containment cooling is typically provided by a containment spray system, along with several fan cooler units located inside containment. In BWRs, containment cooling is typically provided by the RHR system operating in either the suppression pool cooling mode or the containment spray mode.

The containment spray systems in PWRs pump water from the refueling water storage tank or the containment sumps to spray headers located inside containment to condense steam following a LOCA or MSLB. This mitigates any pressure or temperature increases inside containment. The spray systems in BWRs operate similarly, except the source of water is the suppression pool. This system is only used during accident conditions and is normally maintained in standby status. For PWRs which have dedicated containment spray pumps, this reduces the exposure to operating stresses, which can result in aging degradation.

The primary source of operating stress for these components is test and maintenance related activities. Pumps and associated components in systems which use the RHR pumps for containment spray are exposed to more operating stress since the RHR system must function in other non-accident related operating modes, such as shutdown cooling or fuel pool cooling.

Most fan cooler units are used during normal, as well as accident conditions in PWRs. Although BWRs also have fan coolers, they are typically not designed to operate during accident conditions. The fan coolers operate by passing air from the containment atmosphere over cooling coils and, in some designs, through filters. The cooling coils are typically supplied with water by the component cooling water or service water system to cool the air flowing over them. Duct work and dampers direct the air flow to specific areas of the containment. The number of fan coolers in use at any time depends on the operating conditions of the plant. However, since the fan coolers are used during normal plant operation they are in service more than the containment spray components, and are, therefore, exposed to more frequent operating stresses.

7.2 Review of Operating and Environmental Stresses

The review of operating and environmental stresses identified those stresses the containment cooling systems are exposed to and the potential aging mechanisms that may result from these stresses. The degree to which the various components are affected by these aging mechanisms is dependent upon the time they are exposed to them. For example, for containment spray pumps which are normally maintained in a standby status during plant operation, erosion due to prolonged periods of internal water flow are not expected to be a problem. However, these same pumps can experience degradation to their gaskets and seals due to external environmental conditions, such as humidity or high temperature. Monitoring for gasket/seal degradation should, therefore, be included in the plant monitoring program for these components. In a similar manner, plant monitoring programs should be reviewed to ensure that each of the potential aging mechanisms identified for the most critical components has been addressed.

7.3 Results from the Failure Data Analysis

The failure data analysis has shown that aging degradation is present in the containment cooling systems, and that it is a significant contributor to failures within the system. For the containment spray system approximately 60% of the failures reviewed were related to aging, while for fan coolers the aging fraction was approximately 50%. This clearly shows that degradation due to aging must be properly monitored and managed to mitigate excessive failures and system unavailability.

Containment spray system failures are most often detected by inspections and surveillance tests while the system is in test or standby mode. Only a small percentage of failures are detected while the system is in operation. This is due to the primarily standby status of the system during normal plant operation. Since the components are not frequently operated, many of the incipient failures would not be detected if periodic inspections and surveillance tests were not performed. This finding illustrates the importance of inspections and surveillance tests for this system, as well as other standby systems. For the fan cooler units, since they are used during normal plant operation, the majority of their failures are detected while the units are in service. The methods used include inspections and observation of abnormal operation. Test results are also useful for detecting fan cooler failures.

For both the containment spray and the fan cooler systems, the predominant cause of failure was found to be normal service. This indicates that the components are not being subjected to any unusual or unexpected stresses, and that aging degradation due to normal operating stresses is the primary contributor to failure. It should be noted that normal operating stresses cannot be completely eliminated from component operation. However, a good aging management program should mitigate these stresses as much as possible, and be able to monitor the degradation they cause so that it can be controlled before it results in failure.

The data also show that 15% to 20% of the failures are due to human errors involving maintenance. This includes events where a component is repaired improperly and does not operate when reinstalled, as well as events where a component is repaired then improperly reinstalled. Therefore, if an effort is made to reduce human error related failures, it should be concentrated in the area of maintenance, and restoration from test and maintenance.

Failures in the containment spray system most frequently result in degraded operation of the system. This implies that the system can still perform its design function, however, it is not operating as efficiently as possible. For example, a pump seal leak that is not severe enough to result in the pump failing to run is considered a failure since the pump must be taken out of service for repair. However, the pump could still be operated for some time should it be required. This would be considered a degraded operating state for the system. In the data analyzed (1986 to 1991), no failures were found which resulted in a complete loss of containment spray system function.

The fan cooler unit failures most frequently resulted in a loss of redundancy. This is due to the nature of the fan cooler system design, where each unit is considered a redundant train. The most frequent failures are dampers failing to operate, circuit breakers failing to function, or cooling coils developing leaks. These types of failures typically require the unit to be taken out of service for repair, which effectively results in a loss of redundancy. As for the containment spray system, no failures were found in the data analyzed (1986 to 1991) which resulted in a complete loss of fan cooler system function. However, one incident in 1980 was found where corrosion of cooling coils resulted in a complete loss of fan cooler system function in one plant.

The component most frequently failed in the containment spray system is valves. This is a common and expected finding for systems such as this since valves typically have the largest population of any of the components. However, this does indicate that valves require the most attention in terms of man-hours to properly monitor and control aging degradation. It is, therefore, important to have effective and efficient monitoring methods for valves in plant programs. The second most frequently failed components in the containment spray system are instrumentation/controls, and this is followed by circuit breakers, pumps, and heat exchangers. Each of these components should be addressed in plant programs to properly mitigate aging related failures in this system.

The most frequently failed component in the fan cooler system is circuit breakers. Typical failures are failure of the breaker to open or close due to wear of internal subcomponents or burning/pitting of contacts. This is followed by instrumentation/controls, valves, heat exchangers, fan motors, and blowers. Aging of each of these components should be addressed in plant programs.

The predominant aging mechanisms and failure modes for each of the most frequently failed components were identified from the data. This information can be used to help select effective monitoring and maintenance practices to properly manage aging degradation. The aging mechanisms and failure modes for containment spray and fan cooler components are summarized in Table 7.1 and Table 7.2, respectively. It should be noted that this information is based on generic data, and that individual plant designs may cause other failures to dominate.

7.4 Results from the Review of Plant Specific Data

The plant specific data were collected and reviewed to supplement and validate the results of the national database findings. From the data collected at a PWR plant, it was seen that a large percentage of the failures were related to aging degradation, which is consistent with the database findings. For the containment spray system, the most frequently failed component was valves, while for the fan cooler system the most frequently failed component was instrumentation/controls.

In addition to component failure information, the plant specific data provided information on the surveillance and maintenance practices currently used for the containment cooling systems. These are summarized for the containment spray and fan cooler systems in Tables 5.1 and 5.2, respectively.

7.5 Results of the System Unavailability Analyses

The system unavailability analyses showed that increases in failure rates due to aging can adversely effect system unavailability. For the containment spray system design analyzed, the dominant contributor to system unavailability was found to be a human error involving failure to reposition manual valves following surveillance testing. For components that could be affected by aging, pumps and MOVs were found to be important to system unavailability. Check valves failing to open and spray nozzle plugging showed only a small contribution due to the relatively small failure rates associated with them.

Table 7.1 Summary of Aging Mechanisms and Failure Modes for Containment Spray System Components

Component	Major Aging Mechanisms	Percentage	Major Failure Modes	Percentage
Valves	- Wear - Adjustment Drift - Galling Binding - Dirt/Dust Intrusion - Short/Burnout - Loss of Lubrication	49% 17% 14% 7% 4% 3%	- Leakage - Does Not Open - Does Not Close - Does Not Operate - Exceeds Limit	58% 18% 11% 8% 3%
Instruments & Controls	- Calibration Drift - Wear - Internal Defects - Contamination - Degradation of Power Supply - Binding	39% 27% 22% 5% 4% 3%	- Incorrect Reading/ Loss of Function	100%
Circuit Breakers	- Adjustment Drift - Galling Binding - Short/Burnout - Wear - Dirt/Dust Intrusion - Loss of Lubrication - Fatigue - Corrosion	22% 17% 17% 16% 9% 7% 4% 3%	- Does Not Close - Does Not Open - Does Not Operate	59% 18% 17%
Pumps	- Wear - Galling/Binding - Adjustment Drift - Short/Burnout - Service Outside Limits - Dirt/Dust Intrusion - Fatigue	62% 14% 10% 3% 3% 2% 2%	- Leakage - Does Not Run - Does Not Start	48% 24% 14%
Heat Exchangers	- Plugging/fouling - Corrosion - Wear - Vibration	62% 21% 6% 4%	- Plugged - Leakage - Fouled	66% 15% 15%

The parametric analyses simulated increasing failure rates due to aging. For the containment spray system, increases in pump and MOV failure rate were found to have the greatest effect on system unavailability. For a ten fold increase in pump failure rate, system unavailability increased by a factor of three, and the pump contribution to system unavailability exceeds that of the human error. Similarly for MOVs, for a ten fold increase in failure rate system unavailability also increases by a factor of three. It is therefore important that aging of pumps and MOVs be carefully monitored and controlled.

The parametric analyses showed that the effect of increasing failure rates for check valves and nozzles had a minimal influence on containment spray system unavailability. This is due to the relatively small initial failure rates associated with these components. These results show that system unavailability is dominated by those basic events which have the largest failure rate. However, it should be noted that these results are based on the analysis of one specific system design. Findings for other designs may be different.

Table 7.2 Summary of Aging Mechanisms and Failure Modes for Fan Cooler System Components

Component	Major Aging Mechanisms	Percentage	Major Failure Modes	Percentage
Circuit Breakers	- Short/Burnout/Pitting - Wear - Adjustment Drift - Fatigue/Cracking - Galling Binding - Dirt/Dust Intrusion - Loss of Lubrication - Corrosion	30% 15% 14% 13% 10% 6% 2% 1%	- Does Not Close - Does Not Open - Does Not Operate	67% 17% 6%
Instruments & Controls	- Calibration Drift - Wear - Short/Burnout - Contamination - Binding	22% 22% 20% 17% 4%	- Incorrect Reading/ Loss of Function	100%
Dampers	- Wear - Galling/Binding - Adjustment Drift - Fatigue/Cracking - Short/Burnout/Pitting - Loss of Lubrication - Dirt/Dust Intrusion	23% 22% 17% 11% 6% 6% 5%	- Does Not Close - Does Not Operate - Does Not Open - Leakage	40% 21% 20% 15%

The analysis for fan cooler units showed no dominant single contributor to system unavailability. The largest single contributor was a common mode failure of the fan motors. Based on cumulative contributions, maintenance unavailability was the largest contributor to system unavailability, followed by dampers failing to open, circuit breaker malfunction, and fan motor failures. The high contribution from maintenance is due to the relatively large value for unavailability used in the model. This value was obtained from plant specific data and can be attributed in part to a technical specification limiting condition for operation (LCO) that allows two fan cooler units to be out of service at the same time. Also from the analysis, cooling coils did not show a significant influence on system unavailability.

The parametric analyses for fan cooler units showed increases in damper failure rate to have the largest effect on system unavailability. For a ten fold increase in failure rate, system unavailability increases by a factor of approximately 66. In interpreting this result it should be noted that the study modeled the four internal dampers in the fan cooler units as one large damper which is consistent with the plant PRA the study is based on. Other modeling approaches could affect the damper contribution to overall system unavailability. However, these results show that dampers are important to fan cooler unit availability. Therefore, aging degradation of these components should be properly monitored and controlled to mitigate increases in failure rates.

Circuit breakers were also found to influence fan cooler availability when failure rates were increased. When circuit breaker failure rate increases by a factor of 10, system unavailability increases by a factor of approximately 13. Therefore, proper aging management of circuit breakers is also important.

Increases in fan motor failures and cooling coil failures were also examined. The results showed little or no effect on system unavailability for increases in failure rates for these components. This is due to the relatively small initial failure rates for these components as compared to dampers and circuit breakers.

To determine the feasibility of these PRA findings, the data were analyzed to identify any time-dependent trends in component failures. For the containment spray system, an increasing trend was found for pumps, however, MOVs showed a slight decrease in failures with age. For pump failure to run, the increasing trend would triple the failure rate in 20 years. The fan cooler dampers also showed an increasing trend with age. The damper failure rate would increase by a factor of 4.4 in twenty years if the trend continued.

Although the trends observed in the data do not indicate a ten fold increase in failure rates for a life expectancy of 20 years, they do show that some component failures are increasing with age. The degree to which failure rates increase will vary from plant to plant depending on many plant specific factors, therefore, the trends observed from this analysis cannot be considered generic. However, they do indicate that the potential exists for failure rates to increase and this should be addressed in the management of aging in plant programs. This would be particularly important for plants considering extended life operation since the current trends could increase with age.

Using the failure trends calculated from the data, system unavailabilities were calculated as a function of age. For the containment spray system, a pump failure rate increase of 18% per year was used. No other component failure rates were increased. This resulted in a yearly system unavailability increase of 2.6%, which would increase system unavailability by over 50% over the course of a 20 year life, if the trends were to continue. For the fan cooler units, a damper failure rate increase of 22% per year was used, with no other component failure rates increasing. This resulted in a yearly system unavailability increase of 47%, which would result in an increase in unavailability by over a factor of nine over the course of a 20 year life.

It should be noted that these results are based on one specific system design, and data from a national database, which can only be considered to represent industry averages. The intention of presenting these results is to show that the potential exists for failure rates to increase with age, and that these increases can have an adverse effect on system unavailability. This helps to recognize the importance of effectively managing aging. The actual extent to which failure rates increase and the degree to which they affect system performance can only be determined accurately by performing a plant specific analysis.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Phase I Study

The results of this phase I study have helped to understand the aging process in containment cooling systems and how it can be better managed. The predominant aging mechanisms and failure modes have been determined, and the components most frequently affected by aging degradation have been identified. In addition, trends for increasing failure rates with age, and their potential affect on system unavailability have been examined. This information serves to characterize the effects of aging on the containment cooling system, and provides a technical basis upon which future work can be performed. The following specific findings have also resulted from this study:

- Aging degradation exists in containment cooling systems and is a significant contributor to failures. Since these systems play an important role in accident mitigation, plant programs should specifically address aging of containment cooling systems. Each of the aging mechanisms identified in this study should be addressed by at least one monitoring technique.

- The failure data show that most containment spray system failures are detected by surveillance tests and inspections. This is significant since it shows the importance of performing tests and inspections on standby systems to detect degradation before it results in an operational failure.

- There are a number of stresses that cause the various aging mechanisms to become active a d lead to degradation. The predominant stresses have been identified and can be used to develop an effective monitoring program.

- The data show that maintenance related failures are the most common human error type failure. It is recommended that if efforts to reduce human errors are made, they should be concentrated in the area of maintenance, and restoration from test and maintenance.

- The review of industry and plant specific data has shown that the failures occurring in the containment cooling systems are usually not severe enough to result in a complete loss of system function. Typically, the most severe failure will result in a loss of redundancy, however, the system is still able to perform its design function. No aging related failures were found in the data analyzed (1986 to 1991) that resulted in a complete loss of system function. However, one incident in 1980 was found in which aging led to a loss of fan cooler system function. This finding shows the importance of designing these systems with sufficient redundancy.

- Failures for some of the risk significant components show a trend for increasing failure rates with age. This increasing trend can result in a corresponding increase in system unavailability with age, if the trend is not properly controlled. It is recommended that plant programs include a similar plant specific analysis to identify any time-dependent trends in component failure rates so they can be properly managed.

8.2 Future Work

The results of this phase I study have shown that aging degradation is present in containment cooling systems and that it contributes to system failures. It is therefore important to institute effective monitoring and maintenance practices to ensure that aging degradation is properly managed This study has identified the predominant aging characteristics and some of the practices currently used to manage them. Based on the findings from this phase I study, it is recommended that a phase II study be performed. In the phase II study a more detailed look at monitoring and maintenance practices could be performed to determine which practices are the most effective for detecting and mitigating aging degradation. Specific tasks could include the following:

- An in-depth review of current plant maintenance, monitoring, and inspection practices could be performed to identify their strengths and weaknesses. The review could be based on plant specific information, as well as a survey of all operating plants.

- Generic listings of inspection, test, and maintenance practices for each of the risk significant components could be developed. These listings will be useful for reviewing existing aging management programs, or for developing new ones.

- Recommendations could be made regarding specific activities that can be used to formulate effective aging management practices for containment cooling systems. These recommendations could address the most common types of aging problems exhibited industry wide, and problems specific to certain plant operating conditions.

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APPENDIX A

CONTAINMENT SPRAY SYSTEM DESIGN INFORMATION

LIST OF TABLES

Table A.1 Containment Spray Data for Westinghouse Large Dry Containments

Design Parameter	Plant			
	Indian Point Unit 2	**Indian Point Unit 3**	**Zion Units 1&2**	**Diablo Canyon Units 1&2**
		Containment Spray Pumps		
Type:	Horizontal Centrifugal	Horizontal Centrifugal	Horizontal Centrifugal	Horizontal Centrifugal
Material:	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Quantity:	2	2	3	2
Design Pressure (PSIG):	300	300	-	275
Design Temperature (°F):	300	300	-	275
Design Flow Rate (GPM):	2600	2600	3000	2600
Design Head (Ft.):	450	427	477	450
Motor Horsepower:	400	400	600 (electric) 480 (diesel)	-
		Containment Spray Nozzles		
Type:	Hollow Cone Ramp Bottom	Hollow Cone Ramp Bottom	Spraco 1713	Spraco 1713
Quantity:	315	315	343	343
Design Flow (GPM @ PSID):	15 @ 40	15 @ 40	15.2 @ 40	15.2 @ 40
Orifice Size (Inches):	0.325	0.375	-	0.375
		Eductors		
Quantity:	2	2	3	2
Design Pressure (PSIG):	195	195	400	200
Design Temperature (°F):	Ambient	Ambient	400	250
Design Flow (GPM):	112	112	260	-
Suction Flow (GPM):	29.5	29.5	50	55
Suction Fluid:	30% NaOH	30% NaOH	30% NaOH	-
		Spray Additive Tank		
Quantity:	1	1	1	-
Volume (gallons):	5100	5100	5000	-
Design Pressure (PSIG):	300	300	Atmospheric	-
Design Temperature (°F):	300	300	150	-
Operating Temperature (°F):	110 maximum	110 maximum	-	-

Table A.1 Containment Spray Data for Westinghouse Large Dry Containments (cont'd.)

Design Parameter	Plant			
	Byron 1&2 Braidwood 1&2	**Calloway & Wolf Creek**	**Vogtle Units 1&2**	**South Texas Units 1&2**
Containment Spray Pumps				
Type:	Vertical Centrifugal	Vertical Centrifugal	Horizontal Centrifugal	Vertical Centrifugal
Material:	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Quantity:	2	2	2	3
Design Pressure (PSIG):	-	450	300	495
Design Temperature (°F):	-	300	250	300
Design Flow Rate (GPM):	3415 Train A 3925 Train B	3165 Injection 3750 Recirc	2600	1900
Design Head (Ft.):	450	464 Injection 400 Recirc	450	560
Motor Horsepower:	-	500	-	-
Containment Spray Nozzles				
Type:	Spraco	Hollow Cone	Spraco 1713	Hollow Cone
Quantity:	219 Train A 253 Train B	394	342	-
Design Flow (GPM @ PSID):	15 @ 40	15.2 @ 40	15.2 @ 40	-
Orifice Size (Inches)	-	0.438	0.375	0.375
Eductors				
Quantity:	2	2	2	3
Design Pressure (PSIG):	300	-	300	-
Design Temperature (°F):	300	-	300	265
Design Flow (GPM):	130	-	-	-
Suction Flow (GPM):	55	44	39.3	-
Suction Fluid:	-	-	30% NaOH	30% NaOH
Spray Additive Tank				
Quantity:	1	-	1	3
Volume (gallons):	5000	-	4000	1750
Design Pressure (PSIG):	1.3	-	10	100
Design Temperature (°F):	100	-	Ambient	120
Operating Temperature (°F):	-	-	Ambient	65 to 104

Table A.2 Containment Spray Data for B&W and CE Large Dry Containments

Design Parameter	Plant			
	Davis Besse	**Bellefonte Units 1&2**	**Millstone Unit 2**	**Palo Verde Units 1,2,&3**
Containment Spray Pumps				
Type:	Horizontal Centrifugal	Horizontal Centrifugal	Horizontal Centrifugal	Vertical Centrifugal
Material:	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Quantity:	2	2	2	2
Design Pressure (PSIG):	200	350	500	650
Design Temperature (°F):	300	300	300	400
Design Flow Rate (GPM):	2600	2040	1350 Injection 1650 Recirc	3500
Design Head (Ft.):	400	575	450 Injection 360 Recirc	525
Motor Horsepower:	200	-	250	800
Containment Spray Nozzles				
Type:	Full Cone	Spraco 1713	Spraco 1713	Spraco 1713
Quantity:	180	-	180	460
Design Flow (GPM @ PSID):	15 @ 15	15 @ 40	15 @ 40	15.2 @ 40
Orifice Size (Inches)	-	0.375	0.375	-
Spray Additive Tank				
Quantity:	-	-	-	1
Volume (gallons):	-	-	-	850
Design Pressure (PSIG):	-	-	-	15
Design Temperature (°F):	-	-	-	150
Operating Temperature (°F):	-	-	-	60
Chemical Injection Pumps				
Type:	NA	NA	NA	Positive Displacement
Quantity:	NA	NA	NA	2
Capacity (GPM):	NA	NA	NA	0.63
Design Pressure (PSIG):	NA	NA	NA	200
Design Temperature (°F)	NA	NA	NA	150
Motor Horsepower:	NA	NA	NA	1

Table A.3 Containment Spray Data for Westinghouse Subatmospheric and Ice Condenser Containments

Design Parameter	Plant			
	Beaver Valley Unit 1	**Beaver Valley Unit 2**	**McGuire Units 1&2**	**Catawba Units 1&2**
Containment Spray Pumps				
Type:	Horizontal Centrifugal	Horizontal Centrifugal	Vertical Centrifugal	Vertical Centrifugal
Material:	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Quantity:	2	2	2	2
Design Pressure (PSIG):	250	250	300	300
Design Temperature (°F):	-	150	200	190
Design Flow Rate (GPM):	2000	3000	3400	3400
Design Head (Ft.):	285	300	380	400
Motor Horsepower:	-	350	400	500
Recirculation Spray Pumps				
Type:	Vertical Deep-Well	Vertical Deep-well	NA	NA
Quantity:	4	4	NA	NA
Design Flow (GPM):	3300	3500	NA	NA
Design Pressure (PSIG):	265	268	NA	NA
Design Temperature (°F):	280	280	NA	NA
Design Head (Ft.):	260	266	NA	NA
Motor Horsepower:	300	350	NA	NA
Containment Spray Heat Exchangers				
Quantity:	4	4	2	2
Design Load (BTU/HR):	6.1×10^7	1.43×10^8	-	-
Shell Side Fluid:	Recirculation Water	Recirculation Water	Service Water	Service Water
Tube Side Fluid:	Service Water	Service Water	Recirculation Water	Recirculation Water
Design Pressure (PSIG) - Tube Side: - Shell Side:	 150 150	 250 250	 230 200	 250 150
Design Temperature (°F) - Tube Side: - Shell Side:	 280 280	 250 250	 200 200	 200 200

Table A.3 Containment Spray Data For Westighouse Subatmospheric and Ice Condenser Containments (cont'd.)

Design Parameter	Plant			
	Beaver Valley Unit 1	Beaver Valley Unit 2	McGuire Units 1&2	Catawba Units 1&2
Cooling Water Flow (GPM):	4,000	5,500	5,000	3,400
Material - Tube Side: - Shell Side:	Stainless Steel Stainless Steel	Stainless Steel Stainless Steel	Stainless Steel Carbon Steel	- -
Containment Spray Nozzles				
Type:	Spraying System	Spraco 1713	Spraco 1713	Spraco 1713
Quantity:	-	159	-	223
Design Flow (GPM @ PSID):	15 @ 15	15.2 @ 40	15.2 @ 40	15.2 @ 40
Orifice Size (Inches)	-	0.375	0.375	0.375
Spray Additive Tank				
Quantity:	1	1	-	-
Volume (gallons):	5,200	10,000	-	-
Design Pressure (PSIG):	Atmospheric	26	-	-
Design Temperature (°F):	150	150	-	-
Operating Temperature (°F):	-	50 to 95	-	-
Chemical Injection Pumps				
Type:	Horizontal Centrifugal	Positive Displacement	NA	NA
Quantity:	1	2	NA	NA
Capacity (GPM):	54	55 to 60	NA	NA
Design Pressure (PSIG):	225	150	NA	NA
Design Temperature (°F)	Ambient	180	NA	NA
Motor Horsepower:	5	5	NA	NA

APPENDIX B

FAN COOLER SYSTEM DESIGN INFORMATION

LIST OF TABLES

Table B.1 Fan Cooler Data for Westinghouse Large Dry Containments

Design Parameter	Plant			
	Indian Point Unit 2	**Indian Point Unit 3**	**Zion Units 1&2**	**Diablo Canyon Units 1&2**
Fans				
Type:	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Quantity:	5 @ 20%	5 @ 20%	5 @ 20%	5 @ 20%
Design Capacity (CFM) - normal mode: - accident mode:	 70,000 65,000	 70,000 34,000	 87,500 66,000	 110,000 47,000
Operating Speed (RPM) - nomal mode: - accident mode:	 1,200 1,200	 720 720	 1,200 900	 1,200 600
Motor Horsepower - normal mode: - accident mode:	 350 350	 225 219	 200 200	 300 100
Cooling Coils				
Material:	AL6X	AL6X	AL6X	Copper
Heat Removal (BTU/HR) - normal mode: - accident mode:	 2.2×10^6 81×10^6	 2.3×10^6 49×10^6	 3.9×10^6 120×10^6	 3.14×10^6 81×10^6
Cooling Water Source:	Service Water	Service Water	Service Water	Component Cooling Water
Cooling Water Flow (GPM):	2000	1400	2200	2000
Cooling Water Inlet (°F):	95	95	80	90
Design Ambient (°F):	130	130	120	120
Tube Diameter (Inches):	0.625	0.625	0.625	0.625
Tube Thickness (Inches):	0.049	0.035	0.035	0.035
Fins Per Inch:	8	8.5	8.5	8.5

Table B.1 Fan Cooler Data for Westinghouse Large Dry Containments (cont'd.)

Design Parameter	Plant			
	Byron 1&2 Braidwood 1&2	Calloway & Wolfcreek	Vogtle Units 1&2	South Texas Units 1&2
Fans				
Type:	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Quantity:	4 @ 50%	4 @ 50%	8 @ 25%	6 @ 16.7%
Design Capacity (CFM) - normal mode: - accident mode:	106,700 73,700	140,000 67,000	97,000 43,500	53,500 53,500
Operating Speed (RPM) - nomal mode: - accident mode:	1,770 1,170	1200 600	- -	1,770 1,770
Motor Horsepower - normal mode: - accident mode:	150 100	150 75	- 62.5	150 150
Cooling Coils				
Material:	CuNi 90-10	CuNi 90-10	CuNi 90-10	Copper
Heat Removal (BTU/HR) - normal mode: - accident mode:	1.94×10^6 132×10^6	3.38×10^6 100×10^6	2.6×10^6 55×10^6	2.6×10^6 95.1×10^6
Cooling Water Source:	Service Water	Service Water	Service Water	Component Cooling Water
Cooling Water Flow (GPM) - normal mode: - accident mode:	41 2660	1100 2000	2800 2800	450 1800
Cooling Water Inlet (°F) - normal mode: - accident mode:	100	95 95	95	45 125
Design Ambient (°F):	120	-	120	120
Tube Diameter (Inches):	0.625	-	-	0.625
Tube Thickness (Inches):	0.049	-	-	-
Fins Per Inch:	8	-	-	6

Table B.2 Fan Cooler Data for B&W and CE Large Dry Containments

Design Parameter	Plant			
	Davis Besse	**Bellefonte Units 1&2**	**Millstone Unit 2**	**Palo Verde Units 1,2&3**
Fans				
Type:	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Quantity:	3 @ 50%	3 @ 50%	4 @ 33.3%	-
Design Capacity (CFM) - normal mode: - accident mode:	 58,000 117,000	 110,000 53,900	 70,000 34,800	 - -
Operating Speed (RPM) - nomal mode: - accident mode:	 Full Half	 Full Half	 1,760 875	 - -
Motor Horsepower - normal mode: - accident mode:	 - -	 - -	 75 37.5	 - -
Cooling Coils				
Material:	-	Copper	CuNi 90-10	-
Heat Removal (BTU/HR) - normal mode: - accident mode:	 1.8×10^6 75×10^6	 2.26×10^6 148×10^6	 2.2×10^6 80×10^6	 - -
Cooling Water Source:	Service Water	Service Water	Reactor Building Closed Cooling Water	- -
Cooling Water Flow (GPM) - normal mode: - accident mode:	 540 1,600	 887 2,726	 500 2,000	 - -
Cooling Water Inlet (°F):	85	95	85	-
Design Ambient (°F):	120	120	120	-
Tube Diameter (Inches):	-	-	-	-
Tube Thickness (Inches):	-	-	-	-
Fins Per Inch:	-	-	8.5	-

APPENDIX C

DESCRIPTION OF SYSTEM UNAVAILABILITY ANALYSIS FOR SELECTED PWR CONTAINMENT COOLING SYSTEMS

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C. DESCRIPTION OF SIMPLIFIED PRA ANALYSIS

C.1 Containment Spray System

C.1.1 System Description

The containment spray system model is based on the Zion plant design. This design was selected since the PRA was available in-house, and the design includes some features which are fairly common. The system is used to reduce containment pressure (and temperature) and remove iodine from the containment atmosphere following an accidental release inside containment. The system is designed to deliver, with only one pump running, enough NaOH to the containment to form an 8.8 PH solution, when combined with the refueling water and spilled reactor coolant water after the refueling water storage tank has been emptied. All components of the containment spray system are designed as Seismic Class I (ASME Class 2) and are protected from missiles which could result from a loss of coolant accident or a tornado.

The containment spray system has been divided into three independent 100% capacity subsystems with no common header. The system diagram, provided in Figure C.1, illustrates equipment redundancy and the flow path. Providing that a safety injection signal exists, all three 100% containment spray system trains will be activated by a high-high containment pressure signal or by manual initiation if required. Success of any one flow train requires that the pump starts, and that the discharge motor-operated valve opens and remains open. In addition, the MOV in the recirculation lines must remain closed, and the normally open containment isolation valves in each train must remain open.

All three pumps are 3,000 gpm horizontal centrifugal split case pumps. The three normally closed motor-operated discharge valves are set to open automatically. Motor Control Center MCC-1372 powers MOV CS-0002 in train A and is fed directly from bus 147, which also powers pump A. Similarly, MCC-1383A powers MOV CS-0004 in train B and pump B from bus 148. Pump C is diesel engine-driven (not a typical design). However, the train C MOV CS-0006 is fed from MCC-1393C. Water is supplied from the RWST through separate 14-inch diameter suction lines to each pump. Manual valves in the suction and discharge lines are locked open except during maintenance.

C.1.2 Fault Tree Description

A brief review of the FSAR and PRA information was performed to determine if the Zion design was a "typical" containment spray system. System information from Sequoyah, Surry, Calvert Cliffs, and Commanche Peak was reviewed. All had two 100% capacity trains with motor driven pumps. Most had a single normally closed MOV in the flow path. However, Surry had two normally closed MOV's in parallel for each train, which is generally a more reliable design. Calvert Cliffs had two cross ties between trains as well as a Low Pressure Safety Injection Crosstie, which could be used to mitigate MOV and pump failures. Commanche Peak has two pumps per train, both of which must operate, which is typically a less reliable system. Some plants have integral sodium hydroxide addition systems, others do not.

The containment spray fault tree (Figure C.2) modeled the Zion configuration, however, a "house event" was used to mathematically omit train C (with the diesel driven pump). In addition, a second fault tree was developed that combined the containment spray and the sodium hydroxide (NaOH) addition systems (see Section C.2).

C.2 The Sodium Hydroxide Addition System

C.2.1 Design Description

The Sodium Hydroxide Addition, (NaOH) System is an integral part of the Zion containment spray system (see Figure C.1). Eductors in each of the three containment spray pump trains draw sodium hydroxide from the 5,000 gallon spray additive tank and add the solution to the pump suction flow. The hi-hi containment pressure signal sends an opening signal to the normally closed motor-operated valves CS0002, CS0004, and CS0006. Air operated flow control valves regulate the rate of pump bypass (note that in Zion, these air-operated valves are physically prevented from full closure).

C.2.2 Fault Tree Description

The NaOH Fault Tree is presented as Figure C.3. The Tree is a combination of the containment spray and the NAOH systems, as sodium hydroxide addition is dependent on successful containment spray system operation. In a similar fashion, this tree models the Zion design in its entirety and uses a house event to turn off loop C. It should be noted that not all plants have sodium hydroxide addition to the containment spray system.

C.3 Containment Fan Cooling System

C.3.1 Design Description

Five fan cooler units, located in the Containment Building, can be used following a LOCA to remove decay heat in the containment building. During normal operation these units are operated as necessary to maintain containment temperature between 65° and 120° F. In the accident mode, the Fan Cooling System performs the same function as the Containment Spray System with the exception of iodine removal.

Following a LOCA, a safeguards actuation signal (pressure rise in containment) causes the fan coolers to switch automatically to the accident mode. Other initiation signals are:

- Any one of five Safety Injection (SI) signals
- Phase A isolation (manual push button)
- Phase B isolation (manual push button)
- High containment radiation signal

Successful accident operation requires that at least three of the fan cooler units switch to the accident mode and run as long as necessary to cool the containment atmosphere and remove radioactive particulates (a 24 hour time period is assumed). A schematic diagram of the system is provided in Figure C.4 with a detail of a fan cooler train shown in Figure C.5.

The fan coolers depend on electrical power to operate the fan motor. They also require service water to remove containment heat and to cool the fan motor. Figure C.4 shows the service water piping to the fan coolers. Note the split header arrangement that allows both service water trains to supply each fan cooler. Given an accident signal, the fan cooler unit dampers will automatically shift to the accident position. Air will then be drawn from the return air duct through the open accident inlet damper into the filtration plenum, then through moisture separators, HEPA filter, accident outlet damper, and past the cooling coil back into containment.

C.3.2 Fault Tree Description

A brief FSAR review was performed to see if the Zion fan cooler system design was typical. There is no single representative PWR design. Plants have three or more fan coil units, with one to two fans per unit. Some designs have a combination of non-safety and safety related units. The latter units are usually in standby and used as needed during normal operation. The Zion design was adopted as-is, including the system success criteria. Since the Zion PRA did not quantify unavailability at the subcomponent level (fan motors, dampers, breakers etc.) generic data was used for the purposes of this study. The fan cooler Fault Tree is presented as Figure C.6.

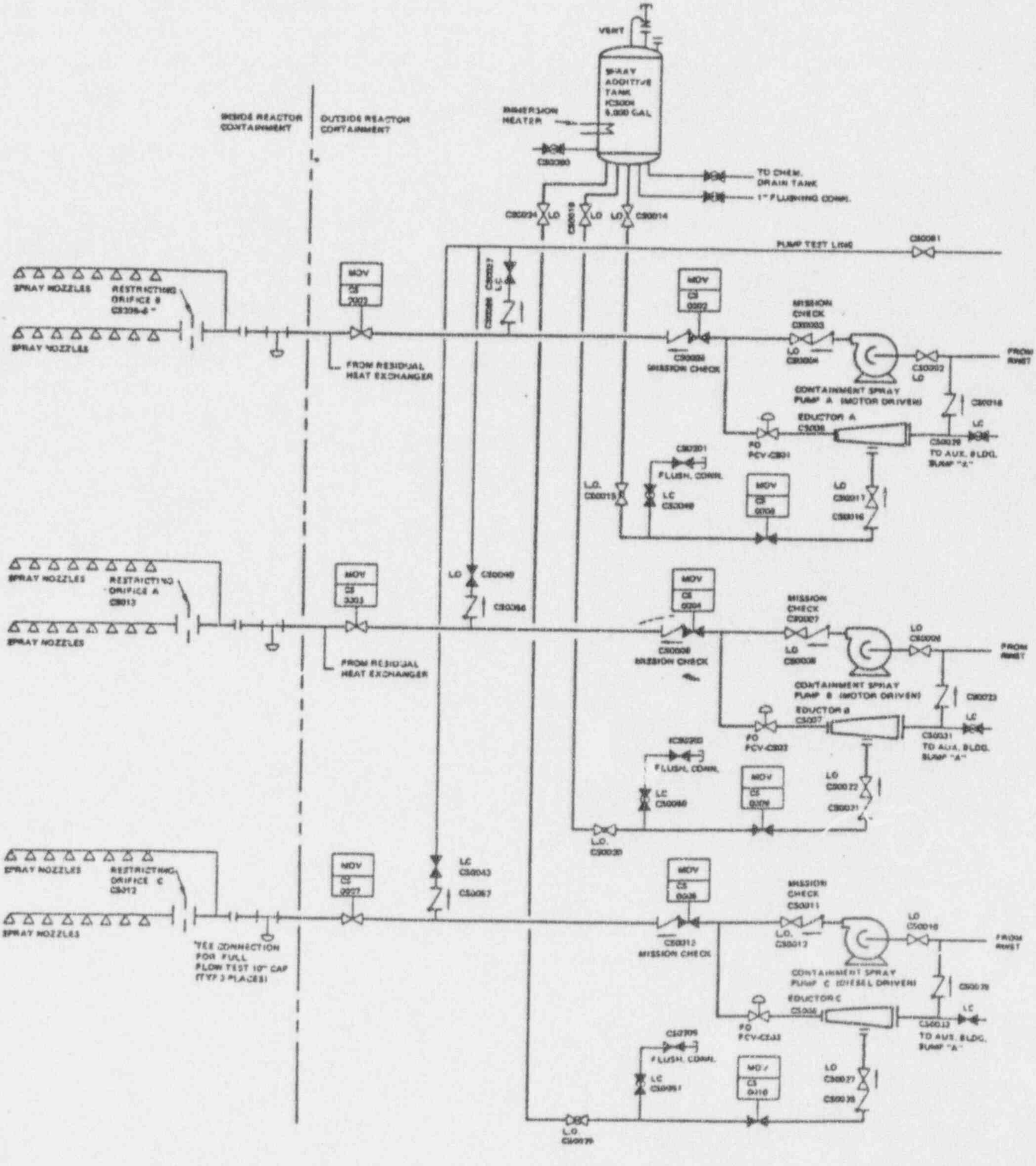
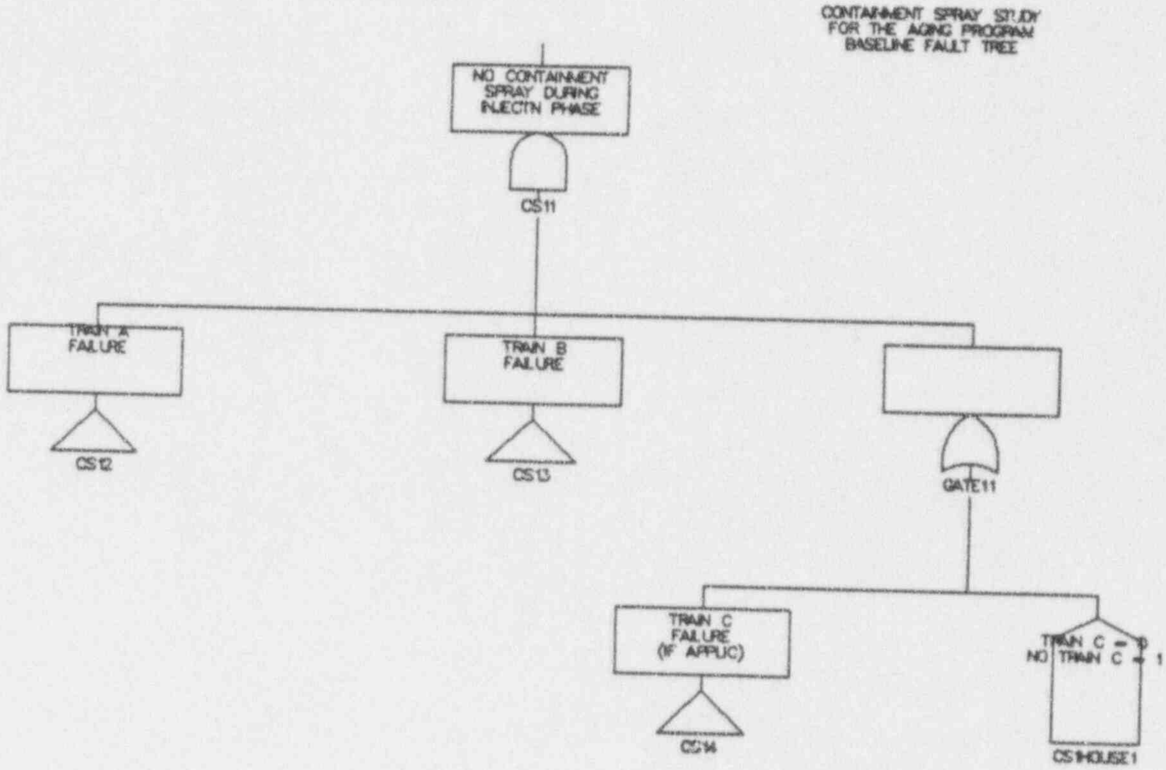


Figure C.1 Containment spray system schematic



Train A shown. The other trains are similar and are omitted here for brevity.

Figure C.2 The containment spray system fault tree

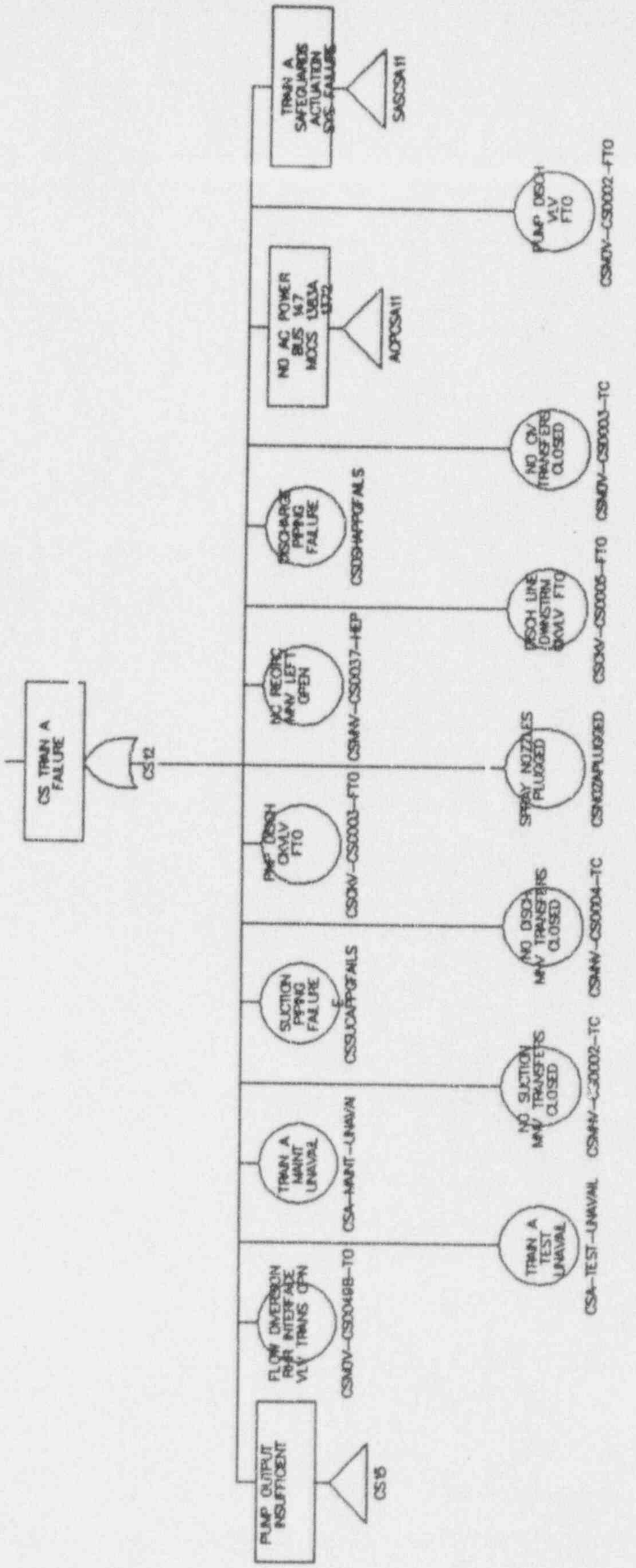


Figure C.2 The containment spray system fault tree (cont'd)

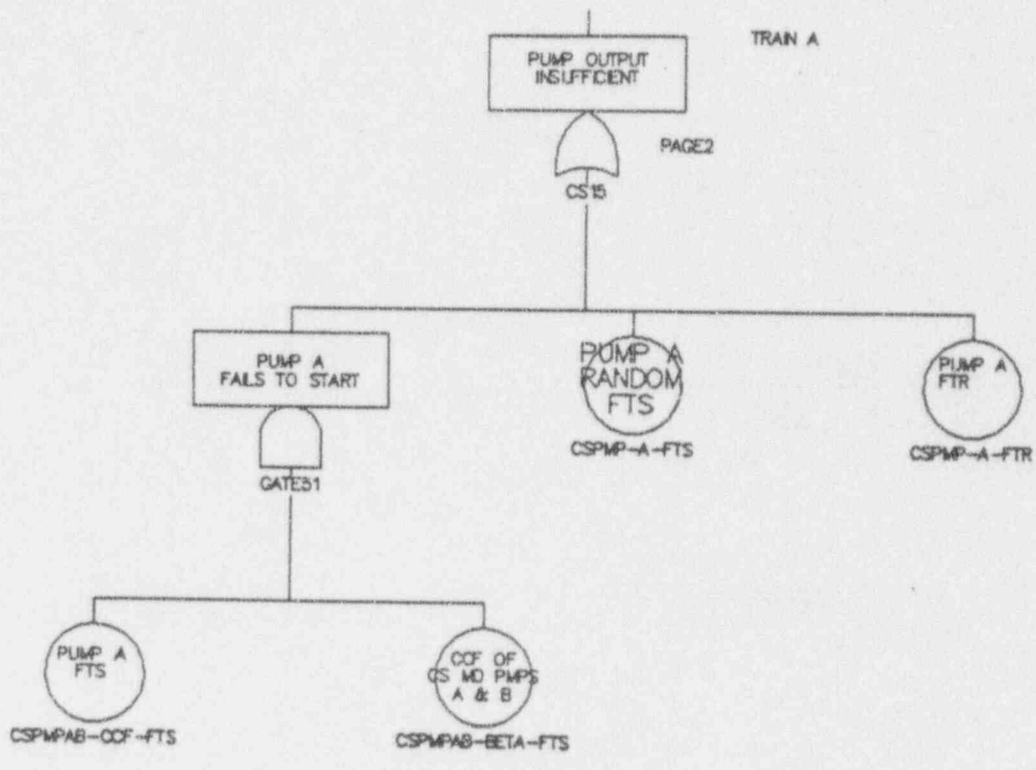


Figure C.2 The containment spray system fault tree (cont'd)

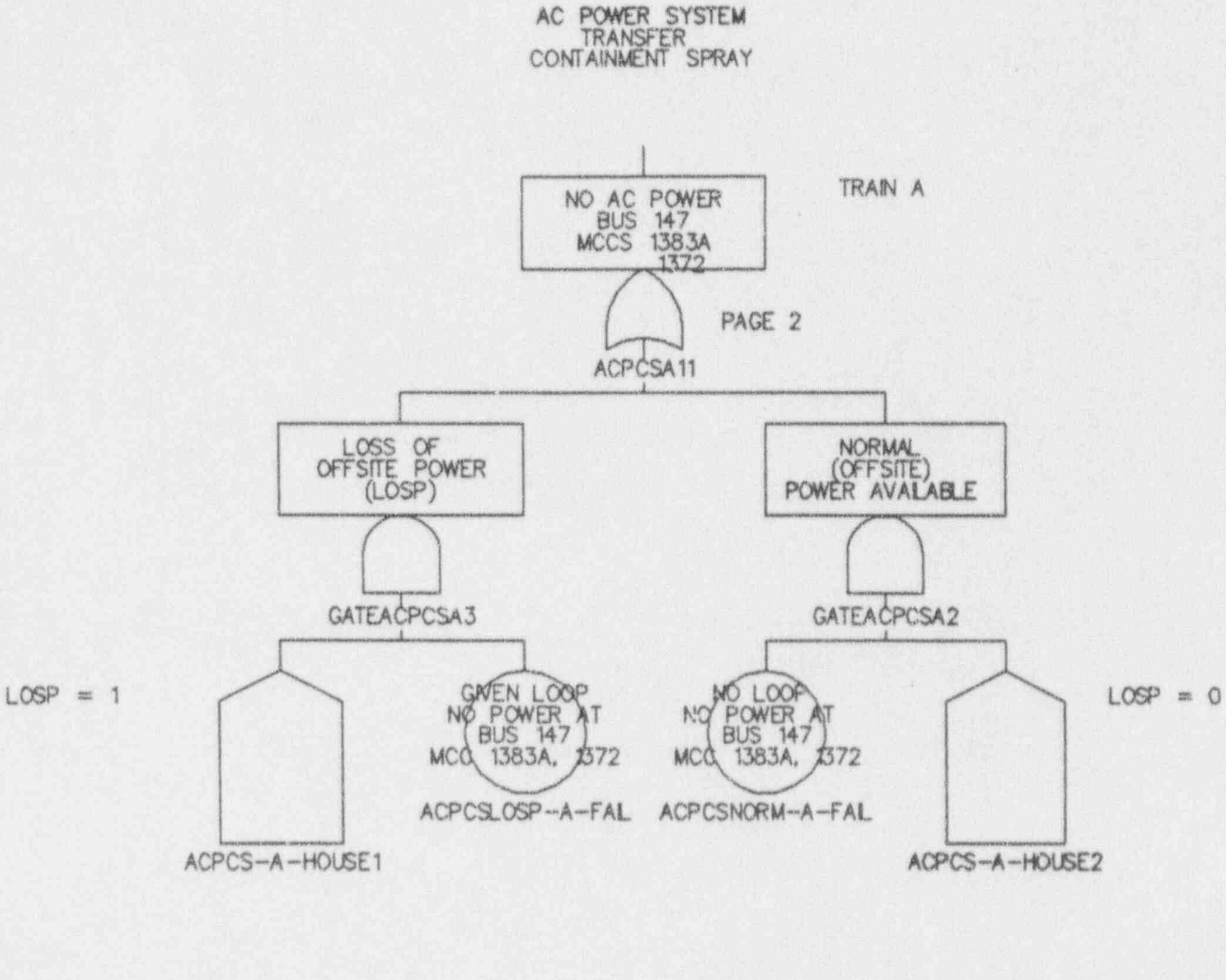


Figure C.2 The containment spray system fault tree (cont'd)

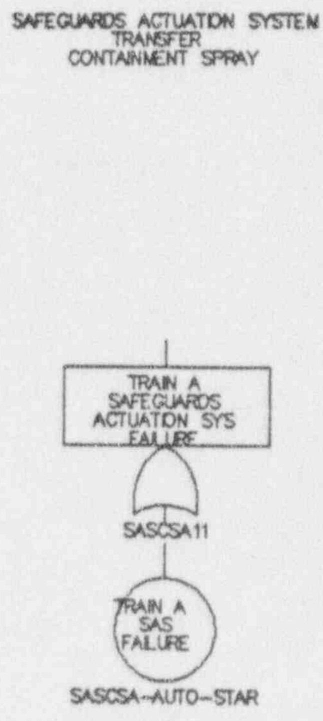


Figure C.2 The containment spray system fault tree (cont'd)

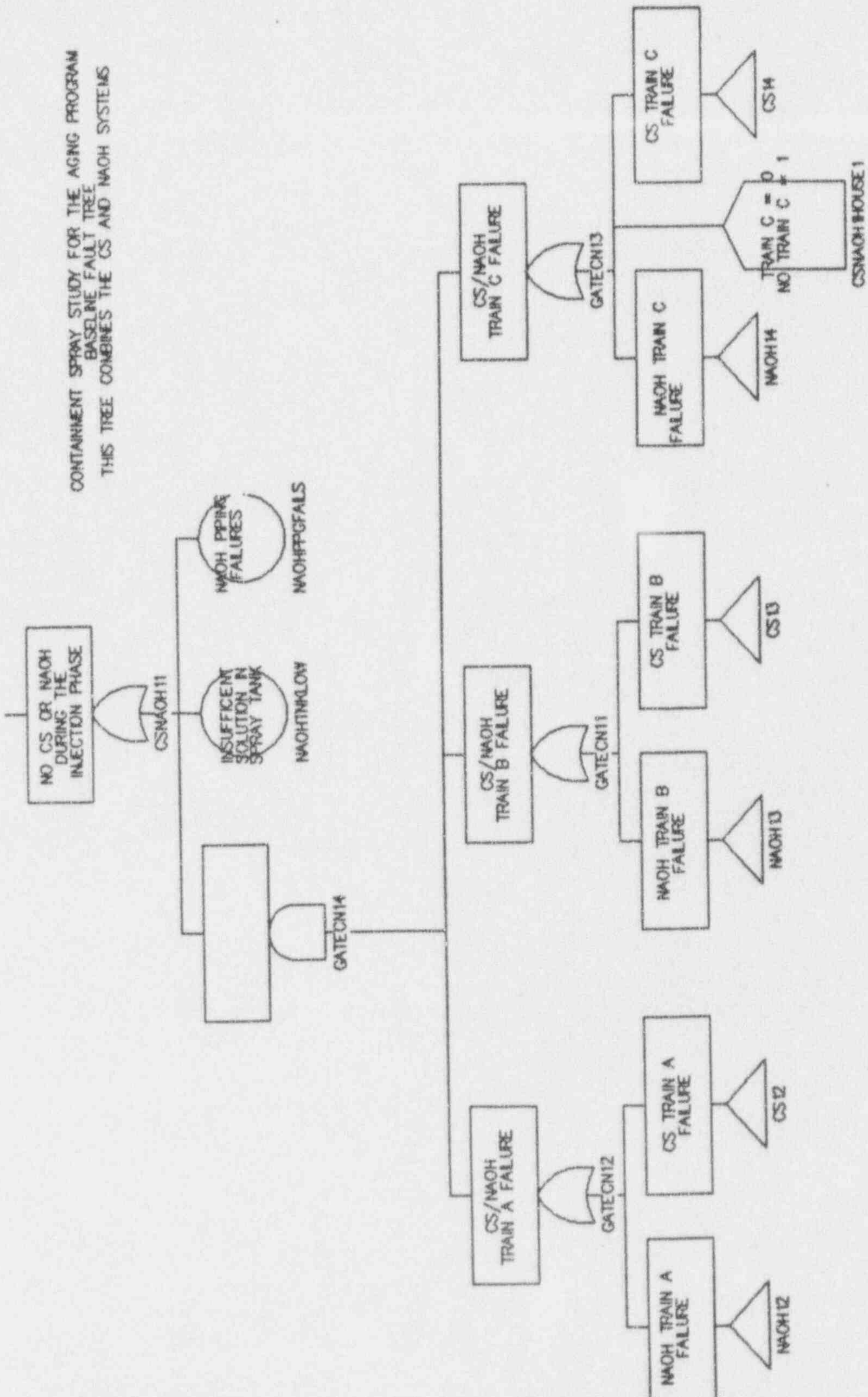


Figure C.3 The containment spray/sodium hydroxide addition fault tree Train A shown. The other trains are similar and are omitted here for brevity.

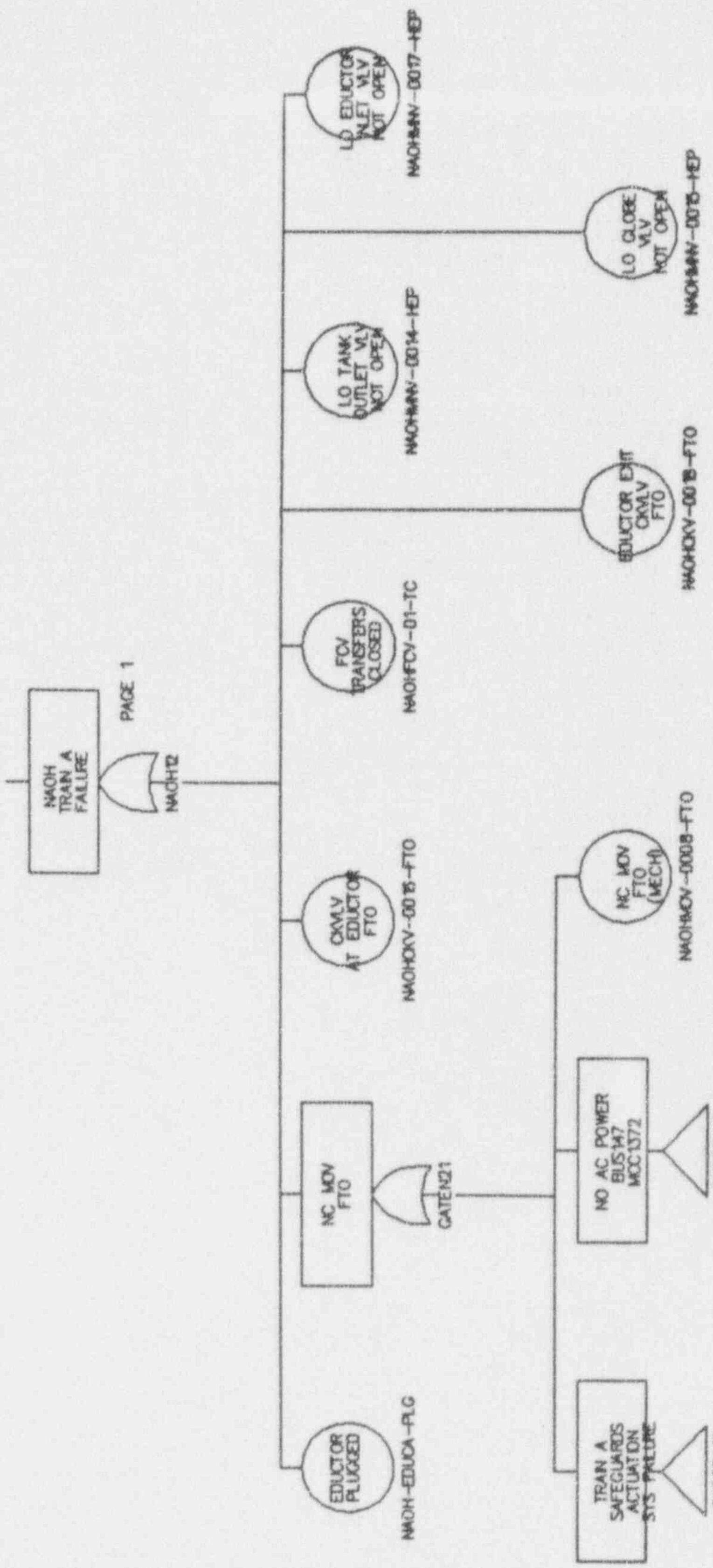


Figure C.3 The containment spray/sodium hydroxide addition fault tree (cont'd)

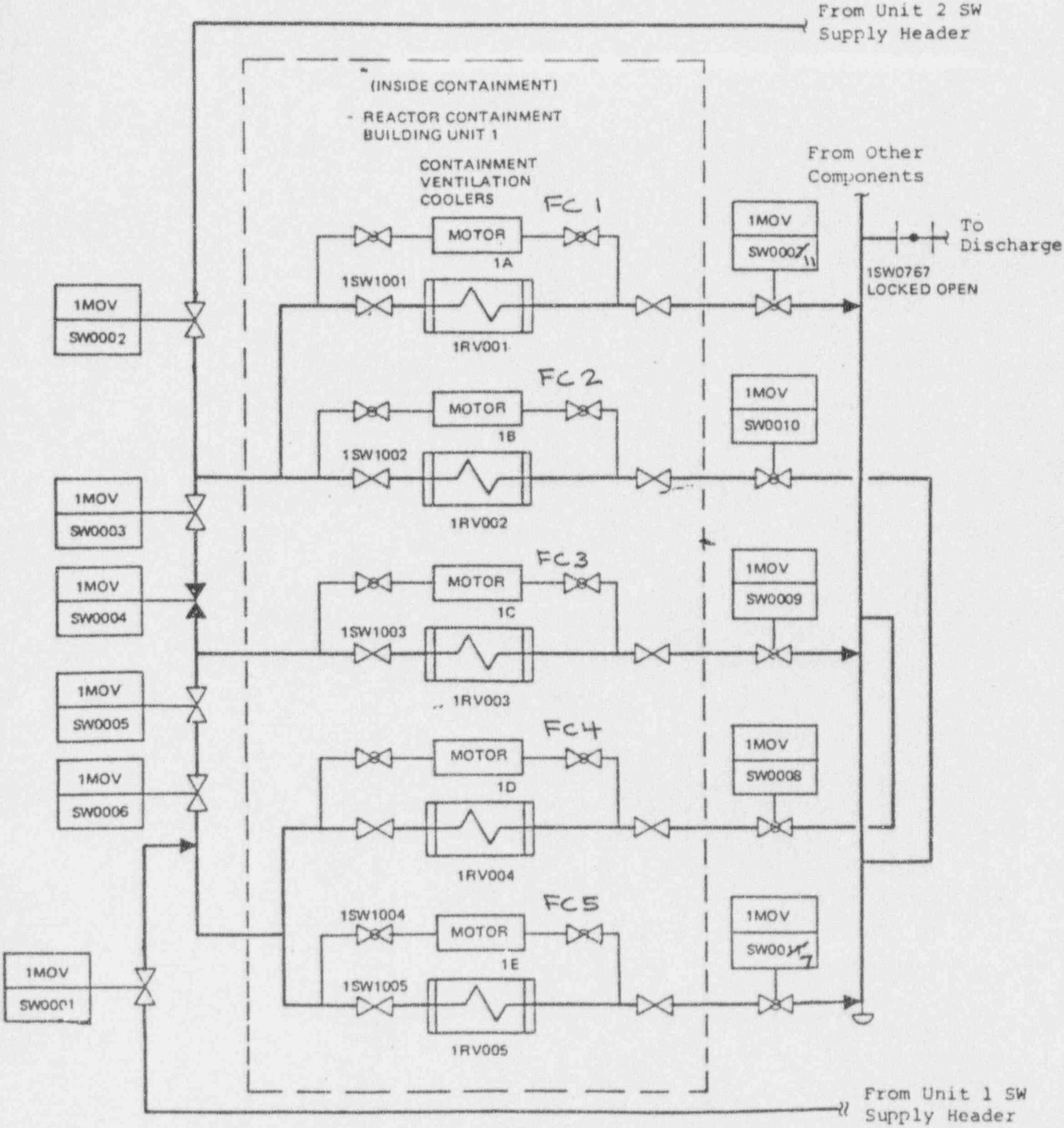


Figure C.4 Zion, Unit 1 service water supply to the fan coolers

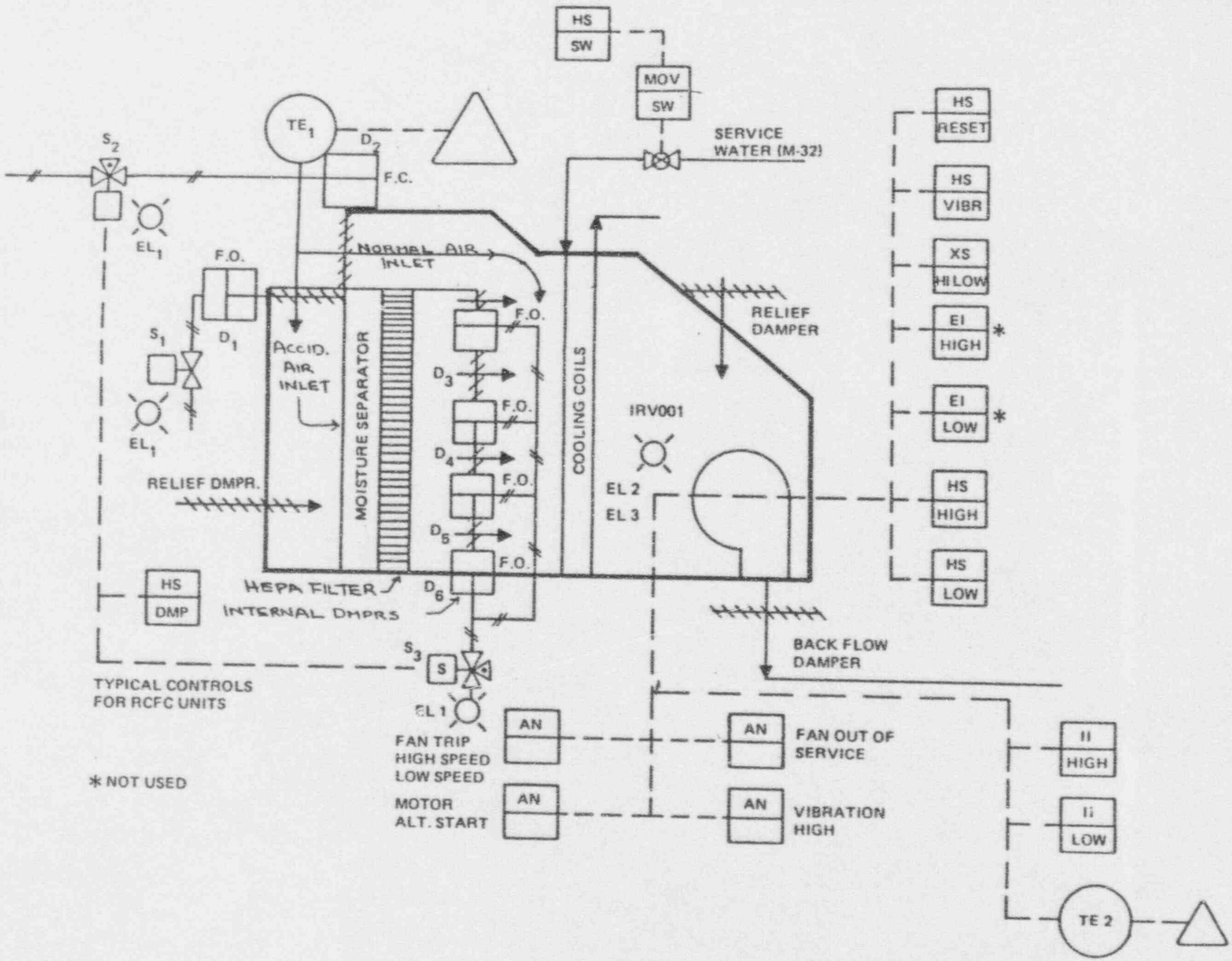


Figure C.5 Containment fan cooler schematic

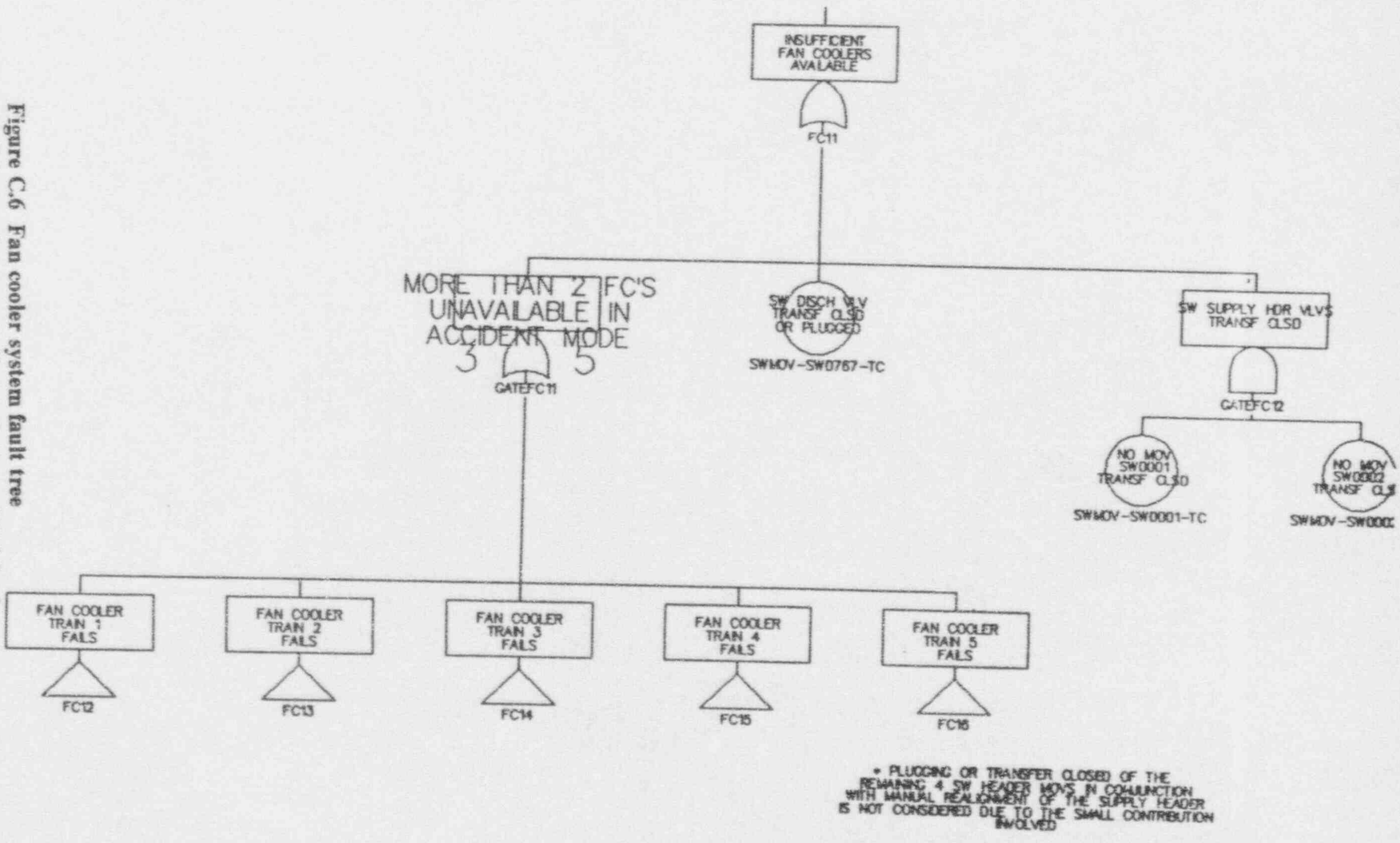


Figure C.6 Fan cooler system fault tree
Train 1 presented. Other trains are similar and are omitted for brevity.

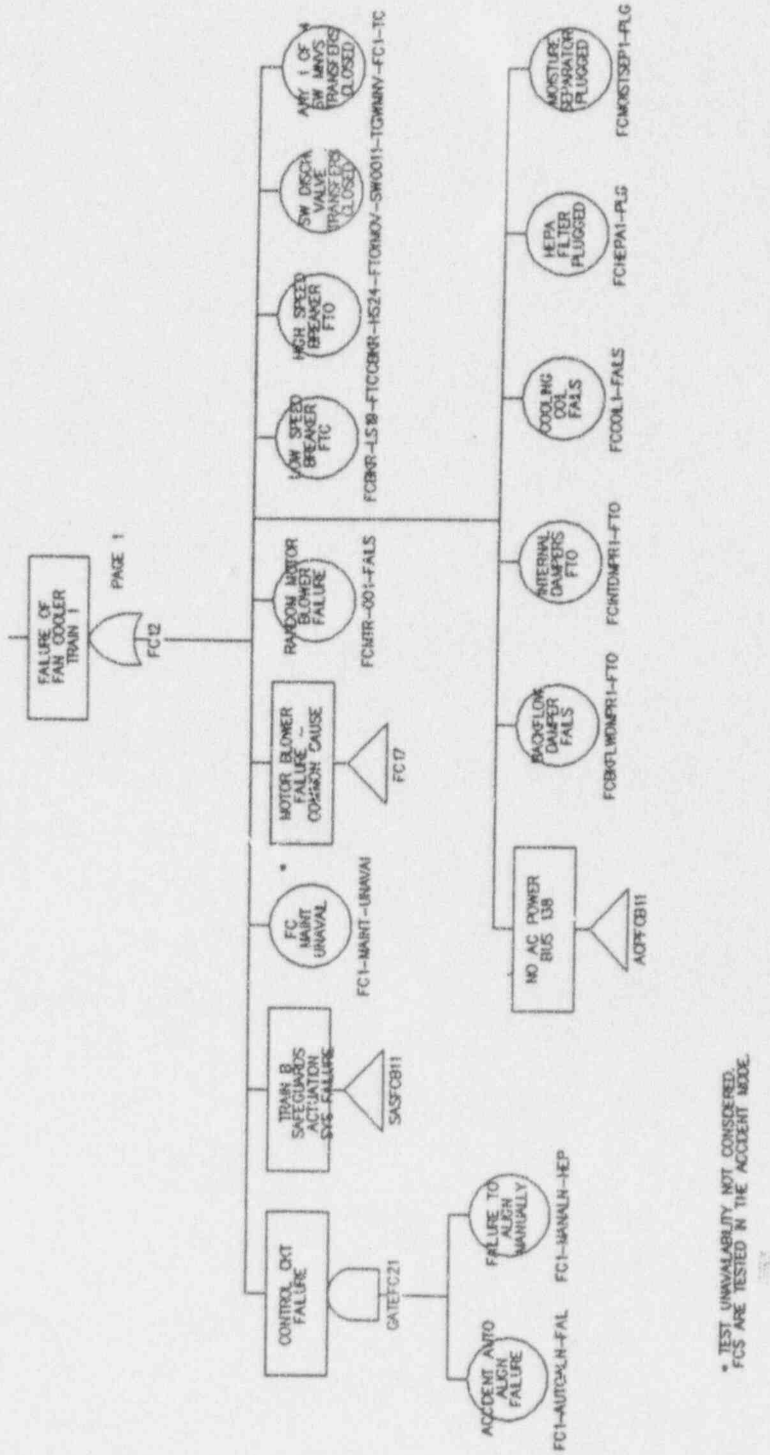


Figure C.6 The fan cooler system fault tree (cont'd)

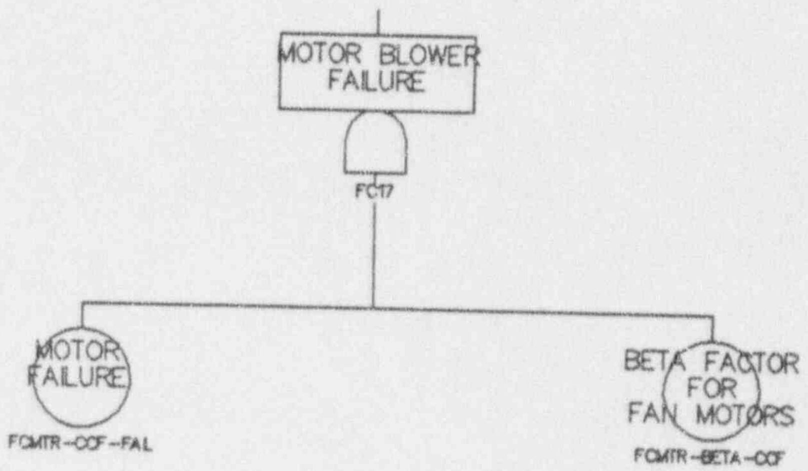


Figure C.6 The fan cooler system fault tree (cont'd)

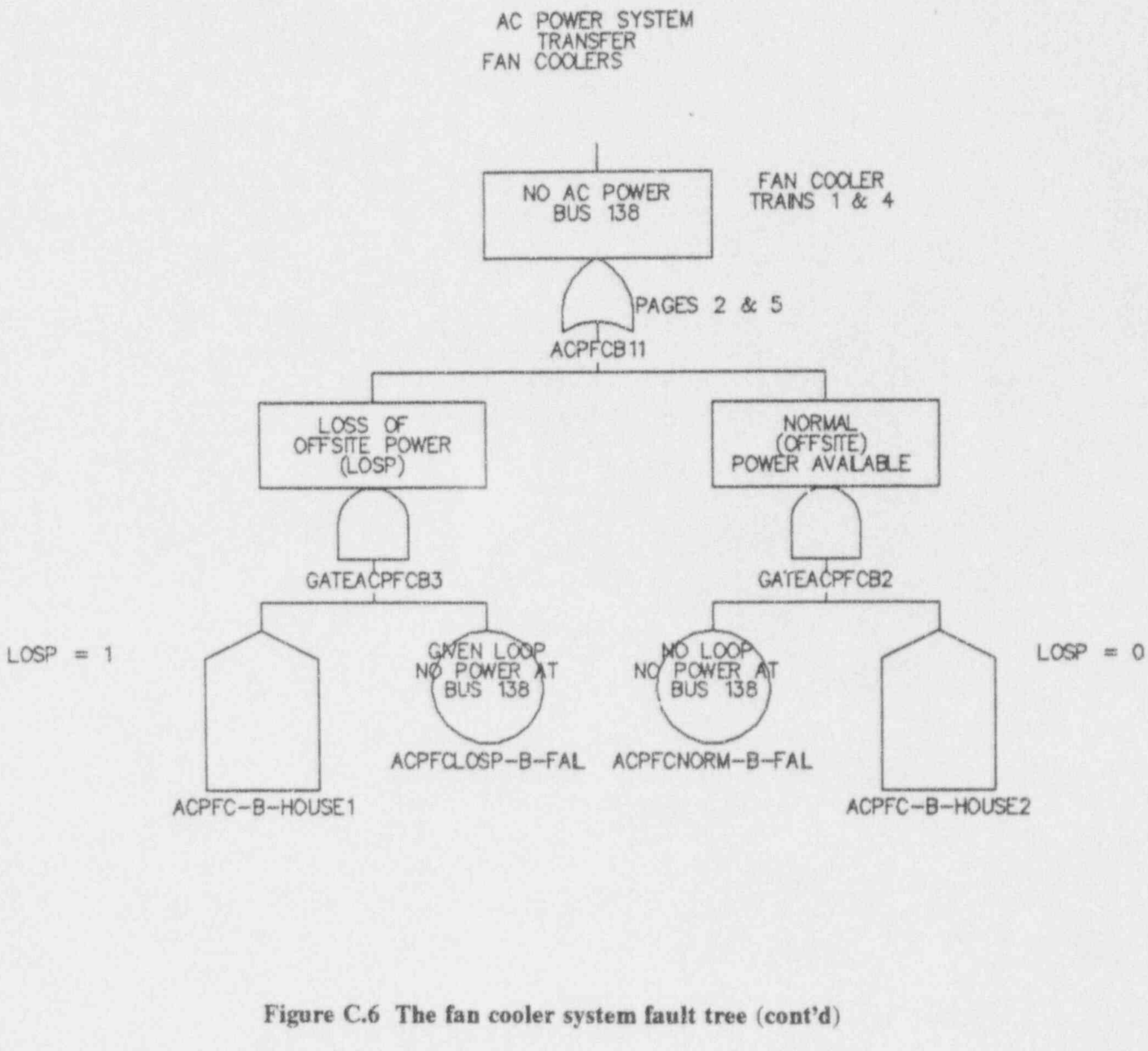


Figure C.6 The fan cooler system fault tree (cont'd)

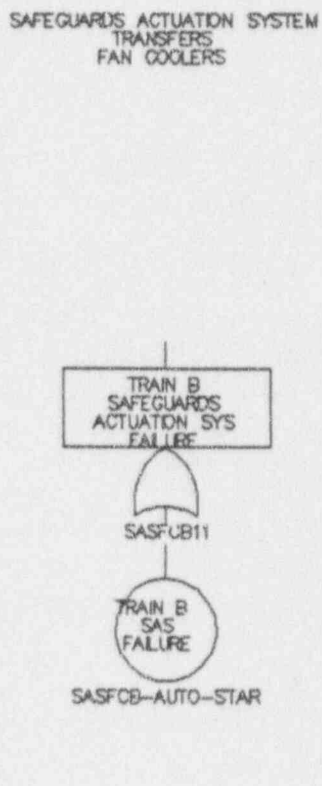


Figure C.6 The fan cooler system fault tree (cont'd)

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

A study was performed to assess the effects of aging on the performance and availability of containment cooling systems in U.S. commercial nuclear power plants. This study is part of the Nuclear Plant Aging Research (NPAR) program sponsored by the U.S. Nuclear Regulatory Commission. The objectives of this program are to provide an understanding of the aging process and how it affects plant safety so that it can be properly managed. This is one of a number of studies performed under the NPAR program which provide a technical basis for the identification and evaluation of degradation caused by age.

The effects of age were characterized for the containment cooling system by reviewing and analyzing failure data from national databases, as well as plant-specific data. The predominant failure causes and aging mechanisms were identified, along with the components that failed most frequently. Current inspection, surveillance, and monitoring practices were also examined.

A containment cooling system unavailability analysis was performed to examine the potential effects of aging by increasing failure rates for selected components. A commonly found containment spray system design and a commonly found fan cooler system design were modeled. Parametric failure rates for those components in each system that could be subject to aging were accounted for in the model to simulate the time-dependent effects of aging degradation, assuming no provisions are made to properly manage it. System unavailability as a function of increasing component failure rates was then calculated.

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

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