1 of 1

Understanding Aging in Containment Cooling Systems*

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ABSTRACT

A study has been performed to assess the effects of aging in nuclear power plant containment cooling systems. Failure records from national databases, as well as plant specific data were reviewed and analyzed to identify aging characteristics for this system. The predominant aging mechanisms were determined, along with the most frequently failed components and their associated failure modes. This paper discusses the aging mechanisms present in the containment spray system and the containment fan cooler system, which are two systems used to provide the containment cooling function. The failure modes, along with the relative frequency of each is also discussed.

INTRODUCTION

The effects of aging degradation on safety-related systems in nuclear power plants has been a continuing concern of the U.S. Nuclear Regulatory Commission (NRC). If not properly managed, aging degradation can adversely affect equipment performance and, hence, the safe operation of the plant. In light of this, the NRC Nuclear Plant Aging Research (NPAR) program strives to provide a better understanding of how to properly manage aging. The NPAR program is described in detail in NUREG-1144¹.

One of the systems studied under the NPAR program is the containment cooling system² since it is one of many plant systems that ensure public safety in the event of an accident. Containment cooling is actually provided by several different plant systems, depending on the type and design of the plant. The containment spray system (PWRs and BWRs) and the containment fan cooler system (PWRs), which are the subject of this paper, were selected for study 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 heat removal in BWR plants, it is an operating mode of the residual heat removal system, which is the subject of a separate NPAR study³.

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SYSTEM DESIGN AND OPERATION

Containment Spray System

A primary function of the containment spray system is to reduce the temperature and pressure inside the containment structure by condensing steam in the event of an unintentional release of coolant from the reactor or its related piping. This adverse environment could occur through either a loss of coolant accident (LOCA) or a main steam line break (MSLB). Reducing the containment pressure and temperature reduces the chances that any radioactive release to the environment would occur by 1) lowering the probability of containment failure due to high pressure and/or temperature, 2) mitigating the pressure differential, and thus the driving force between the containment and the atmosphere. Some designs use chemical sprays to assist in fission product cleanup inside containment.

The containment spray function is a standby function which is only initiated during accident conditions. The system providing this function can have several different designs, depending on the type and design of the plant, and may or may not be a standby system. In pressurized water reactors (PWRs), there is typically an independent containment spray system, with dedicated pumps and associated equipment, which is maintained in standby status during normal plant operation. In boiling water reactors (BWRs), the residual heat removal (RHR) system is typically used to perform the containment spray function. The RHR system also operates in several other modes, and, therefore, is not always in standby status.

The containment spray system functions by pumping water through spray nozzles located inside containment to cool the containment atmosphere. In a typical PWR design, the water is initially taken from the refueling water storage tank (RWST) and then, when the RWST is depleted, from the containment sump. In BWRs the water is taken from the suppression pool, and the RHR pumps are used to provide the spray motive force. The spray system typically includes two or more independent trains, each with dedicated pumps, spray rings, spray nozzles, and numerous valves and piping. Chemicals can also be injected into the spray from a chemical injection system to help remove fission products from the air. A common PWR containment spray system schematic is shown in Figure 1.

Containment Fan Cooler System

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.

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). 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 particula-

Figure 1 Common PWR containment spray system design

tes 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.

AGING ASSESSMENT

In order to characterize the effects of aging in containment spray and fan cooler systems, the Nuclear Plant Reliability Data System (NPRDS) was searched to obtain failure information. The search of the NPRDS database covered the five and one-half year period from January 1986 to June 1991, and produced approximately 1400 records related to failures of the containment spray system, and approximately 800 records related to failures of fan cooler systems. These records were reviewed and analyzed to determine system and component aging characteristics. In addition to the NPRDS review, licensee event reports (LERs), and actual plant data were obtained and analyzed to corroborate the NPRDS findings². This paper focuses on the results of the NPRDS analysis.

Aging Characteristics for Containment Spray Systems

As part of the data analysis, a determination was made as to whether each failure was aging related. To make this determination, the NPAR definition of aging, as described in Reference 1, was applied. By this definition, a failure is considered aging 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

Figure 2 Common fan cooler unit schematic

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. In addition, components must have been in service for a minimum of six months to eliminate burn-in or infant mortality type failures.

The NPRDS data indicate that aging degradation plays a major role in containment spray system failures, with 59% of the failures being aging related (Figure 3). Typical examples of aging 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. In some cases, insufficient information was available to determine whether or not the failure was related to aging. These were classified as "potentially aging related" since they could have resulted from aging degradation.

The data were also examined to identify the cause of failure. To do this, 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 daily operation and testing. 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 aging 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.

SOURCE: NPRDS 1/86 TO 6/91

Figure 3 Fraction of containment spray system failures related to aging

Normal service is the predominant failure cause for the containment spray system, accounting for 74% of the failures (Figure 4). 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 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.

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. Most failures are detected while the system is being tested (Figure 5). Approximately one-third of the failures are detected while the system is in standby, and less than 10% are detected during maintenance. 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 6). The data also show that the failure detection method most useful while the system is in standby is inspections, which includes system

SOURCE: NPRDS 1/86 TO 6/91

Figure 4 Causes of containment spray system failures

SOURCE: NPRDS 1/86 TO 6/91

Figure 5 Status of the containment spray system during failure detection

walkdowns. This includes planned inspections, which are performed on a routine basis, as well as unplanned inspections or casual observations. Detection methods used to a lesser degree are maintenance actions, alarms, and operational abnormalities.

TEST RESULTS 58%

SOURCE: NPRDS 1/86 TO 6/91

Figure 6 Detection methods for containment spray system failures

The predominant number of failures result in degraded operation of the system (Figure 7). 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 a better understanding of how aging degradation affects the containment spray system components, the data were analyzed to identify the components most frequently failed. No failures were found for those containment spray system components that are predominantly in standby status, such as the containment spray rings and spray nozzles. Of those components that are operated periodically, valves account for the predominant number of failures in the system (Figure 8). These data were not normalized to account for population effects since the intent of this analysis was 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, respectively.

The aging mechanisms and failure modes for the most frequently failed components were identified from the data to help form 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

DEGRADED OPERATION
60%

SOURCE: NRPDS 1/86 TO 6/91

Figure 7 Effect of containment spray system failures

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 results are summarized in Table 1. In addition to identifying the aging mechanisms and failure modes, the percentage of failures attributed to each was also determined based on the data reviewed.

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, one of the results could be a decrease in system availability. To determine the significance of this, a system unavailability analysis was performed to simulate the effects of increasing component failure rates due to uncontrolled aging.

As the basis of this analysis, an existing 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 artificially increased to simulate the effect of increasing failure rates due to aging. The system unavailability was recalculated for each case.

The containment spray system design 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

SOURCE: NPRDS 1/86 TO 6/91

Figure 8 Most frequently failed containment spray system components

out of two trains to inject into the containment when signaled. For this simplified analysis, only the injection phase of containment spray was modeled.

The base case unavailability for the containment spray system was calculated to be 4.1×10^{-3} per demand. The combination of events that lead to a failure (cutsets) show that the failure to correctly reposition manual valves after surveillance testing are the dominant events leading to system unavailability. These human errors appear in 11 of the top 15 cutsets, which, when combined, contribute to 85% of the system unavailability.

For the components that can be affected by aging, failure of the pumps to start, including common cause failures, contributes to 21% of the system unavailability. Motor Operated Valve (MOV) failure to open is the next largest, contributing to 15% of the system unavailability. Maintenance unavailability, test unavailability, and nozzle plugging are much smaller contributors at 1.4%, 1.0%, and 0.4%, respectively.

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.

An increase in pump and motor operated valve (MOV) failure rate has the greatest influence on total system unavailability (Figure 9). If the pump failure rate were to 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 top cutset contributing to system unavailability involves pump failures instead of the human errors. Similar results are seen for MOVs. These results show that, for the particular design analyzed, if pump or MOV aging degradation is not properly controlled and failure rates increase over time, failures of these components can become an important contributor, and lead to an increase in containment spray system unavailability. If all component failure rates were to increase due to uncontrolled aging, a dramatic increase in system unavailability would result, as shown in Figure 9. It should be noted that for other system configurations, other components may be more important than those chosen for this illustrative example.

Figure 9 Containment spray system unavailability versus component failure rate

Aging Characteristics for Fan Cooler Systems

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 10). 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.

SOURCE: NPRDS 1/86 TO 6/91

Figure 10 Fraction of fan cooler unit failures related to aging

Normal service is the predominant failure cause for fan coolers (Figure 11). 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.

Most fan cooler failures are detected while the units are in service (Figure 12). 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.

SOURCE: NPRDS 1/86 TO 6/91

Figure 11 Causes of fan cooler failures reported to NPRDS

SOURCE: NPRDS 1/86 TO 6/91

Figure 12 Status of fan coolers during failure detection

While the units are in service, operating abnormalities and inspections are the predominant methods used to detect failures (Figure 13). 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 them. 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 13 Detection methods for fan cooler failures

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 14). 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.

SOURCE: NPRDS 1/86 TO 6/91

Figure 14 Effect of fan cooler failures reported to NPRDS

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. 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 15). 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 failed components are instrumentation and controls, valves, heat exchangers (i.e., cooling coils), fan motors, and blowers. The aging mechanisms and failure modes for the fan cooler system components were identified, and the results are summarized in Table 2.

An unavailability analysis was also performed for a typical fan cooler system. 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 a PWR with 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.

SOURCE: NPRDS 1/86 TO 6/91

Figure 15 Most frequently failed fan cooler components reported to NPRDS

The base case containment fan cooler system unavailability was calculated to be 5.3×10^{-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. 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.

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 a cumulative contribution from all cutsets in which it appears, the unavailability analysis 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.

A parametric study similar to that done for the containment spray system was performed for the fan cooler system. For each event analyzed, 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.

For the system design modeled, an increase in fan damper failure rate due to uncontrolled aging would have the greatest influence on system unavailability (Figure 16). 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 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. These results indicate that, for this particular design, aging of dampers and circuit breakers should be properly controlled since an increase in failure rate could result in a significant increase in system unavailability.

Figure 16 Fan cooler system unavailability versus component failure rates

CONCLUSIONS

This phase I aging analysis has provided a basis for understanding the effects of aging in containment cooling systems. For the containment spray and fan cooler systems, aging characteristics, such as aging mechanisms, failure modes, detection methods, and components most frequently failed were identified. 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 study², and summarized in Tables 1 and 2 should be addressed by at least one monitoring technique.

- 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. It should also be noted that for standby systems, testing can be a significant contributor to aging degradation.

- Approximately 30% of fan cooler system failures are detected by abnormal operation. This indicates that approximately one third of the failures are not detected by current testing or inspections. Therefore, the need for improved IS&M practices should be evaluated.

- 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 result in a loss of redundancy, however, the system is still able to perform its design function.

- If aging is not properly controlled and component failure rates increase with age, this will result in a corresponding increase in system unavailability. Therefore, plant programs should include measures to identify any time-dependent trends in component failures so they can be properly managed.

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Table 1 Summary of aging mechanisms and failure modes for containment spray system components

Component	Major Aging Mechanisms	Percentage	Major Failure Modes	Percentage
Valves	<ul style="list-style-type: none"> - Wear - Adjustment Drift - Galling/Binding - Dirt/Dust Intrusion - Short/Burnout - Loss of Lubrication 	<ul style="list-style-type: none"> 49% 17% 14% 7% 4% 3% 	<ul style="list-style-type: none"> - Leakage - Does Not Open - Does Not Close - Does Not Operate - Exceeds Limit 	<ul style="list-style-type: none"> 58% 18% 11% 8% 3%
Instruments & Controls	<ul style="list-style-type: none"> - Calibration Drift - Wear - Internal Defects - Contamination - Degradation of Power Supply - Binding 	<ul style="list-style-type: none"> 39% 27% 22% 5% 4% 3% 	<ul style="list-style-type: none"> - Incorrect Reading/ Loss of Function 	<ul style="list-style-type: none"> 100%
Circuit Breakers	<ul style="list-style-type: none"> - Adjustment Drift - Galling/Binding - Short/Burnout - Wear - Dirt/Dust Intrusion - Loss of Lubrication - Fatigue - Corrosion 	<ul style="list-style-type: none"> 22% 17% 17% 16% 9% 7% 4% 3% 	<ul style="list-style-type: none"> - Does Not Close - Does Not Open - Does Not Operate 	<ul style="list-style-type: none"> 59% 18% 17%
Pumps	<ul style="list-style-type: none"> - Wear - Galling/Binding - Adjustment Drift - Short/Burnout - Service Outside Limits - Dirt/Dust Intrusion - Fatigue 	<ul style="list-style-type: none"> 62% 14% 10% 3% 3% 2% 2% 	<ul style="list-style-type: none"> - Leakage - Does Not Run - Does Not Start 	<ul style="list-style-type: none"> 48% 24% 14%
Heat Exchangers	<ul style="list-style-type: none"> - Plugging/fouling - Corrosion - Wear - Vibration 	<ul style="list-style-type: none"> 62% 21% 6% 4% 	<ul style="list-style-type: none"> - Plugged - Leakage - Fouled 	<ul style="list-style-type: none"> 66% 15% 15%

Table 2 Summary of Aging Mechanisms and Failure Modes for Fan Cooler System Components

Component	Major Aging Mechanisms	Percentage	Major Failure Modes	Percentage
Circuit Breakers	<ul style="list-style-type: none"> - Short/Burnout/Pitting - Wear - Adjustment Drift - Fatigue/Cracking - Galling Binding - Dirt/Dust Intrusion - Loss of Lubrication - Corrosion 	<ul style="list-style-type: none"> 30% 15% 14% 13% 10% 6% 2% 1% 	<ul style="list-style-type: none"> - Does Not Close - Does Not Open - Does Not Operate 	<ul style="list-style-type: none"> 67% 17% 6%
Instruments & Controls	<ul style="list-style-type: none"> - Calibration Drift - Wear - Short/Burnout - Contamination - Binding 	<ul style="list-style-type: none"> 22% 22% 20% 17% 4% 	<ul style="list-style-type: none"> - Incorrect Reading/ Loss of Function 	<ul style="list-style-type: none"> 100%
Dampers	<ul style="list-style-type: none"> - Wear - Galling/Binding - Adjustment Drift - Fatigue/Cracking - Short/Burnout/Pitting - Loss of Lubrication - Dirt/Dust Intrusion 	<ul style="list-style-type: none"> 23% 22% 17% 11% 6% 6% 5% 	<ul style="list-style-type: none"> - Does Not Close - Does Not Operate - Does Not Open - Leakage 	<ul style="list-style-type: none"> 40% 21% 20% 15%

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