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THE EFFECTS OF AGING ON BOILING WATER REACTOR CORE ISOLATION COOLING SYSTEM[1]

Bom Soon Lee
Engineering Technology Division
Brookhaven National Laboratory
Upton, NY

ABSTRACT

A study was performed to assess the effects of aging on the Reactor Core Isolation Cooling system in commercial Boiling Water Reactors. This study is part of the Nuclear Plant Aging Research program sponsored by the U.S. Nuclear Regulatory Commission. The failure data from national databases, as well as plant specific data were reviewed and analyzed to understand the effects of aging on the RCIC system. This analysis identified important components that should receive the highest priority in terms of aging management. The aging characterization provided information on the effects of aging on component failure frequency, failure modes, and failure causes.

INTRODUCTION

An aging study of Reactor Core Isolation Cooling (RCIC) systems in commercial boiling water reactors (BWRs) 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 (NRC), Office of Research, Division of Engineering. Its goal is to provide a technical basis for understanding and managing the effects of aging in nuclear plants. A more detailed description of the NPAR program can be found elsewhere (Ref. 1,2).

The RCIC system was chosen because, as a safety-related system, it plays a vital role in the safe operation of the plant. For station blackout scenarios, the RCIC system is important for preventing core melt in BWRs (Ref. 3, 4). The RCIC system includes a steam turbine-driven pump, and associated valves, interconnecting piping, pipe supports/restraints, electrical power supply components and instrumentation/controls.

This study analyzed national data base operating experience from the Nuclear Plant Reliability Data System (NPRDS) and Licensee Event Reports (LER). Maintenance data from an operating plant were also obtained and analyzed. In addition, a plant with a completed PRA was chosen for an unavailability analysis. The PRA model of the RCIC system for that plant was used to represent the common essential features of RCIC system designs and to analyze varying age-related failure rates. This analysis identified the components which have a dominant effect on system availability. By performing a parametric study in this analysis, the effects of uncontrolled aging degradation on system availability also were evaluated. However, this unavailability analysis in not discussed in this paper. In this paper, aging effects on the RCIC system, prioritization of components for aging management, and aging characterization of some of the components are discussed.

OPERATING DATA ANALYSIS

Effects of Aging on RCIC System

Between January 1986 to December 1991, there were 920 RCIC system failures reported to NPRDS from the 31 BWR units in the USA. Seventy-eight percent of the failures are due to aging, 9 % possibly due to aging, and 13 % due to non-aging causes. Therefore, the aging-related failures (aging and possibly aging combined) are almost 87 % of all the failures in the RCIC systems, which clearly indicates that aging is an important issue for this system.

Analysis of the NPRDS data showed that the effects of component failures on RCIC system function become increasingly more serious as the components age. During the period of 1986 - 87, about 22 % of the component failures resulted in loss of system function or degraded system operation, which increased to 30 % and 36 % for the periods of 1988 - 89 and 1990 - 91, respectively, as shown in Figure 1. Throughout this period, about the same number of BWR plants were in operation, therefore the populations of components were relatively constant. This finding agrees with that from LER analysis which showed increased aging failures in the LER events as the plants got older. LERs contain events that are more safety significant

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1. This work was performed under the auspices of the U.S. Nuclear Regulatory Commission.

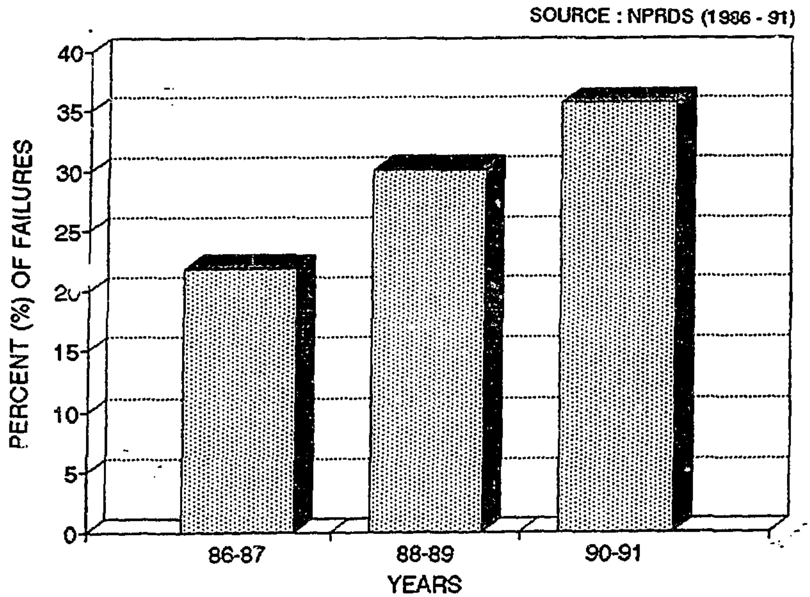

Figure 1. Fraction of RCIC component failures that caused loss of system function or degraded system operation

than those reported to NPRDS. Thus, the increased fractions of LERs caused by aging-related failures mean they resulted in more safety significant events as the components got older.

Prioritization of Components for Aging Management

An importance prioritization or ranking of the RCIC components can be a valuable tool for effective aging management. Table 1 shows the rankings obtained using four different criteria: number of aging-related failures reported to NPRDS, number of loss of system function failures reported to NPRDS, number of aging-related failures reported as LERs, and contribution to system unavailability. The information for the last criterion was obtained by conducting an unavailability analysis, which is discussed in reference 2. Valves fail most often mainly because they are more numerous than other components, but they are ranked 5th when the criterion of number of loss of system function failures is used. The reason is because the main failure mode for valves is leakage, which generally degrades the system operation, but does not necessarily cause a loss of system function. On the other hand, the failure frequency of the governors is low, but most of their failures cause a loss of system function, putting them in a higher rank when the criterion of number of loss of system function failures is used.

This study shows that if only one criterion is used for prioritization, important components may be overlooked. For example, number of failures is the criterion most commonly used, however, this would not identify governors and pumps as important components. By considering all four importance criteria, it is concluded that aging management of valve operators, switches/bistables, governors, valves, circuit breakers, and pumps is most important to reduce and mitigate the aging effects on RCIC system. These components should receive the highest priority in aging management programs.

Effects of Aging on RCIC Component Failure Frequency

Out of the 31 BWR units that have RCIC systems, 26 were selected for normalization based on the number of failures reported. The failure frequency curve for the RCIC components shows a peak at 3 - 4 years of age, followed by two peaks at 11 - 13 years and 17 years, as shown in Figure 2. Since this component failure frequency is the combined value for seven major components, it is important to know which components contributed to these peaks. Data analyses for the major components showed that failures of valves and switches/bistables mainly caused the peak at 3 - 4 years; failures of valve operators also contributed to this peak. The second failure frequency peak at 11 - 13 years is due to the increased failures of valves, switches/bistables, circuit breakers, and valve operators. The increased failures of valves are responsible for the third peak at 17 years.

Table 1
Importance Rankings for RCIC Components

	Criteria			
Ranking	Number of Aging-related Failures (NPRDS)	Significant System Effect (NPRDS)	Number of Aging-related Failures (LER)	Unavailability
1	Valves	Valves Operators	Valve operators	Switches/Bistables
2	Switches/Bistables	Switches/Bistables	Switches/Bistables	Pumps
3	Valve Operators	Circuit Breakers	Governors	Valve Operators
4	Circuit Breakers	Governors	Valves	
5	Transmitters	Valves		
6	Governors	Turbines		
7	Turbines	Transmitters		
8	Pumps	Pumps		

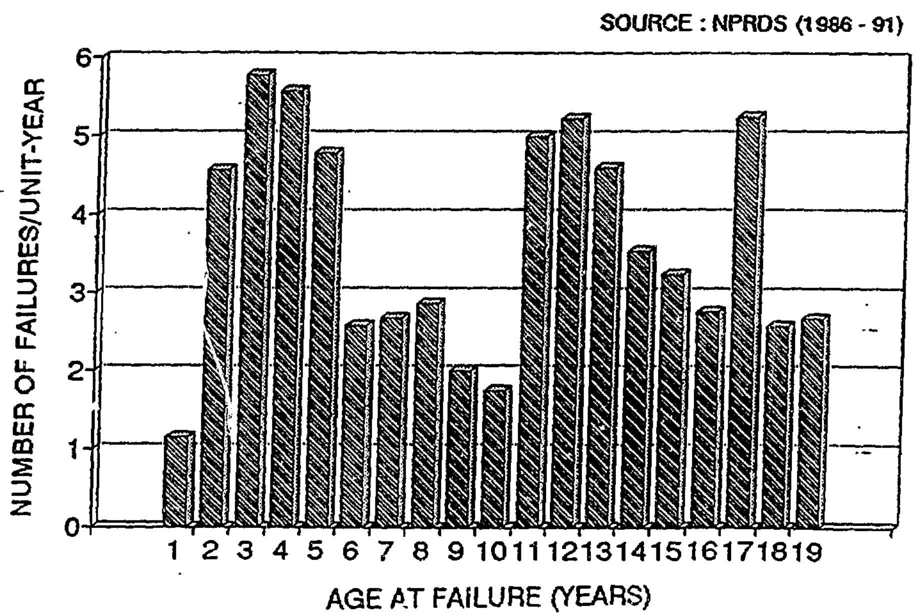

Figure 2. Combined failure frequency for seven components normalized with 26 plants

Aging Characterization

The aging characteristics of all the major components discussed above were studied by analyzing the operating data. However, in this paper, only the results on valves, valve operators, turbines, and pumps are presented. The results of the analyses of LERs and plant specific data agreed with those of the NPRDS data. Thus, only the results from the NPRDS data analysis are given here.

Valves

Failure Frequency   When the valve failures from 26 plants are normalized to show the failure frequency per unit-year as a function of age at failure, the curve shows three peaks at the ages of 3, 11, and 17 (Figure 3). These peaks coincide with those for the failure frequency curve for the RCIC system in Figure 2, which indicates that valve failures are the main contributor to the three peaks in the system failure frequency curve.

There are between 50 and 100 valves in a typical RCIC system, depending on the BWR type. These fall into two major groups, steam valves and water valves, and it is important to know which group is more susceptible to aging degradation.

These two groups of valves were analyzed separately; the results are shown in Figures 4 and 5. As expected, due to the harsher environment, the failure frequencies for the steam valves are much higher than those for the water valves. Since there are fewer steam valves, the actual difference in valve failure rates is even higher than these figures show. The failure frequencies for the steam valves (Figure 4) stay almost constant until 11 years, when they peak. The failure frequency of water valves peaks at 5 years, after which it drops very low until 15 years, when the frequency again begins to increase. The possible reasons for the effects of aging on the failure frequency will be discussed later, using the results of failure mode and cause analysis.

Failure Mode   The failure modes for the steam valves were analyzed for three age periods, 1-9, 10-14, and 15-18 years, based on the shape of the frequency curve in Figure 3. The results, in Figure 6, show the relative proportion of each failure mode. The failure mode codes are from the NPRDS, and those for the valves are the following:

- EL - External Leakage
- IL - Internal Leakage
- FC - Failure to Close
- OR - Failure to Operate as Required
- MO - Found during Testing, Surveillance, Inspection, or Maintenance
- FO - Failure to Open

Over time, leakage remained the predominant failure mode. However, there was some increase in external leakage in place of internal leakage as the valves age.

A similar analysis on water valves shows more dramatic effects of aging on failure mode (Figure 7). During the early years (1 - 7 years), more than half of the failures were internal leakage, but, for older valves (12 - 19 years), about 80 % of the failures were external leakages. This indicates that the failure causes for these two periods are different, which will be discussed next.

Failure Cause   Figure 8 shows the failure causes for steam valves for the three different periods. The NPRDS cause codes are the following:

- AD - Normal/Abnormal Wear
- BE - Dirty Internals
- BC - Out of Mechanical Adjustment
- BB - Mechanical Damage/Binding
- BD - Aging/Cyclic Fatigue
- BG - Corrosion

As the valves get old, there are increased failures caused by dirty internals, out of mechanical adjustment, mechanical damage, and corrosion. However, between 50 and 70 % of all the valve failures in the NPRDS data are categorized as normal/abnormal wear. This description indicates that the failure was due to aging, but it is not specific enough to provide more useful information.

The proximate causes developed by BNL provide more detailed information about the failures (Figure 9). The BNL codes for the proximate causes are the following:

- WS - Worn Seat/Disc
- WP - Worn Packing
- CI - Corrosion Product or Dirt Buildup
- WG - Worn Bonnet Gasket, Worn Gasket

Causes grouped under "Other" in the figure include out of adjustment packing, worn wedge, worn seat ring, worn tappet nut, worn cylinder wall, broken or damaged stem, and worn hinge pin.

In the early ages (1 - 9 years), worn seats caused about 37 % of the steam valve failures, worn packing about 22 %. For the older steam valves (15 - 18 years), worn packing caused about 35 %, and worn seats about 30 %. In addition to increased packing problems for the older valves, corrosion product buildup and worn gaskets become more important, causing 20 % and 10 % of the failures, respectively. These proximate causes may explain the increased failure frequency at 17 years shown in Figure 4.

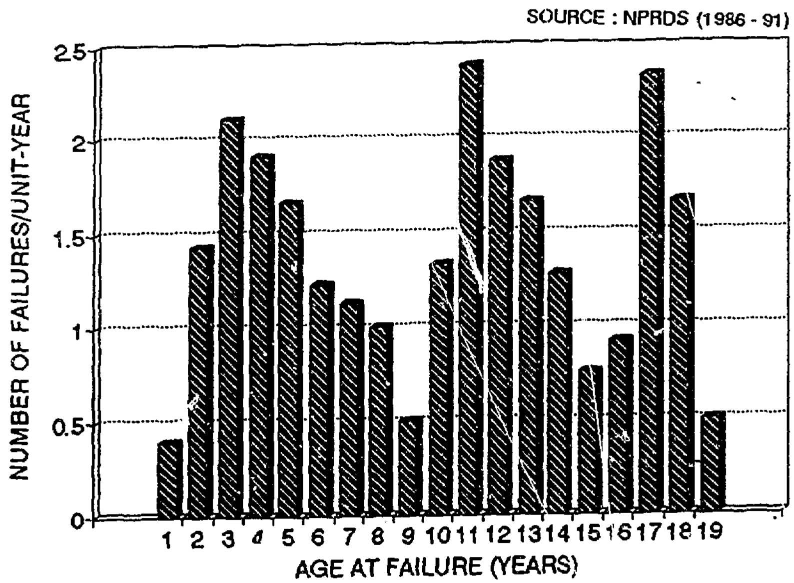

Figure 3. Normalized valve failure frequency as a function of age at failure

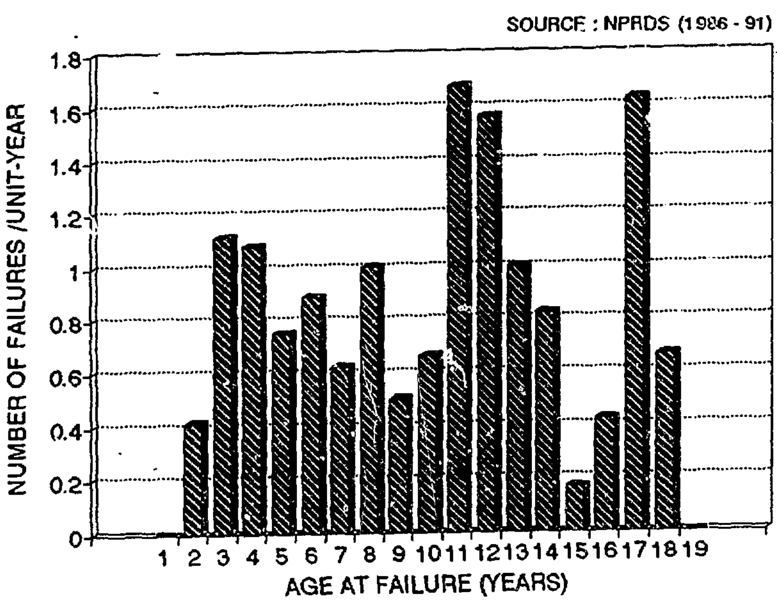

Figure 4. Normalized steam valve failure frequency as a function of age at failure

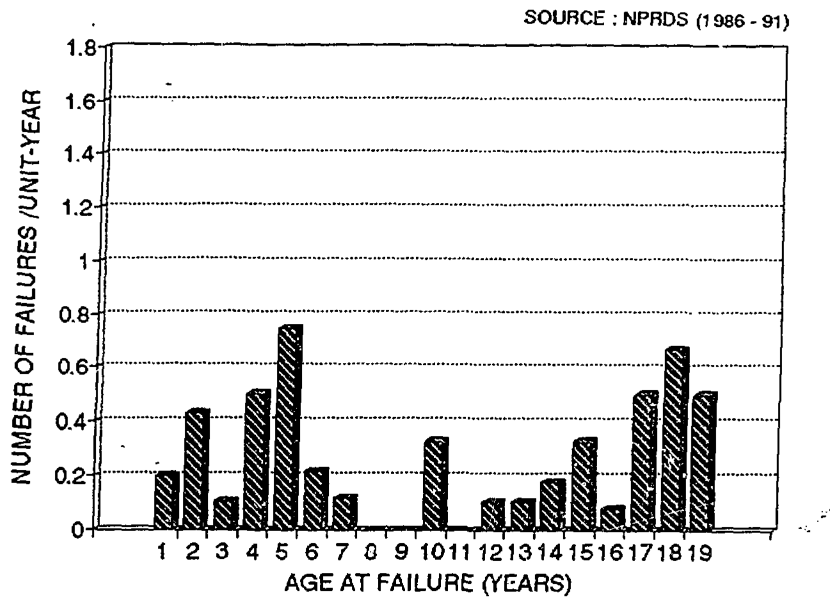

Figure 5. Normalized water valve failure frequency as a function of age at failure

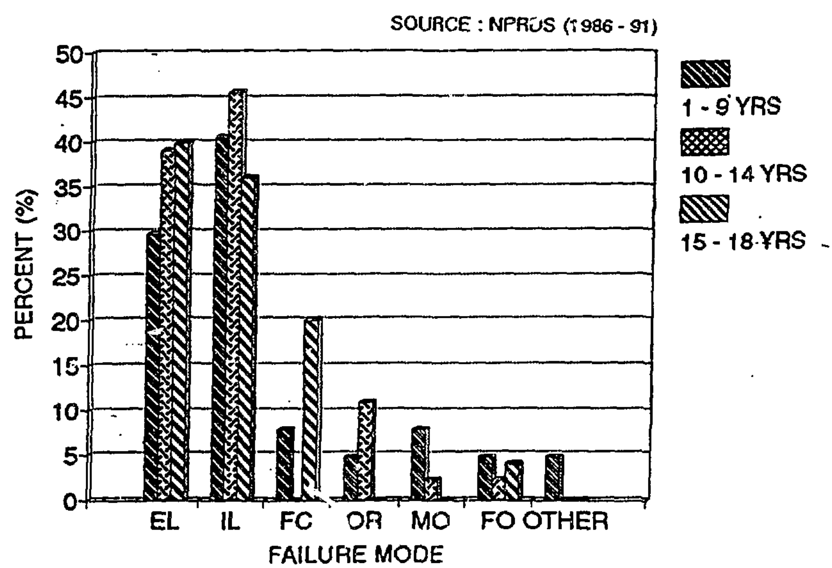

***Figure 6.* Failure modes for steam valves**

These proximate causes also explain the failure modes shown in Figure 6. The increased external leaks are caused by more failures due to worn packing and worn gaskets, while a slight decrease in internal leaks in later years is due to fewer failures caused by worn seat.

Figure 9 also shows that a worn gasket was the proximate cause for about 10 % of the steam valve failures after 15 years, but was not identified earlier.

The effects of aging on the failure mode of water valves are quite dramatic. During the early years, external leaks and internal leaks account for about 23 % and 52 % of the failures, respectively (Figure 7). In later years, external leak is the failure mode for almost 80 % of the failures. This significant effect of aging on failure modes may be explained by their proximate causes. Figure 10 shows that failures caused by worn packing and worn gasket increased significantly at later years, from 16 % to 35 % and from zero to 24 %, respectively, while the portion of the failures due to worn seats decreased from about 45 % to about 12 %. The analysis for proximate causes for water valves also show that gaskets begin to fail after about 12 years, causing about one quarter of the failures.

The analyses of failure modes and causes may explain the different shapes of the failure frequency curves between steam and water valves. For the water valves, in the earlier years, the main failure mode is internal leakage caused by worn seats and accumulation of corrosion products; however, in the later years, the main failure mode is external leakage caused by worn packing and worn gaskets. Thus, it seems to take some years until packing and gaskets age and fail for the water valves. On the other hand, for steam valves, the main failure modes stay about the same over 19 years, with internal and external leaks contributing almost equally. This is mainly because packing failures start much earlier than those for the water valves, and continue to increase, causing the failure frequency of the steam valves to stay higher than that of the water valves. Since packing materials are usually Polytetrafluoroethylene (PTFE), Aramid, and graphite, high temperature accelerates the aging degradation processes (Ref. 5).

Valve Operators

Failure Frequency The failures of valve operators caused approximately 15 % of the RCIC system component failures. Figure 11 shows the effects of aging on the failure frequency, plotting the number of valve operator failures per unit-year as a function of component age, normalized for 26 plants. As valve operators age, no dramatic change in the failure frequency can be seen, except that there are two frequency peaks, at around 3 years, and around 11 years. These peaks coincide with those in the system failure frequency curve in Figure 2, indicating that failures of valve operators contributed to the system failure peaks at 3 -4 years and 11- 13 years.

A valve operator has several subcomponents, each of which has different aging characteristics. Over the years, many subcomponents are repaired and replaced, which affects the shape of the failure frequency curve. Also, the valve operators receive more frequent periodic testing and maintenance than other components, which can detect the aging-related degradation before the aging effects accumulate. These may explain why the failure frequency curve is not a typical bath-tub curve and why the failure frequency decreases after the peaks. To understand what caused the two peaks, the failure causes are analyzed separately for different age groups.

Failure Cause There were several different causes for the failures of valve operators with no dominating ones (Figure 12). These included out of mechanical adjustment, normal/abnormal wear, mechanical damage/binding, burned/burned out, and defective connection/loose parts. The "Others" category in this figure includes dirt build-up, foreign material, lubrication problem, blocked, and insulation breakdown. The insulation breakdown did not cause failures until 13 years. However, during 14 - 19 years period, 7 % of the valve operator failures were caused by the insulation breakdown.

The analysis for proximate causes identifies the subcomponents that caused the failures. The major ones are motor, torque switch, limit switch, and tripper finger, as shown in Figure 13. This figure also shows that motor and limit switch are affected by aging more than others. Also, no particular subcomponent failures are responsible for the two frequency peaks, at around 3 years and around 11 years, except that the failures of tripper fingers caused almost 20 % of the valve operator failures during the 11 - 13 years of age. Dirty contacts caused about 8 % of the failures during the 14 - 19 years; this proximate cause was not reported until this period. Much research on motor-operated valves has been conducted under NPAR and other programs, and the detailed results of the component level research on valve operators are available in references 6, 7, and 8.

Turbine

There were 22 aging-related turbine failures, of which 5 (21 %) resulted in the loss of RCIC system function. Seven turbine failures (32 %) degraded the system's operation. This information indicates that the turbine is an important component for RCIC operation, even though the number of failures is low.

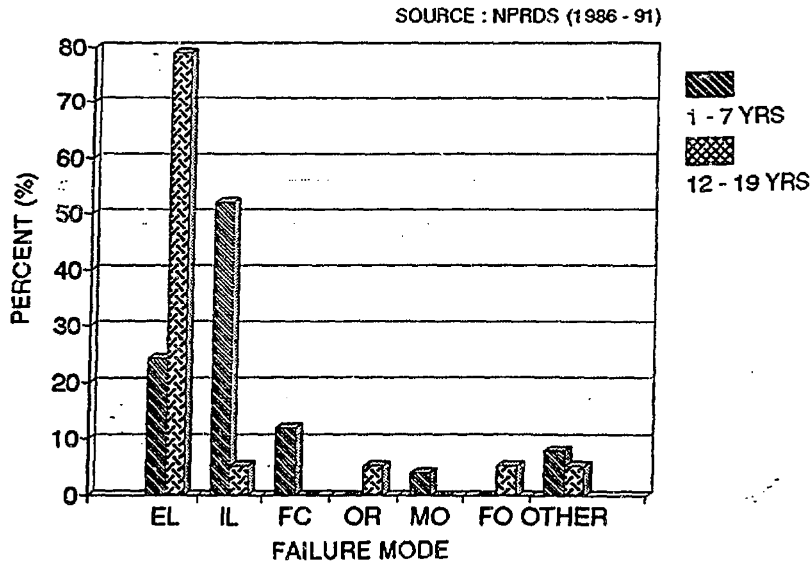

Figure 7. Failure modes for water valves

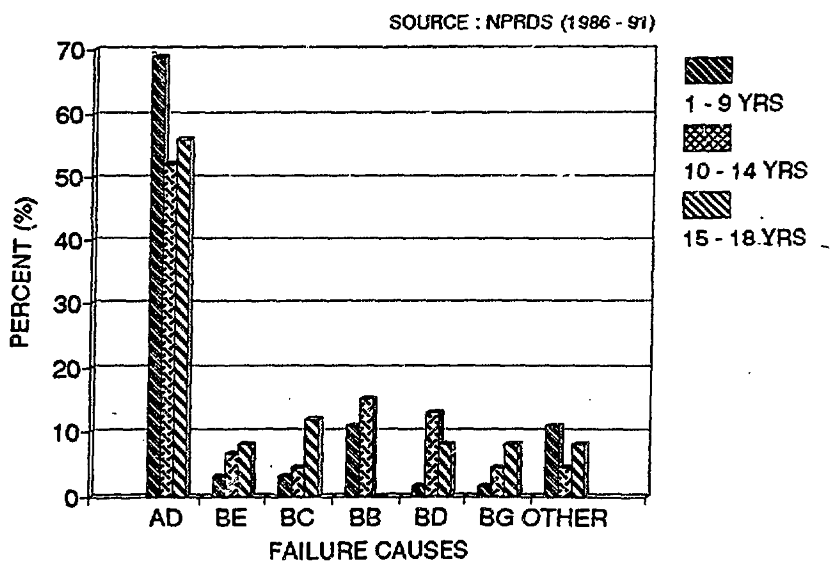

Figure 8. Failure causes for steam valves

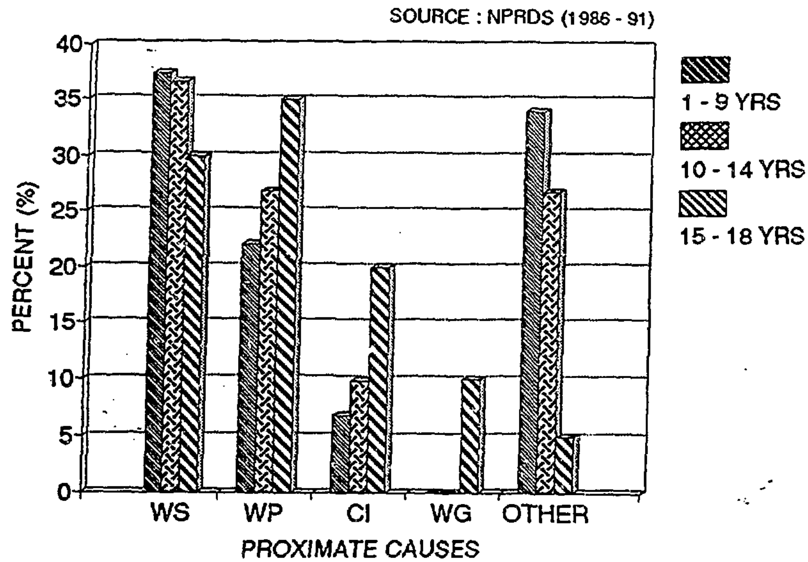

Figure 9. Proximate causes for steam valve failures

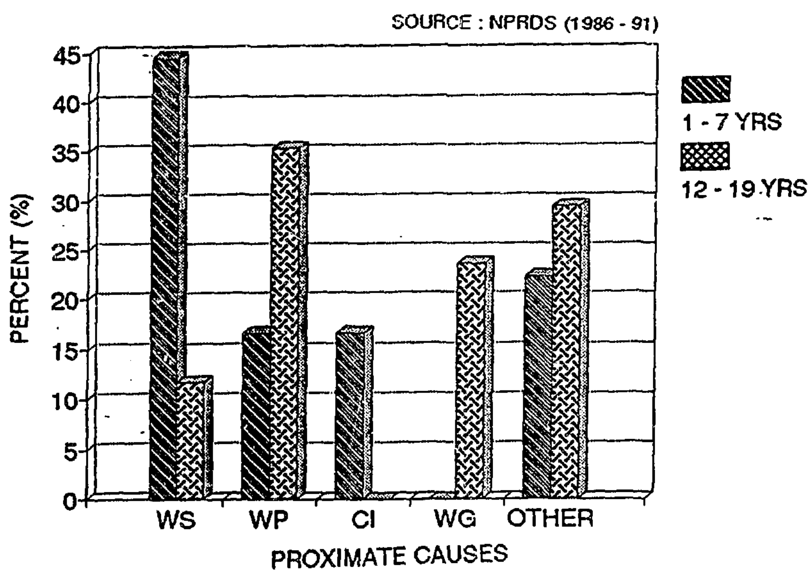

Figure 10. Proximate causes for water valve failures

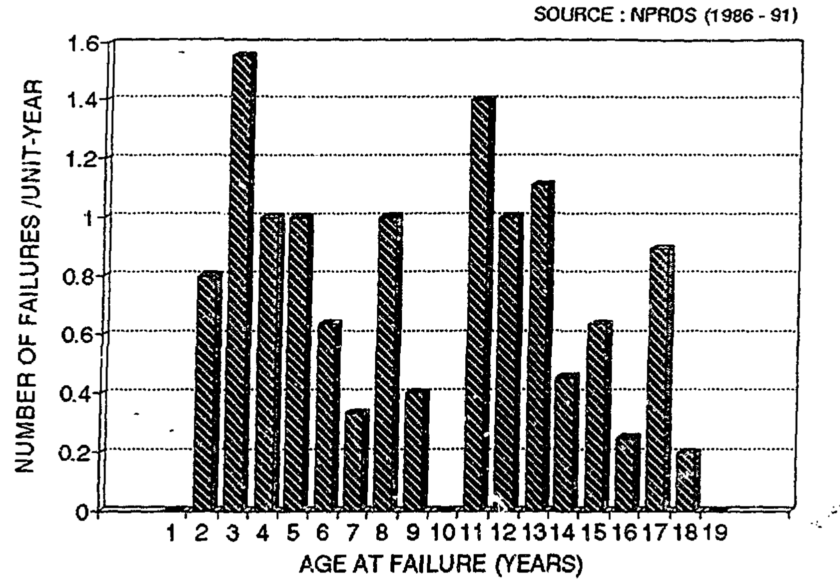

Figure 11. Normalized failure frequency for valve operators as a function of age at failure

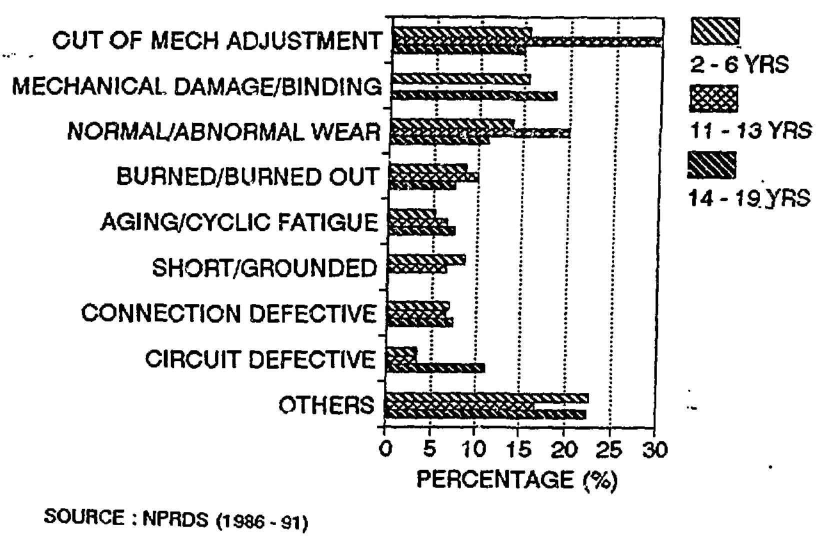

Figure 12. Failure causes for valve operators

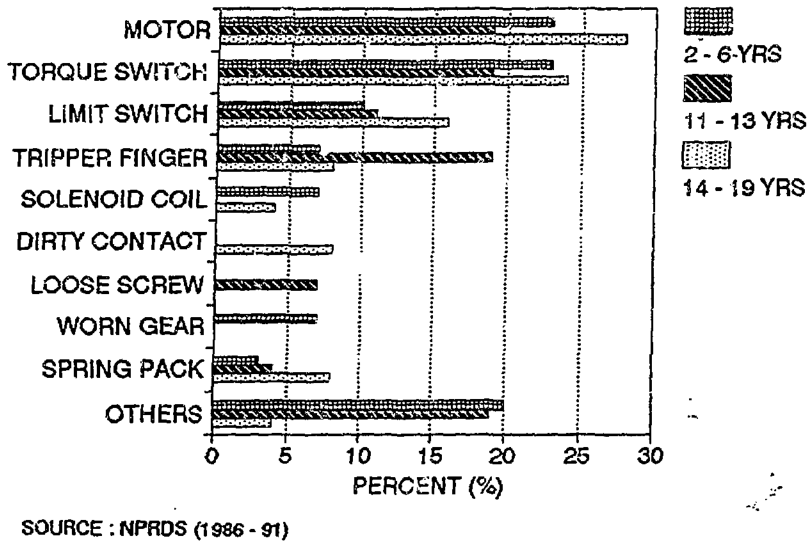

Figure 13. Proximate causes for valve operator failures

The important failure modes are failure to run (20 %) and failure to operate as required (20 %), while 35 % of the failures were assigned to the failure mode "found during testing, surveillance, inspection, or maintenance". The major failure causes are normal/abnormal wear (28 %), out of mechanical adjustment (22 %) and mechanical damage/binding (11 %). Again, there were too few data to identify any meaningful trend in the failure frequency.

Pumps

There were 11 aging-related pump failures; 5 of them were RCIC pump failures, and the rest were 5 water leg pump failures and one condensate pump failure. Both the RCIC pump and the water leg pump are essential for the system operation. One water leg pump failure resulted in a loss of system function, which was caused by a pump motor overload trip due to lack of lubrication for the bearings. Another similar failure and a condensate pump shaft leak resulted in a degraded system operation. Three of the RCIC pump failures were external leaks caused by seal failures, which did not affect the system operation; one failure was a lubrication oil leak due to a worn gasket, which also did not affect the system. Another RCIC pump failure was caused by excessive vibration due to a worn bearing. An oil leak from a drain plug caused a failure of a water leg pump, which did not affect the system.

As shown above, the aging-related failures of pumps are mostly leakage of water or oil due to worn seal/gasket and worn bearings due to lack of lubrication. These failures could be prevented with proper aging management that includes improved maintenance programs.

CONCLUSIONS

As a result of this study, aging processes in the RCIC system are better understood through aging characterization of the system and components. The components most frequently affected by aging degradation and those that need priority aging management are identified by the suggested importance rankings. The information obtained from this study should provide a technical basis upon which future work can be performed.

The following specific findings were obtained:

- Most RCIC component failures reported to NPRDS are due to aging-related degradation (87 %). The analysis of the corrective maintenance records of an operating BWR plant showed that 83 % of the RCIC component failures are due to aging-related degradation, which verifies the national data base results.
- The effects of the component failures on the RCIC system function become more serious as the components age. During the period of 1986 - 87, about 22 % of the component failures resulted in loss of system function or degraded system operation, which increased to 30 % and 36 % for the periods of 1988 - 89 and 1990 - 91, respectively.

- Based on failure data analysis and unavailability analysis which utilized PRA techniques, it was concluded that the aging management for valve operators, switches/bistables, valves, governors, circuit breakers, and pumps is important to reduce and mitigate the aging effects on the RCIC system and plant safety.

- The system failure frequency curve has two major peaks, at 3 -4 years and 11 - 13 year. The failures of valves and switches/bistables mainly caused the system failure frequency peak at 3 - 4 years. The failures of valve operators also contributed to this peak. The second peak is due to the increased failures of valves, switches/bistables, circuit breakers, and valve operators.

- The failure frequency for the steam valves are much higher than that for the water valves. Steam valves operate in a harsher environment than water valves; this result suggests that more attention should be paid to the maintenance of steam valves.

REFERENCES

1. Morris, B.M., Vora, J.P., "Nuclear Plant Aging Research Program Plan," NUREG-1144, July 1985.

2. B.S.Lee, "The Effects of Aging on Boiling Water Reactor Core Isolation Cooling System," Draft, NUREG/CR-6087, BNL-NUREG-52390.

3. Carolina Power & Light Company, " Carolina Power & Light Company Brunswick Steam Electric Plants Units 1 and 2, Probabilistic Risk Assessment", April 1988.

4. Kolaczkowski, A. M., et al., "Analysis of Core Damage Frequency: Peach Botton, Unit 2 Internal Events", NUREG/CR-4550, Vol.4, Rev. 1, Pt. 1, August 1989.

5. B.S. Lee, M. Villaran, M. Subudhi, "Aging Assessment of Bistables and Switches in Nuclear Power Plants," NUREG/CR-5844, BNL-NUREG-52318, January 1993.

6. W. L. Greenstreet, G. A. Murphy, and D. M. Eissenberg, "Aging and Service Wear of Electric Motor-Operated Valves Used in Engineered Safety Feature Systems of Nuclear Power Plants," NUREG/CR-4234 Vol. 1, ORNL-6170/V1, June 1985.

7. H. D. Haynes, "Aging and Service Wear of *Electric Motor-Operated Valves Used in Engineered* Safety Feature Systems of Nuclear Power Plants-Aging Assessment and Monitoring Method Evaluations, NUREG/CR-4234 Vol. 2, ORNL-6170/V2, August 1989.

8. U.S. NRC, NRC Generic Letter 89-10 and Supplements, 1989.