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Condition Monitoring and Testing for Operability of Check Valves and Pumps

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Condition Monitoring and Testing for Operability of Check Valves and Pumps*

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Abstract

A detailed analysis of historical failure data available through the Institute of Nuclear Power Operations' Nuclear Plant Reliability Data System (NPRDS) has been conducted for both check valves and pumps. This analysis, which originated as a part of the Nuclear Regulatory Commission's (NRC) effort to evaluate the effects of age and wear on nuclear systems components, involved the manual review and characterization of several thousand component failure records according to parameters inherent in the NPRDS database and supplemented by those defined by the analyst for each component type. For example, failure information relative to component size, age, system of service, and NSSS vendor was readily available from the NPRDS database and could be compared relatively easily. Determination of parameters such as extent of degradation, affected area, and detection method, however, had to be determined based on manual review and characterization of individual failure narratives.

This paper discusses some of the results of the analyses of historical check valve failure data from 1984 through 1992 and pump failure data from 1990 through 1993. A comparison of the findings of the analyses is made, and emphasis is placed on evaluation of the effectiveness of certain failure detection methods for each component type. Generally speaking, while it was observed that check valve degradation or failure was likely to be detected by code or regulatory required testing, it was discovered that pump degradation or failure was most likely to be discovered by voluntarily implemented plant programs.

Failure rates were found to be strongly influenced by the valve or pump application. The type of plant (BWR or PWR) was also found to significantly influence both the overall failure rate and the method of failure detection.

Check Valve Studies

Background and Methodology

As a result of significant check valve failure events occurring in the mid-1980's, industry and regulatory attention was directed toward identifying and understanding check valve performance issues. One element involved in this process was the review of historical failure data. A collaborative effort among the ASME Operations & Maintenance Committee Working Group on Check Valve Performance (OM-22), NRC, and Oak Ridge National Laboratory (ORNL) involved the review of over 5000 NPRDS failure narratives for check valve failures occurring during the years 1984-1990. The resulting detailed analysis of 1227 of these failures was published in 1993 [1]. A primary goal of this study was to evaluate failure data to identify any significant correlations of failure rates with component age, plant age, or other parameters while considering the effect of the number of valves in service during the analysis period (i.e., component population effects). The study focused on failures involving degradation of valve internal parts. A "failure" was defined as a degradation of one or more valve functions (e.g., failure to open, failure to close, loose/broken parts), not in terms of any resultant system or plant effects.

Desiring to gather additional information and to identify any performance trends, the NRC requested ORNL to update the original check valve analysis for two additional study periods, 1991 and 1992. Supplemental data not available from NPRDS and therefore not included in the 1984-1990 study included data on specific valve type (e.g., swing, lift) as well as information obtained from direct utility surveys sponsored by the Nuclear Industry Check Valve Group (NIC). Results of the 1991 study were published in 1995 [2]; those for 1992 should be available soon.

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Results

Extent of degradation

One of the parameters characterized and analyzed for the check valve studies was extent of degradation. This parameter is not inherent in raw NPRDS data and therefore has to be characterized by the analyst. It is important to understand that the extent of degradation assigned is based on the loss or degradation of one or more valve functions, and not on real or potential system or plant effects. Accordingly, extent of degradation to the component was characterized as either "moderate" or "significant." Figure 1 shows the trend in check valve failure data from 1984 through 1992 according to extent of degradation. While the data from 1984-1990 indicates that more than 50% of the failures involved significant internal degradation, it is apparent that the trend is toward a decrease in the percentage of significant failures, dropping below 40% in both 1991 and 1992. It is important to note, however, that the screening process employed by ORNL to exclude failure reports from further analysis changed after the 1984-1990 study. While all the studies excluded failure reports involving no internal seat leakage, nonfailures, and noncheck valves, the 1991 and 1992 studies intentionally included all failures involving internal seat leakage (the 1984-1990 study excluded minor seat leakage events). This change in practice inherently resulted in more moderate type failures in the later studies, but provided a more realistic measure of the kinds of failures being reported. Results from the 1991 and subsequent analyses can therefore be compared on a more consistent basis.

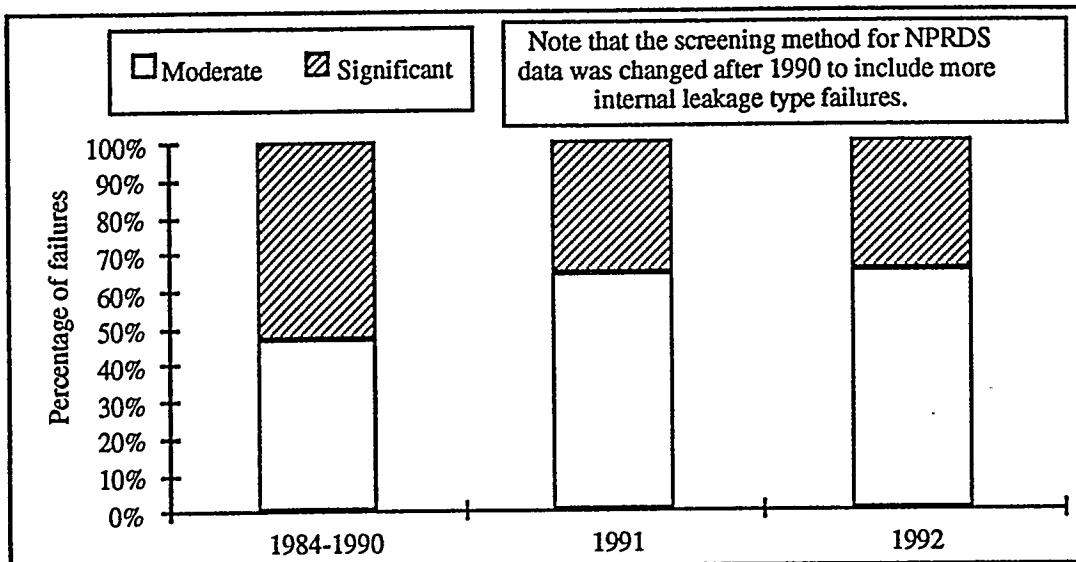


Figure 1. Trend of check valve failures by extent of degradation: 1984-1992

System

One parameter included in the NPRDS database is that of system of service. Figure 2 shows the distribution of significant 1991-1992 failures by relative failure rate for the ten systems with the highest overall failure rates during that period. (Only systems with at least 400 valve-years of service during the time period were considered.) Five systems exhibited failure rates between two and three times the overall relative failure rate. These included RCIC, suppression pool support, diesel starting air, HPCI, and main steam. It is important to recognize that many of the failures in the HPCI and suppression pool support systems involved vacuum breaker valves, and most of the failures occurring in the diesel starting air system involved lift/piston check valves that were either stuck open or stuck closed. Results from the study of 1984-1990 data were consistent with this result, indicating that ESW, feedwater, diesel starting air, and main steam systems, respectively, had the highest relative failure rates for that period.

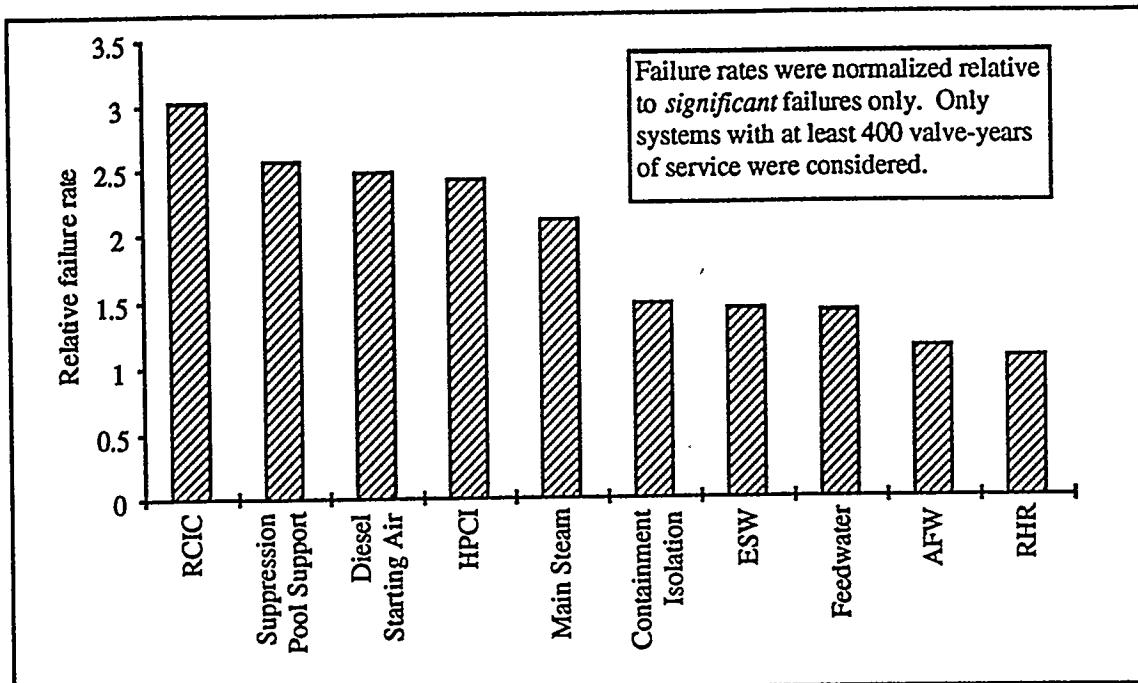


Figure 2. Relative failure rate for ten systems with the highest overall failure rates for significant 1991-1992 check valve failures

Valve size

Figure 3 shows the relative failure rate and fraction of valve population for all 1991-1992 failures by size group. Valves in the smallest group (less than or equal to 2 in.) failed at a rate about equal to the overall relative failure rate, while those in the largest group (greater than 10 in.) failed at a rate about 1.3 times that of the overall average. Those between 2 and 10 in. failed at rates below the overall average. The 1991-1992 data shows a slight increase in the relative failure rate of valves in the smallest size group compared to 1984-1990 data (not shown).

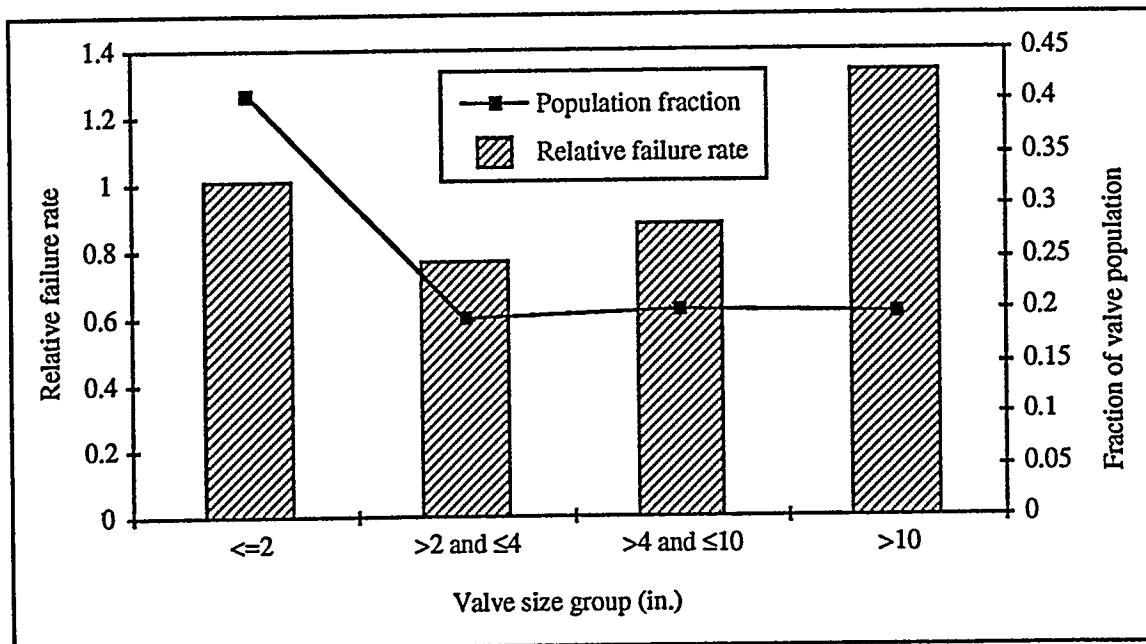


Figure 3. Relative failure rate and population by size group for all 1991-1992 check valve failures

Valve age group

In general, data from 1984 through 1992 has not shown a significant relationship between failure rate and either valve or plant age. Relative failure rate by valve age group for 1991-1992 failures is shown in Fig. 4. As can be seen, no appreciable differences in relative failure rates according to component age are apparent; however, a slight increase is noted from less than 5 years of age to 15 years of age. These results are consistent with those of the 1984-1990 analysis. The greater than 20 year age group shows the highest relative failure rate, at just over 1.2. Data for this age group was not available for the 1984-1990 study, due to the younger age of many plants.

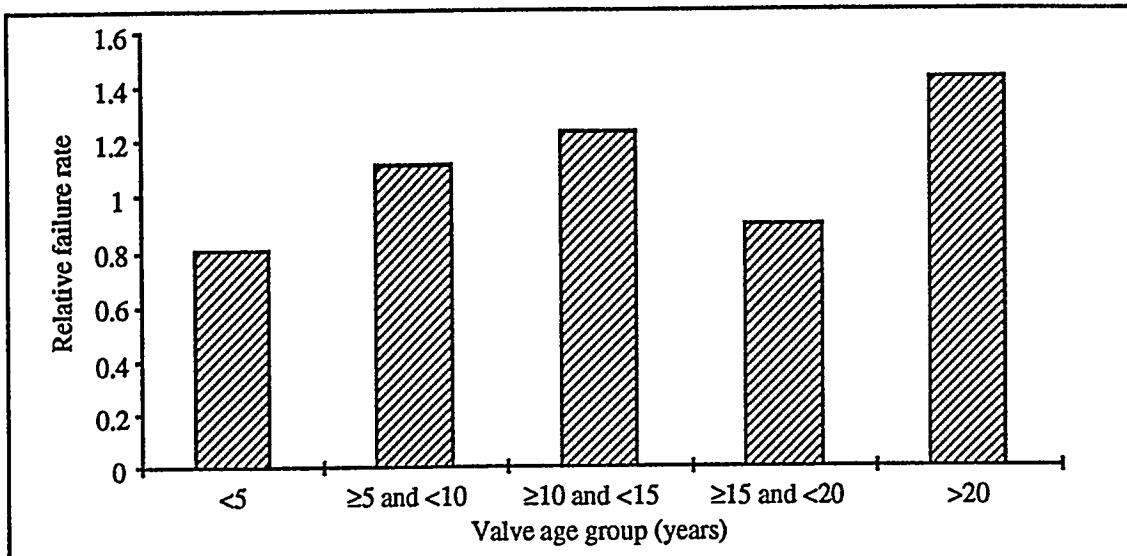


Figure 4. Relative failure rate by valve age group for all 1991-1992 check valve failures

NSSS and plant type

For 1991-1992 failures, Fig. 5 shows the relative failure rate and population by NSSS, while Fig. 6 shows relative failure rate by plant type. From both figures, it is apparent that the higher relative failure rates occur in BWR plants. This finding is consistent with 1984-1990 data. Although it is not certain why this trend continues, it has been theorized that more failures may have been discovered in BWRs than in PWRs due to the BWR plants' practice of leak testing more valves and including more valves in inservice testing programs. Further cross-correlation of the data has shown that BWR plants have a much higher fraction of failures detected programmatically than do PWRs, a result which may substantiate the theory.

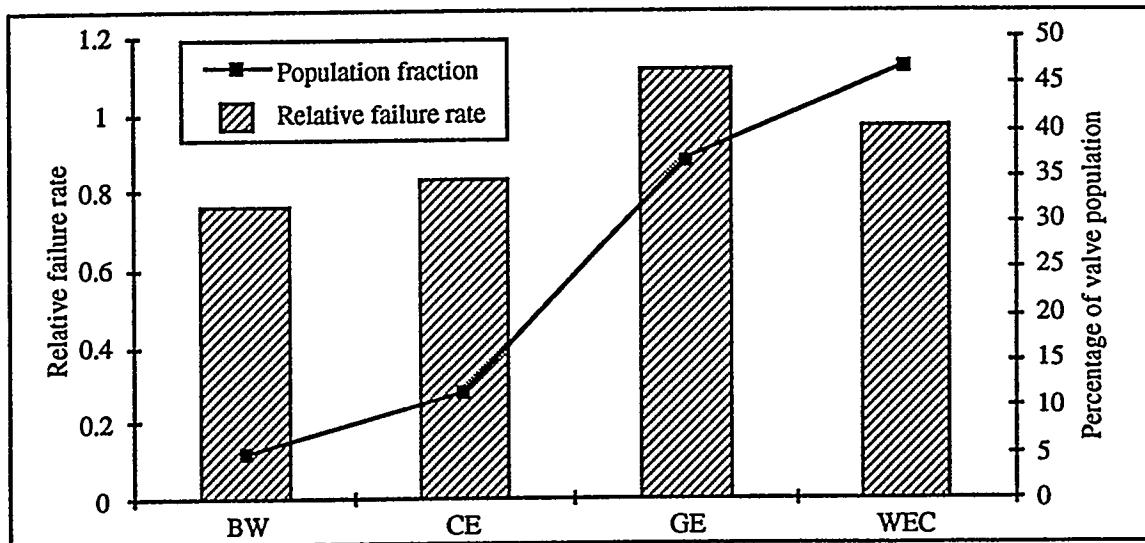


Figure 5. Relative failure rate and population by NSSS for all 1991-1992 check valve failures

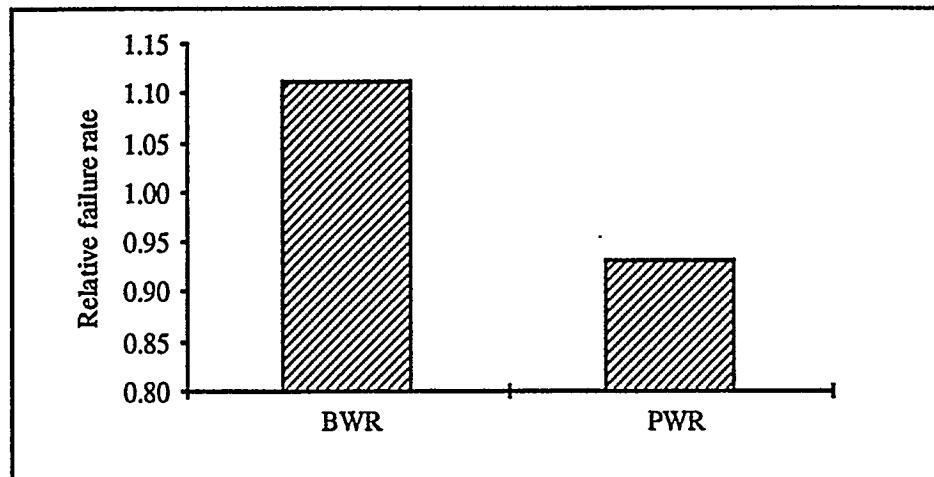


Figure 6. Relative failure rate by plant type for all 1991-1992 check valve failures

Method of detection

Figures 7, 8, and 9 show, in absolute number of failures, the distribution of failures by method of detection. Figure 7 plots the significant failures occurring from 1984 through 1992 by method of detection, Fig. 8 plots the same data for 1991-1992 only, and Fig. 9 shows all 1991-1992 failures. The method of detection for the check valve analyses was defined as either "programmatic" or "nonprogrammatic." Check valve failures detected "programmatically" included those observed during the conduct of some code or regulatory required function, such as a surveillance test, inservice inspection or test, leak test, or periodic preventive maintenance. Those detected "nonprogrammatically" were those detected during routine or incidental observation, by abnormal equipment operation, during special inspection, or where the detection method was unclear from the failure narrative.

While the number of significant failures detected programmatically from 1984 through 1992 was only slightly greater than those detected by nonprogrammatic means (522 to 427), it is encouraging that in the later years, the programmatically detected failures dominated. For significant 1991-1992 failures, 221 failures were detected programmatically vs only 74 by nonprogrammatic means. And as shown in Fig. 9 for all (i.e., including both significant and moderate categories) 1991-1992 failures, the ratio is even greater: 654 failures detected programmatically to just 184 detected by other means. The data suggest that in the more recent years the increased attention given to ensure check valve operability has resulted in significant improvements in failure detection by programmatic means.

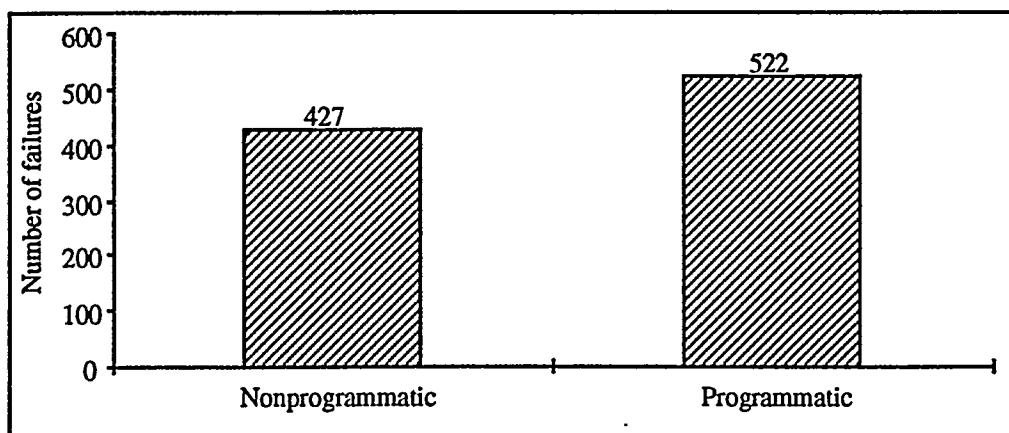


Figure 7. Distribution of significant 1984-1992 check valve failures by method of detection

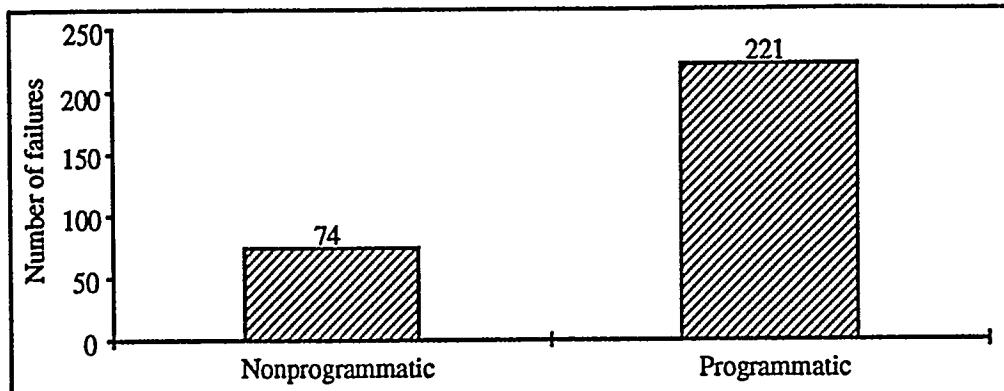


Figure 8. Distribution of significant 1991-1992 check valve failures by method of detection

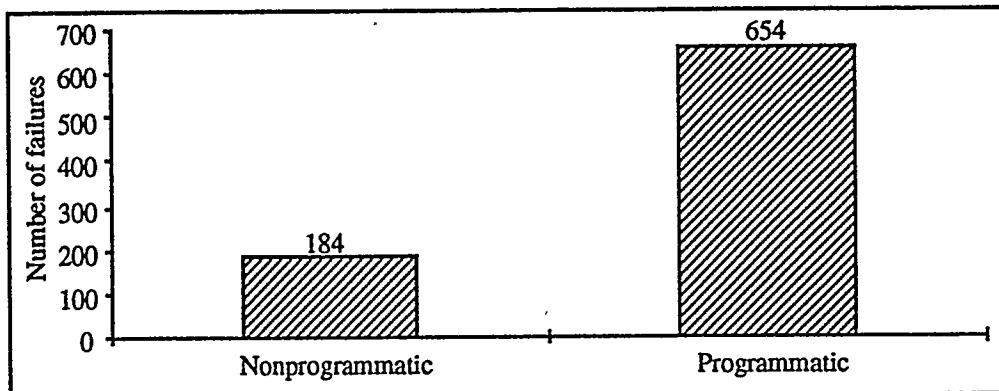


Figure 9. Distribution of 1991-1992 check valve failures by method of detection

Affected area

Another cross-correlation of interest is that of discovery process and affected area. Figure 10 plots 1991-1992 check valve failures by affected area and general discovery process. From this chart it is apparent that the dominant method of detection, irrespective of affected area, has been programmatic. Figure 11 replots the same information without programmatically detected failures so that the relationship between other general detection methods versus failure area is clarified. It is interesting to note that a large fraction of failures involving all areas (except those where general wear is cited) were detected by routine observation. Except for programmatically detected failures, the highest fraction of failures involving the hinge pin area were detected by abnormal equipment operation.

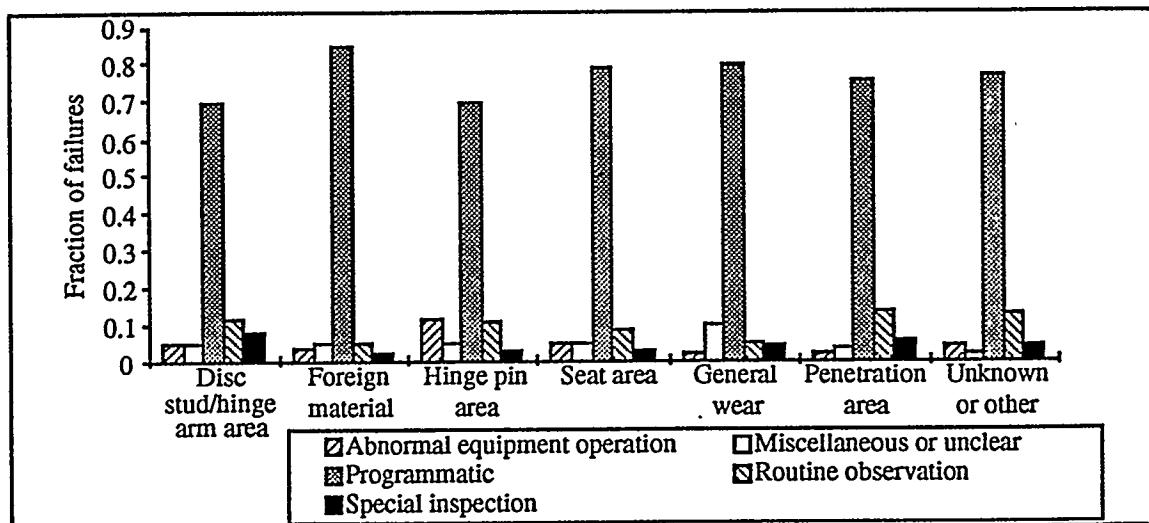


Figure 10. Distribution of 1991-1992 check valve failures by affected area and general discovery process

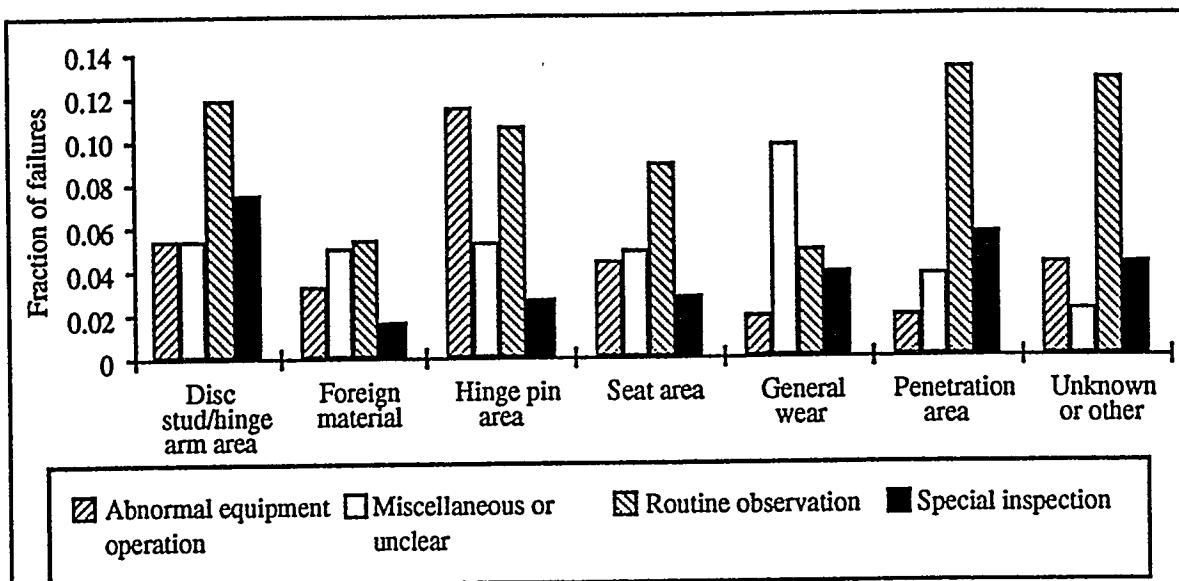


Figure 11. Distribution of 1991-1992 check valve failures by affected area and general discovery process (without programmatically detected failures)

Figure 12 again plots 1991-1992 failures by affected area and general discovery process, but this time only failures that were judged to be significant in terms of extent of degradation are included. Again, the dominant method of detection for all areas was programmatic. Figure 13 replots the same data without programmatically detected failures for clarification. It is interesting to note that for the disc stud/hinge arm, foreign material, hinge pin, and seat areas, many of the failures not detected programmatically were found by abnormal equipment operation.

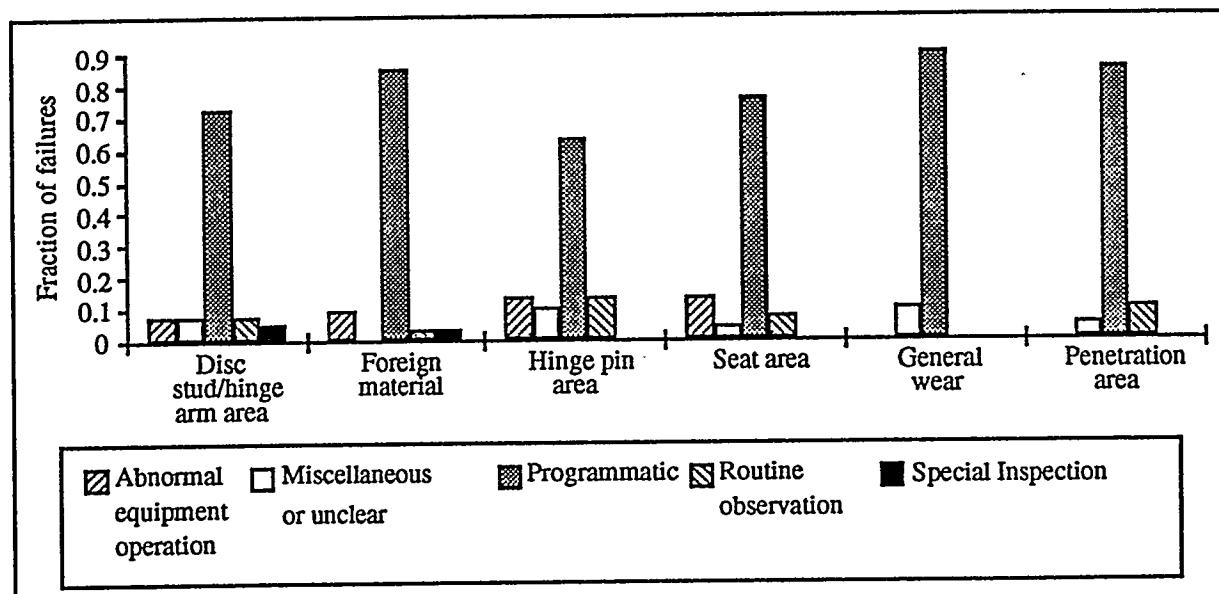


Figure 12. Distribution of significant 1991-1992 check valve failures by affected area and general discovery process

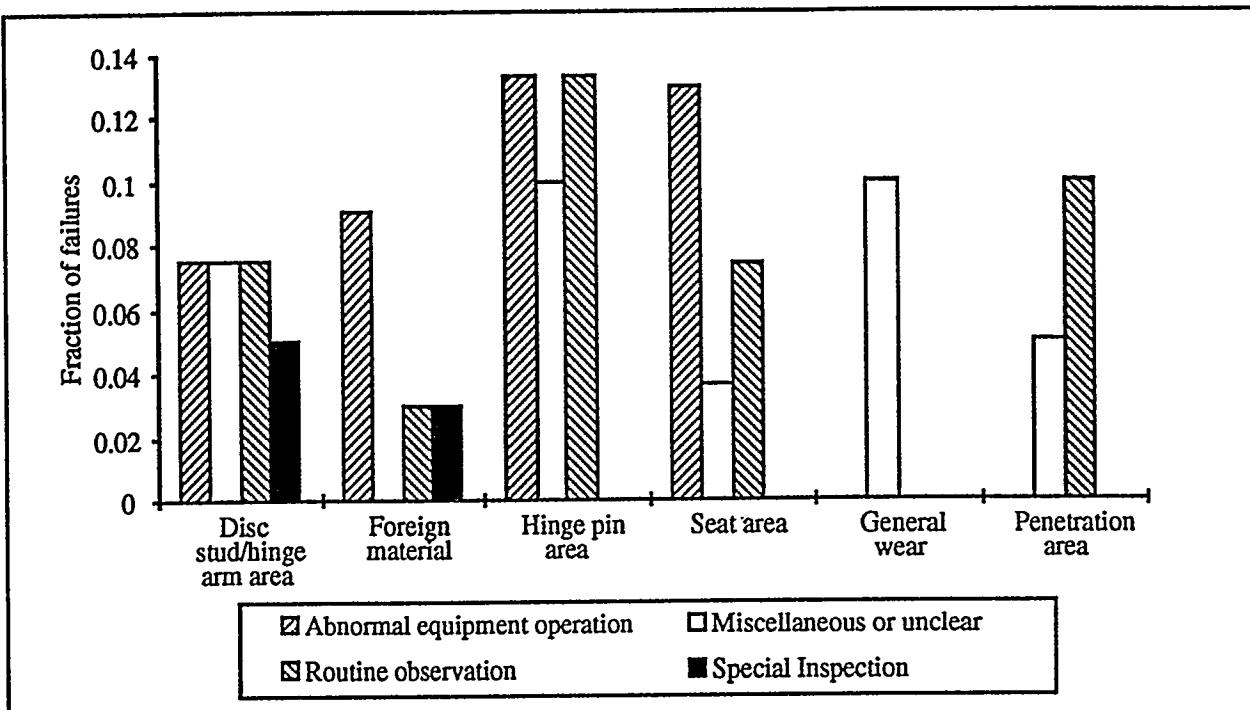


Figure 13. Distribution of significant 1991-1992 check valve failures by affected area and general discovery process (without programmatically detected failures)

Pump Study

Background and Methodology

Although the design and normal operating functions of fluid systems used at current generation reactors are diverse, almost all normally operating and standby fluid systems share the common feature of depending upon pumps to provide motive power for the process fluid. Malfunctions of other components, such as valves, instrumentation, controls, motors, and power supplies can often be minimized or overcome by human intervention. In the case of pumps and their drivers, however, many failures cannot be dealt with by manual interaction.

Recognizing the importance of reliable pump operation in these systems, ORNL undertook a study of pump failure data available from NPPRDS. The pump study used, as closely as possible, the same methodology applied to evaluate check valve failures. The differences in methodology that should be noted are:

- (1) The check valve studies evaluated all check valve failures. The pump study was limited to specific pump and pump motor applications.
- (2) Due to fundamental differences in failure modes and their significance, the extent of degradation categories for pumps were different than those applied to check valves. (For purposes of this paper, however, pump failures are divided into "significant" failures and all failures.)
- (3) The study periods for the two types of components were different.

Results

The pump failure data review [3] studied and characterized failures occurring in the years 1990-1993 of centrifugal pumps and used in safety-related service in several critical systems at BWR and PWR plants. The systems included are identified in Table 1.

Table 1. Systems included in the pump failure study

<u>PWR plants</u>	<u>BWR plants</u>
• Auxiliary feedwater (AFW)	• Component cooling water (CCW)
• Component cooling water (CCW)	• High pressure coolant injection (HPCI)
• Containment spray (Cont. spray)	• Emergency service water (ESW)
• Charging/high pressure safety injection (CVCS/HPSI)	• Low pressure core spray (LPCS)
• Emergency service water (ESW)	• Reactor core isolation cooling (RCIC)
• Low pressure safety injection/residual heat removal (RHR)	• Low pressure coolant injection/residual heat removal (RHR)

In addition to studying the failures of the pumps themselves, the failures of motor drives used for these pump applications were studied. Non-motor drives (turbines used on AFW, RCIC, and HPCI pumps) were not included because of previous studies of the experience with turbine drives [3, 4, 5].

A total of 7210 pump-years of experience was accumulated by the studied pumps during the 1990-1993 period (2405 at BWRs and 4805 at PWRs). There were 797 failures of the studied pumps and 143 failures of the associated motors reported to the NPRDS database during the period.

Extent of Degradation

Although the fundamental characterization of failures by extent of degradation for pumps was done at a slightly greater level of resolution than for check valves, the failures are segregated here into two categories – all failures and significant failures only. Those failures that are classed as significant are those for which the pump either would not operate at all, would not operate to the level required to perform its safety function, or was operating at a degraded level with near-term continued operation in jeopardy.

The reported failure rates and the distribution of all pump and motor failures by extent of degradation for BWR and PWR plants is shown in Figure 14. It should be emphasized that although the rates are shown in absolute terms, the authors strongly discourage blindly using these failure rate values for other purposes without considering other factors such as reporting practices and recovery time.

There were clearly more pump than motor failures (more than 5 times as many, considering all failures). However, there were only 3 times as many pump failures compared to motor failures for those failures classed as significant. This is an important finding, since the existing ASME Code test requirements for pumps [7] do not explicitly address motor monitoring. ASME Working Group OM-6 (charged with responsibility for pump test requirements) is beginning to consider the merits of specifically incorporating motor testing into the Code. While there are other factors to be considered, such as the practicality of periodic motor testing and whether periodic inservice testing or monitoring would be effective at detecting motor degradation prior to failure, the failure data clearly indicate that motors are an important factor in overall pump drive train reliability.

Another finding of particular interest is that although motor failure rates for BWR and PWR units are similar, the pump failure rate for PWRs is approximately double that of BWR units. This was found to be true for all failures and significant failures only.

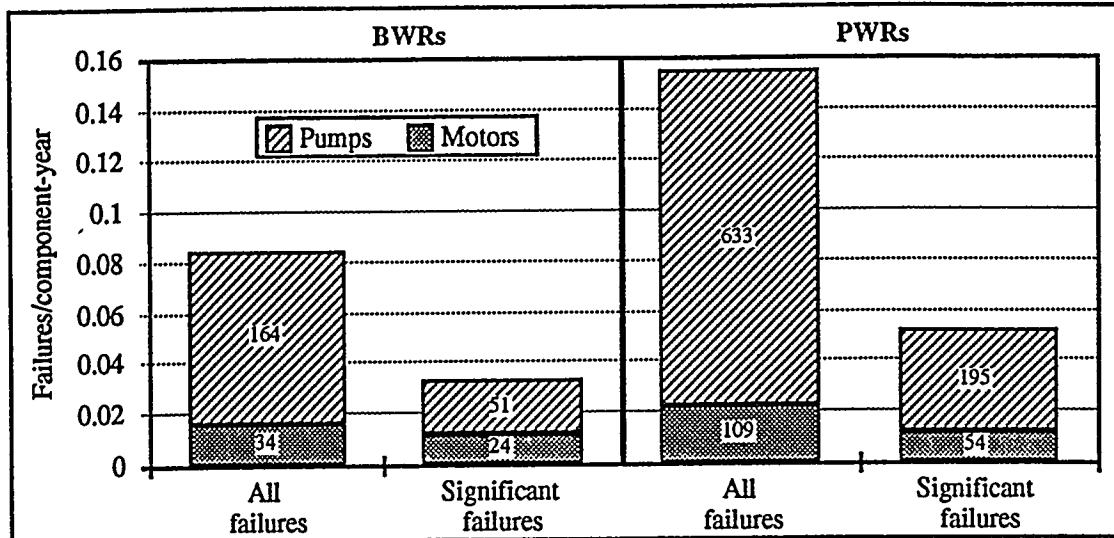


Figure 14. Pump and motor failures by extent of degradation and reactor type.

System

The system in which pumps are used was found to be an important factor in regards to both failure rate and mode. Figure 15 shows the absolute failure rates for pumps and motors by system for BWR and PWR plants. Some features of particular note are:

- ESW pumps and motors at both plant types have substantially higher overall failure rates. The failure rates for significant failures in ESW are almost three times those of the next closest system (CCW) at BWRs, almost twice that of the next highest system at PWRs (AFW).
- The failure rate for BWR system pumps is strongly related to the system usage. For example, normally operating systems (such as ESW and CCW) have higher failure rates than do systems that are occasionally used (such as RHR and RCIC), which in turn have higher failure rates than systems whose primary usage is for testing (HPCI and LPCS).
- In general, the same system usage effect appears in the PWR data. The primary exception is AFW, which has both an overall and significant failure rate that is comparable to those of CCW and CVCS/HPSI. Note that the CVCS/HPSI data represents a mixture—at some plants, the HPSI pumps are used solely for testing or emergency response, while at others, they serve the dual function of charging. Thus, the actual usage of CVCS/HPSI pumps can be at either extreme.

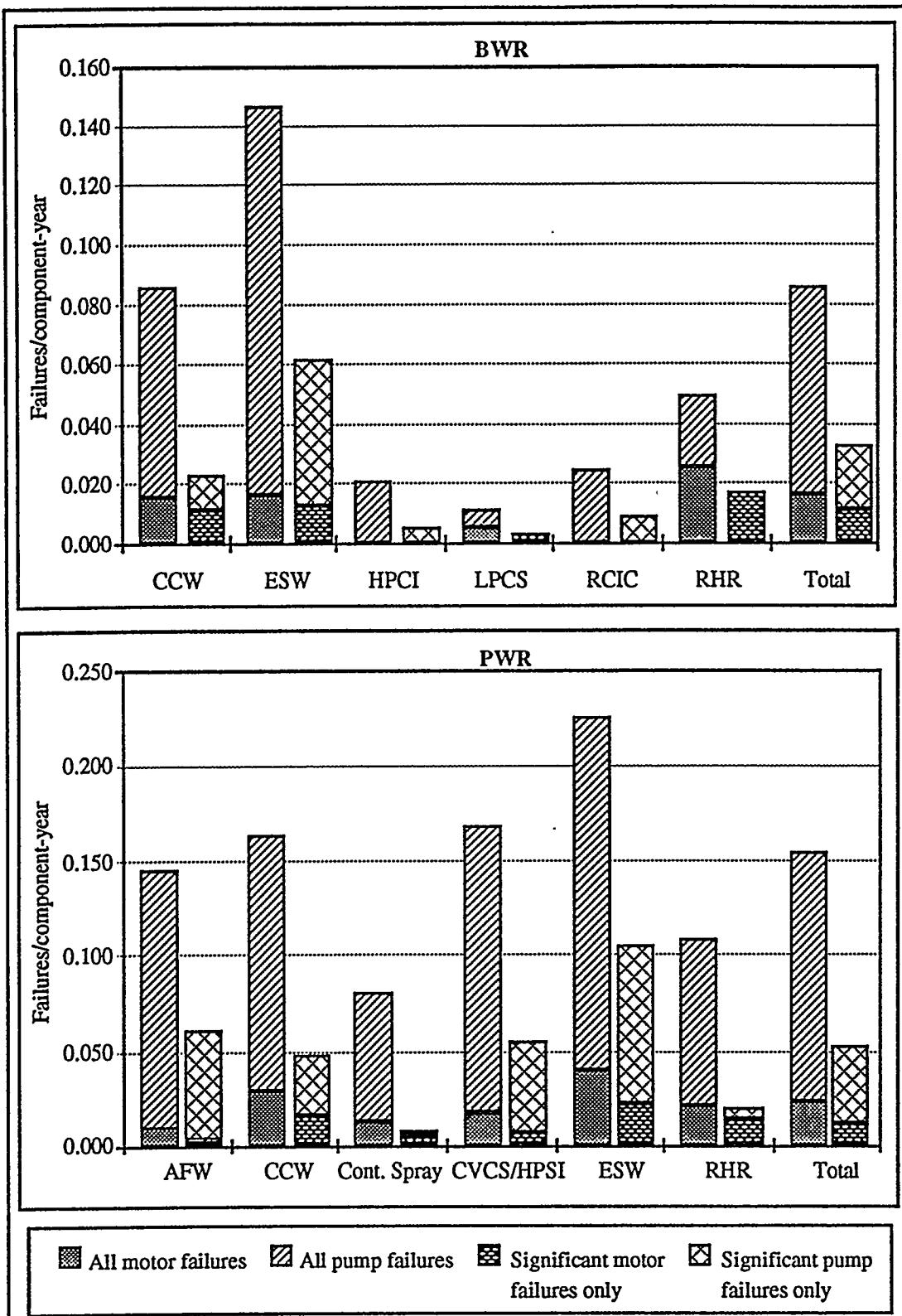


Figure 15. Absolute failure rates for pumps and motors by system and reactor type. Note that the y-axis scaling is different for the two graphs.

Age Group

The relative failure rate as a function of component age for all pumps (motors not included) at BWR and PWR plants is shown in Figure 16. For the BWR plants, there is a clear age-related trend in that the failure rate drops significantly after a period of infant mortality. The same trend appears to occur, to a lesser extent, for the PWR plants in the transition from <5 to ≥ 5 and <10 year group, but then reverses in subsequent age groups. For the significant failures only, the PWR plant failure rate trend as a function of age group resembles the classical "bath tub" shape.

The fact that BWR plants have had better experience than PWR plants is clearly illustrated in this Figure 17, where the ratio of PWR to BWR failure rates as a function of age group for significant failures is shown. During the early years of operation, the performance of pumps at BWR and PWR units is similar. But over time, the failure rate relationship changes dramatically.

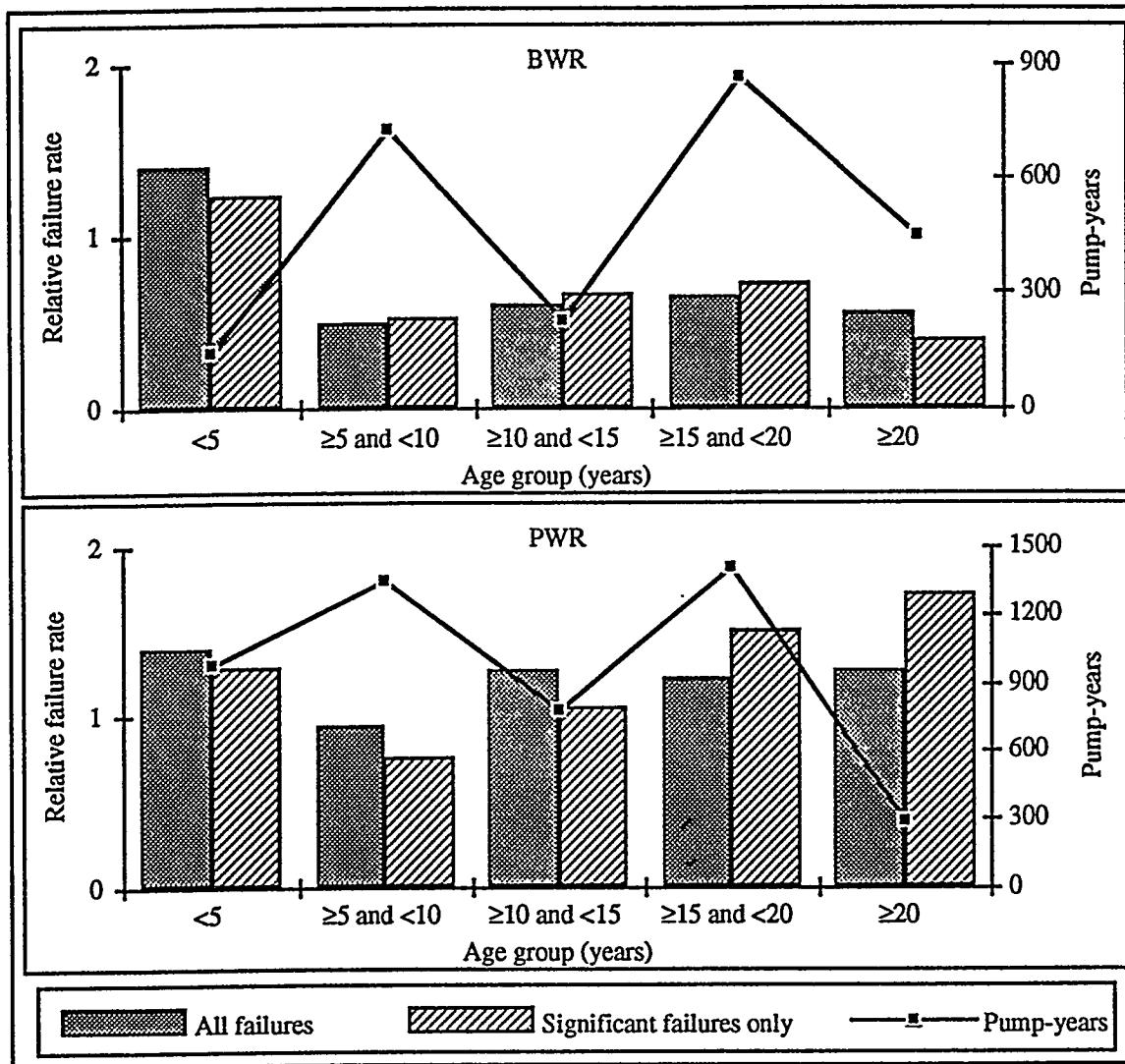


Figure 16. Relative failure rates for pumps by age group and reactor type.

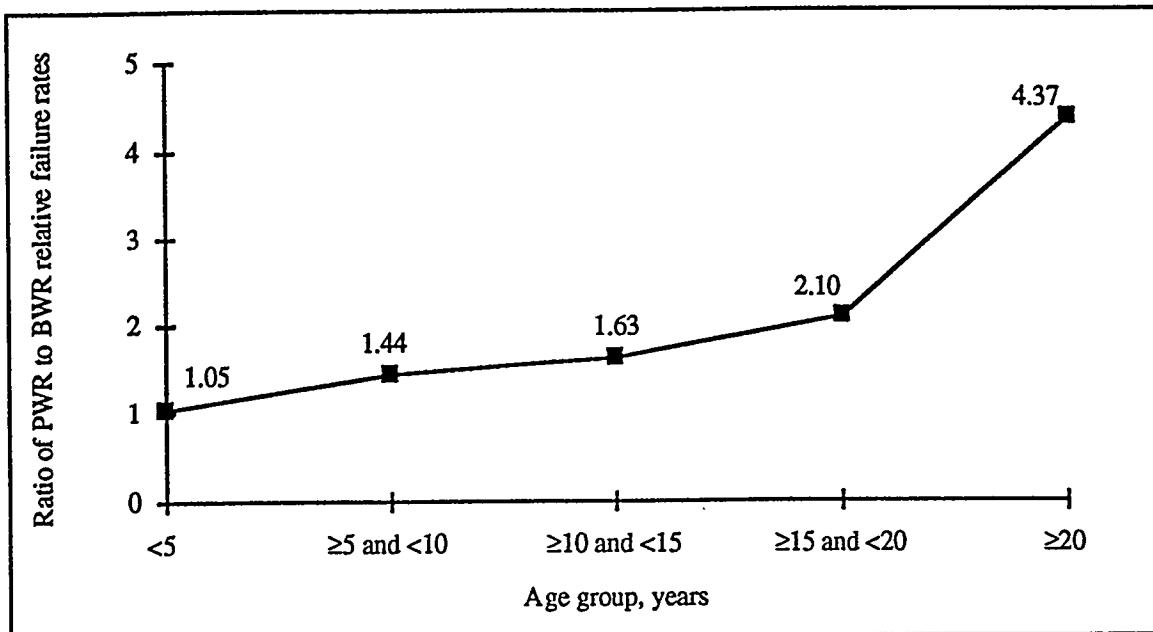


Figure 17. Ratio of PWR to BWR relative failure rates as a function of plant age for significant failures

Affected area

All failures were characterized by the affected area. Table 2 presents the numbers of failures by extent of degradation and reactor type and a comparison of the normalized failure rates at BWR and PWR plants. It is notable that PWR pumps had higher failure rates in all areas than BWR pumps (excluding the "Unknown" category).

Table 2. Pump failures by affected area and reactor type

Affected area	All failures		Significant failures only		PWR to BWR failure rate (significant failures)
	BWR	PWR	BWR	PWR	
Alignment/balance	2	5	1	3	1.50
Bearing	23	133	18	74	2.06
Shaft, coupling, keys	8	19	6	18	1.50
Internals	26	77	22	69	1.57
Oil leak	13	11	0	0	N/A
Other	14	133	4	14	1.75
Seal/packing	87	280	5	40	4.00
Unknown	2	2	2	2	0.50
Total	633	164	54	195	1.91

Tables 3 and 4 tabulate the numbers of significant failures by affected area and system for PWR and BWR plants. Of 69 significant failures involving internals, 49 were in ESW pumps; 12 of 18 shaft/coupling/key failures occurred in ESW pumps. However, only 12 of 74 significant failures in which a bearing was affected involved ESW pumps.

**Table 3. Number of PWR pump failures by affected area and system
(significant failures only)**

Affected area code	AFW	CCW	Cont. Spray	CVCS/ HPSI	ESW	RHR	Total
Alignment/balance	2	0	0	1	0	0	3
Bearing	14	22	2	22	12	2	74
Shaft, coupling, keys	0	2	0	4	12	0	18
Internals	6	5	0	9	49	0	69
Oil leak	0	0	0	0	0	0	0
Other	7	0	0	6	1	0	14
Seal/packing	15	7	1	7	8	2	40
Unknown	0	0	0	0	2	0	2
Total	42	26	2	44	77	4	195

**Table 4. Number of BWR pump failures by affected area and system
(significant failures only)**

Affected area code	CCW	ESW	HPCI	LPCS	RCIC	RHR	Total
Alignment/balance	0	1	0	0	0	0	1
Bearing	3	13	1	0	1	0	18
Shaft, coupling, keys	0	6	0	0	0	0	6
Internals	0	22	0	0	0	0	22
Oil leak	0	0	0	0	0	0	0
Other	0	4	0	0	0	0	4
Seal/packing	0	5	0	0	0	0	5
Unknown	0	2	0	0	0	0	2
Total	3	46	1	0	1	0	51

Method of detection

While the check valve failure studies classified failures by two general detection method classifications, three general methods of detection were used for pumps – regulatory/code, plant programmatic, and nonprogrammatic. Failures included under the regulatory/code category were those that were detected during regulatory/code required testing by means prescribed by the ASME Code. The failures detected by plant programmatic means are those that were detected by plant programs that are routinely implemented, but not mandated by regulation. Failures detected by the third category, nonprogrammatic, are those that were detected by neither of the other two methods.

This deviation from the classification used in the check valve studies (i.e., adding the plant programmatic category) came in part from the observation that a significant number of failures were detected by plant programmatic means not implemented as a part of a regulatorily mandated surveillance test. But more significantly, the change in classification was prompted by the simple recognition that many pump failures manifest themselves by means that allow detection by human senses - sight, smell, sound, and touch. Check valve failures, other than those involving external leakage (which were explicitly excluded from the studies) do not lend themselves to such detection means. Some of the plant programmatically detected failures were found during the process of preparing for or conducting regulatorily required testing, but were noted not because of the regulation or code criteria, but because of good practices and observation patterns of utility employees.

Figures 18-20 show the numbers of failures by detection means for all failures (Fig. 18), all failures except those involving only seal or packing leakage (Fig. 19), and significant failures only (Fig. 20). Although many of the failures detected by plant programmatic means involved seal or packing leakage only where visual observation was the specific means of detection, Figures 19 and 20 indicate that plant programmatic means were also the leading means for detecting other failures.

Figure 21 illustrates the distribution of significant failures by detection means and affected area for three critical areas. The number of failures for each category is shown at the top of each chart column. Over five times as many bearing problems

at PWR plants were detected by plant programmatic means than by regulatory/code testing. Further review of these bearing failures detected by plant programmatic means indicated that the principal ways of detecting the problems were routine oil monitoring (either sampling or simple visual observation) and operators noticing hot or noisy/excessively vibrating bearings. Of the 10 failures involving bearings at PWRs in which regulatory/code monitoring was employed, 5 were detected by elevated temperature (for which monitoring is not required in the more recent versions of the Code), 1 by failure to start, and only 4 by vibration.

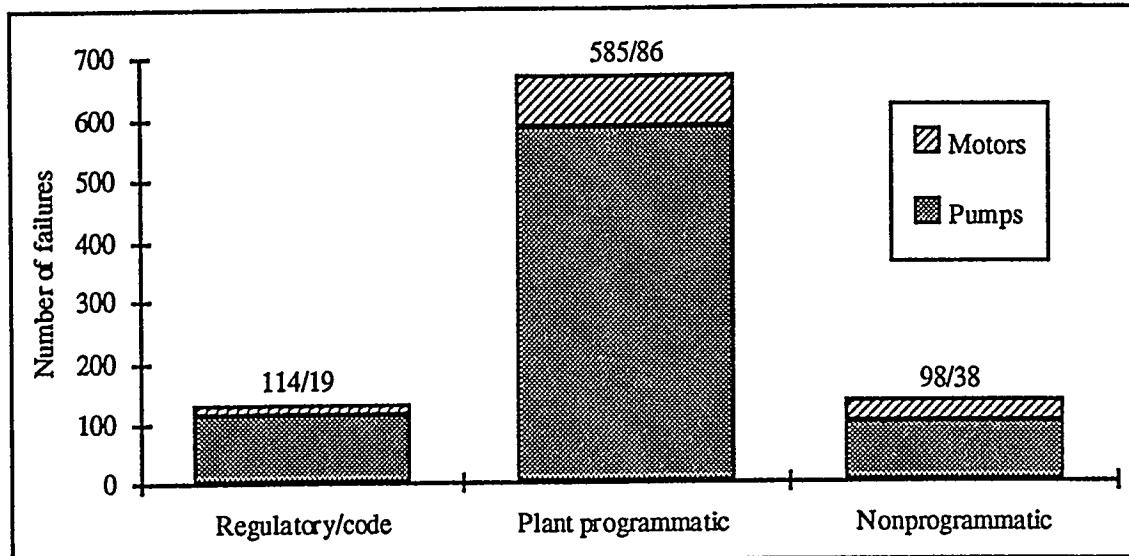


Figure 18. Distribution of failures by general method of detection (all failures).

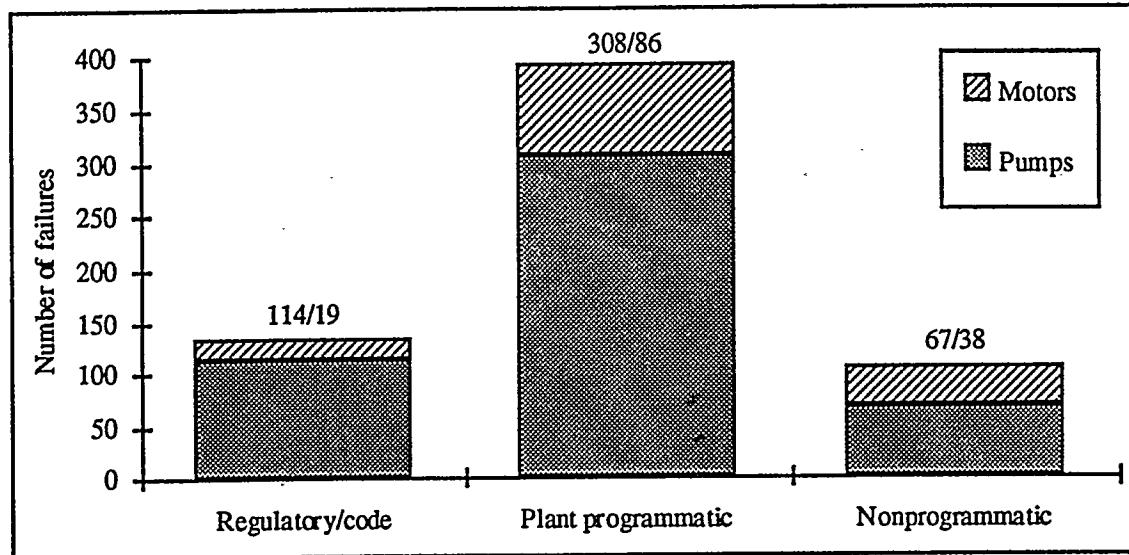


Figure 19. Distribution of failures by general method of detection (seal failures excluded).

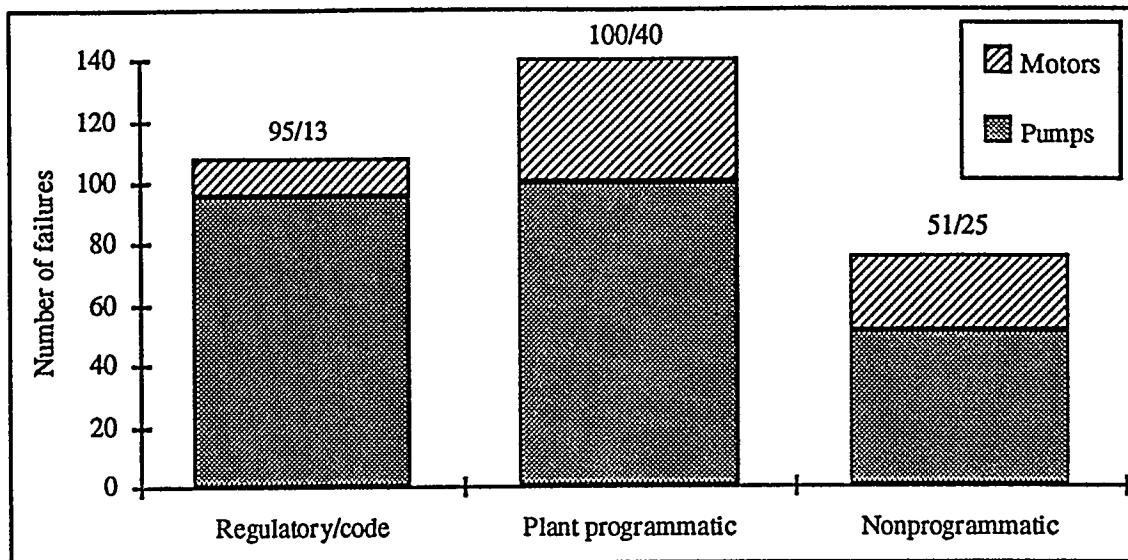


Figure 20. Distribution of failures by general method of detection (significant failures only).

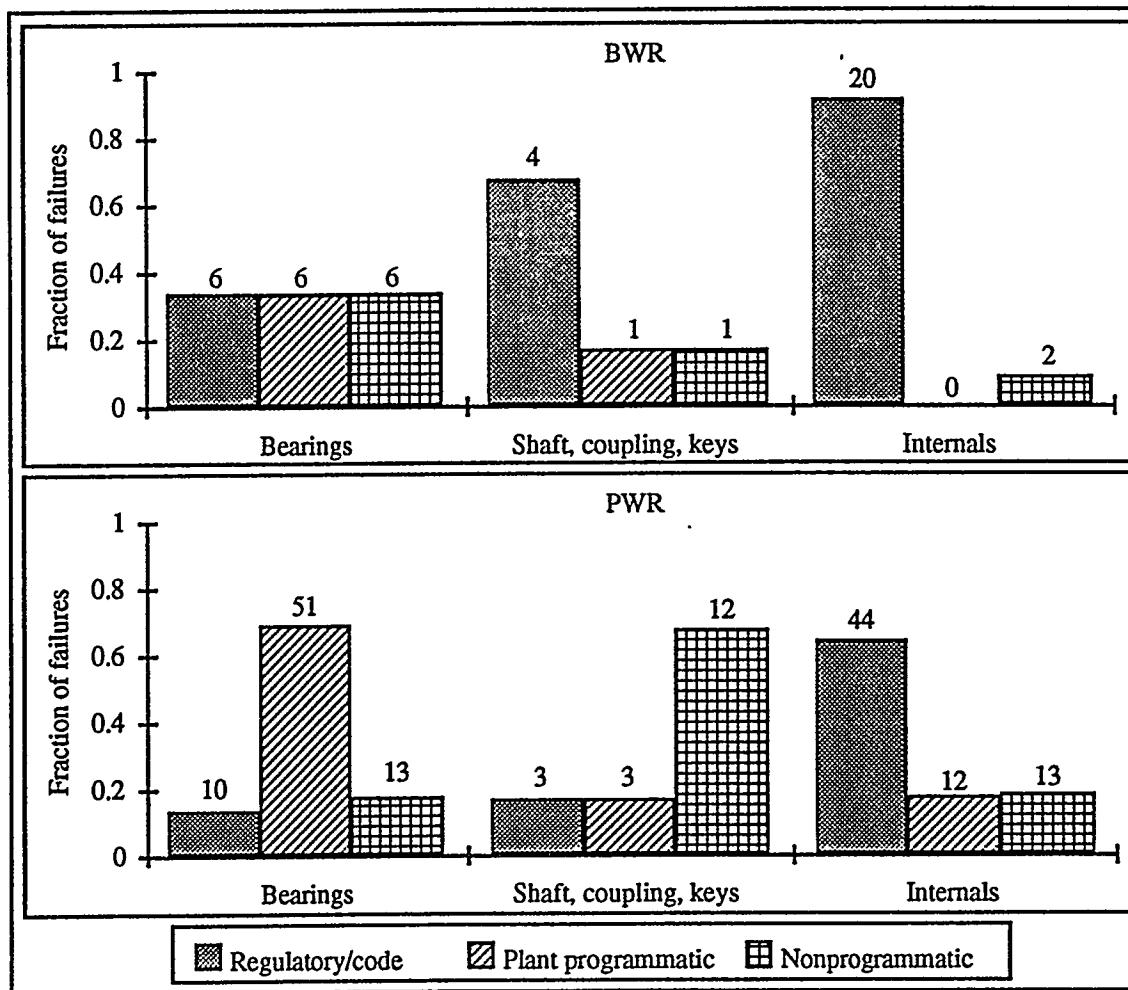


Figure 21. Distribution of significant pump failures by affected area and method of detection.

Tables 5 and 6 show the distribution of significant pump failures by system and detection process. Systems that are not included in these tables had no significant level failures.

Table 5. Distribution of significant PWR pump failures by system and detection process

General detection process	AFW	CCW	Cont. Spray	CVCS/HPSI	ESW	RHR	Total
Regulatory/code	11	2	1	4	45	0	63
Plant programmatic	27	21	1	25	12	3	89
Nonprogrammatic	4	3	0	15	20	1	43
Total	42	26	2	44	77	4	195

Table 6. Distribution of significant BWR pump failures by system and detection process

General detection process	CCW	ESW	HPCI	RCIC	Total
Regulatory/code	0	30	1	1	32
Plant programmatic	2	9	0	0	11
Nonprogrammatic	1	7	0	0	8
Total	3	46	1	1	51

From the information shown in these tables and further review of the data, several particularly useful insights into the effectiveness of monitoring practices were gained:

- As was shown previously, ESW pumps had the highest failure rates of any of the systems studied. ESW pumps were an even more important contributor for those failures detected by regulatory/code mandated means. There were 95 significant level pump failures detected by regulatory/code mandated testing; 75 were in the ESW system. Of these 75 ESW pump failures, 61 involved internals wear; thus, almost two-thirds of all regulatory/code detected pump failures (for significant level failures) were associated with degradation of ESW pump internals.
- Of the 95 regulatory/code detected failures, 32 occurred at BWR plants. Of the 32 BWR failures, 30 were in the ESW system; 20 of the 30 ESW failures involved internals degradation.
- Of the 63 pump failures detected by regulatory/code required monitoring at PWR plants, 45 occurred in the ESW system. Of these 45 ESW pump failures at PWR plants, 41 involved internals degradation.
- Summarizing the last two bullet items, almost two-thirds (61 of 95) of the failures detected by regulatory/code required monitoring involved internals degradation of ESW pumps.
- Further review of these failures showed that 39 of the 95 regulatory/code detected pump failures were in ESW pumps at only five units. Thus, over 40% of all significant pump failures detected by regulatory/code required testing were found in one system at five units. The primary factor in the higher failure rates at these units was the quality of water being pumped (either high silt levels or foreign material presence).
- The distribution of failures detected by plant programmatic means at PWR units was decidedly more evenly distributed, with approximately equal fractions coming from four systems: AFW, CCW, ESW, and CVCS/HPSI.
- A total of 51 significant pump failures occurred at BWR units. Of these 51 failures, 46 (90%) involved ESW pumps. In contrast, 77 of the 195 significant PWR pump failures (40%) involved ESW pumps.
- Of the pump failures detected by regulatory/code testing, 83% (5 out of every 6) were classified as significant (i.e., level 4 or 5). This is not unexpected, since most failures thus reported fall into the required action range. Those failures that were not classified as significant either involved some increased vibration level (which was not deemed excessive by conventional criteria) or were nuisance type reports (for example, a pump delivered 24 gpm instead of the required 25 gpm under recirculation conditions).
- Only 17% of the significant bearing failures were detected by regulatory/code testing; almost 2/3 of the significant bearing failures were detected by plant programmatic means.

Summary

Although the check valve and pump studies differed somewhat in their approaches, some general comparisons can be made with regard to certain of their common parameters:

Extent of degradation

Although there were over five times the number of pump failures than motor failures, only three times as many pump failures as motor failures were classified as significant. In absolute terms, the percentage of significant component failures is about equal for pumps/motors from 1990-1993 (considering all plants) and for check valves during 1991 and 1992 - about 35%. Also, the percentage of significant component failures during this period was slightly higher for BWRs than for PWRs; about 38% versus 34% for both pumps/motors and check valves. It is important to note here that the system effects of significant check valve failures and significant pump/motor failures are normally dramatically different. For example, when a significant pump or motor failure occurs, one train of a system is typically lost until repairs can be made. On the other hand, even when a check valve sticks open (the most common significant failure mode), the system effect is negligible in many cases and can be dealt with by human intervention in most others.

System

Failure rates for both types of components were found to depend highly upon system of service. (For this paper, failure rates were plotted in absolute terms for pumps and motors, and were also segregated by plant type. Overall relative failure rates only were calculated for check valves; they were not further subdivided according to plant type.) Both check valves and pumps/motors in the ESW system exhibited relatively high failure rates as compared to other systems. Other factors influencing failure rates by system were found to include system usage, process fluid, specific pump or check valve type (e.g., swing check versus lift/piston check) and plant type.

Component age group

Results of the analyses by age group differed for pumps and check valves. For 1991-1992 check valve failures, no significant differences in relative failure rates according to component age were apparent. For pump failures occurring during 1990-1993, however, other patterns were evident. For BWRs, the failure rate (all failures and significant failures only) drops after a period of infant mortality. This occurs also in PWRs, but the failure rate again rises after about ten years of age. For significant PWR pump failures only, the trend resembles the classic bath tub shape. The oldest age group for both check valves (all failures) and PWR pumps exhibits the highest overall failure rate.

Plant type

It was discovered that check valves in BWR plants have exhibited higher relative failure rates than those in PWR applications. This finding taken by itself may be misleading, however, since the data suggests that there are simply more check valve failures being detected at BWRs due to their inservice and leak testing programs. Pumps in BWRs have had much less failure experience than their PWR counterparts. Plotted as a function of age, it is clear that during the early years of operation, pump performance is similar, regardless of plant type. Over time, however, the superior performance of pumps in BWR applications becomes apparent; in the \$ 20 years age group the relative failure rate of PWR pumps is over four times that of BWR pumps.

Affected area/method of detection

While the check valve studies used only two general detection method classifications (programmatic and nonprogrammatic), the pump study added a third category. For pumps, then, the three general detection method classifications as assigned by ORNL were regulatory/code (corresponding to "programmatic" detection for check valves), plant programmatic, and nonprogrammatic. The plant programmatic category was added for pumps because of the recognition that many pump failures are detected by plant personnel by observation of some anomaly rather than by implementation of some code or regulatory criteria.

For check valves, the most common method of detection was programmatic. This holds true regardless of analysis period or level of degradation. When 1991-1992 failures were broken down further by general discovery process, the fraction of failures detected by programmatic means was far greater than the other detection processes (e.g., routine observation,

abnormal equipment operation), independent of affected area. The trend in failure detection method from 1984 through 1992 also shows an increase in the percentage of failures detected programmatically. Analysis of the data for check valves indicates that testing requirements mandated by codes and regulations are effectively detecting most check valve problems.

The same does not hold true for pumps. Voluntarily implemented plant programmatic controls were responsible for the detection of 73% of all pump failures and 41% of the significant pump failures. Regulatory/code required testing was responsible for only 14% of all failures and 39% of significant failures. The data also revealed that of the 95 significant failures detected by regulatory/code required testing, 75 failures involved ESW pumps. Of these 75 ESW pump failures, 61 involved internals wear; 56 of the 61 failures were indicated by failure to meet required flow or head. In summary, almost two-thirds of all pump failures detected by regulatory/code methods involved internals degradation of ESW pumps.

About 60% of all significant ESW pump failures were detected by regulatory/code required monitoring. In contrast, only 15% of the significant failures of pumps used in PWR plants in systems other than ESW were detected by regulatory/code required monitoring. More than four times as many significant pump failures in non-ESW systems at PWR plants were detected by nonmandated plant programs as by regulatory/code required methods.

Observations and Conclusions

When compared on the basis of certain specific parameters, some similarities between the historical performance data of check valves and pumps can be noted. For example, both component types exhibited similar percentages of failures classified as significant in terms of extent of component degradation. For both pumps and check valves, the system of service was found to play an important part in determining the rate at which the components fail. When investigated even farther, it has also become apparent that other factors play an important role in failure rate determination, including system usage, process fluid, and specific component type. Some results relative to component age group were also comparable, such as the increase in relative failure rate for both PWR pumps and check valves in the >20 years age group.

Analysis of component behavior according to other parameters, however, reveals some differences in their performance history. Some differences were noted in terms of performance according to age group. In general, check valve performance has shown no definitive pattern based on age group, except that older valves have consistently shown a somewhat higher relative failure rate. Some pump failure patterns, however, have shown an age-related correlation. Differences according to plant type have appeared also. Check valve failure rates have been shown to be higher for BWR plants than for PWRs; pump failure experience has been better at BWRs. The two findings may not be in conflict, however. It has been theorized that the higher check valve failure rate at BWRs may simply be the result of better inservice testing and monitoring practices at BWRs that tend to identify more failures than do the PWR practices.

Probably the most significant difference in the performance history of check valves and pumps as revealed by analysis of their NPRDS failure records is that of their method of detection. For check valves, the data clearly shows that most failures have been detected by (code or regulatory required) programmatic methods. This finding holds true regardless of affected area of the component. For pumps, however, the greatest fraction of failures have been found not by code or regulatory required testing or monitoring programs, but rather by the good practices of plant personnel. In the case of check valves, since the occurrence in the mid-1980's of potentially serious events (involving components in which their severely degraded condition went undetected), much industry and regulatory attention was devoted to the development and implementation of plant monitoring and testing programs. Review of NPRDS failure trend data from 1984 through 1992 has shown that these programs have been effective; the percentage of failures detected programmatically has increased, and overall extent of degradation has declined. Failure rates for most parameters showed a decline, and NPRDS reporting practices showed improvement.

For pumps and their motors, voluntarily implemented plant programs have been more successful at finding degraded operation than have regulatory/code mandated methods. There appear to be several reasons why this has been the case:

- (1) The ASME Code has historically allowed pumps to be tested at any reference point, including minimum flow. Hydraulic and vibration data collected at minimum flow conditions may be of minimal value. Also, operation at these conditions may contribute to accelerated pump wear and degradation.
- (2) One of the leading causes of both pump and motor degradation has been bearing wear. The Code requirements for vibration testing have not been effective in identifying bearing-related problems.

- (3) Voluntarily implemented plant programs tend to focus on effective activities. Tasks that provide no value are usually discontinued. Regulatorily mandated tasks which provide minimal return on the resource investment cannot be dismissed.
- (4) Human observations are a valuable diagnostic tool. More bearing failures were detected by operator observation than by implementation of regulatory/code mandated testing.

The observations that bearing degradation was both a leading source of pump and motor failures and was primarily detected through nonprogrammatic means suggests that alternative bearing health monitoring techniques, for example spectral analysis, high frequency demodulation, or shock pulse methods, would be likely to significantly improve programmatic detection experience.

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