1 PUMP INSIGHTS

1.1 Introduction

This section provides an overview of CCF data for the pump component that has been collected from the NRC CCF database. The set of pump CCF events is based on industry data from 1980 to 2000. The pump CCF data contains attributes about events that are of interest in the understanding of: degree of completeness, trends, pump segment affected, causal factors, linking or coupling factors, and event detection methods.

Not all pump CCF events included in this study resulted in observed failures of multiple pumps. Many of the events included in the database, in fact, describe degraded states of the pumps where, given the conditions described, the pumps may or may not have performed as required. The CCF guidance documents (NUREG/CR-6268, *Common-Cause Failure Database and Analysis System*.[1,2,3,4]) allow the use of three different quantification parameters (component degradation value, shared cause factor, and timing factor) to measure degree of failure for CCF events. Based on the values of these three parameters, a Degree of Failure was assigned to each pump CCF event.

The Degree of Failure category has three groups—Complete, Almost Complete, and Partial. Complete CCF events are CCF events in which each component within the common-cause failure component group (CCCG) fails completely due to the same cause and within a short time interval (i.e., all quantification parameters equal 1.0). Complete events are important since they show us evidence of observed CCFs of all components in a common-cause group. Complete events also dominate the parameter estimates obtained from the CCF database. All other events are termed partial CCF events (i.e., at least one quantification parameter is not equal to 1.0). A subclass of partial CCF events are those that are Almost Complete CCF events. Examples of events that would be termed Almost Complete are: events in which most components are completely failed and one component is degraded, or all components are completely failed but the time between failures is greater than one inspection interval (i.e., all but one of the quantification parameters equal 1.0).

Table 1-1 summarizes, by failure mode and degree of failure, the pump CCF events contained in this study. The majority of the pump CCF events were fail-to-run (54 percent), suggesting that often the pump must be running at rated conditions for failures to develop and/or for those failures to be detected. While most events (68 percent) were classified as Partial, a significant fraction of events (32 percent) were classified as either Complete or Almost Complete.

Table 1-1. Summary statistics of pump data.

Failure Mode	Degree of Failure			Total
	Partial	Almost Complete	Complete	
Fail-to-Start (FTS)	86	12	27	125
Fail-to-Run (FTR)	101	13	35	149
Total	187	25	62	274

1.2 CCF Trends Overview

Figure 1-1 shows the yearly occurrence rate, the fitted trend, and its 90 percent uncertainty bounds for all pump CCF events over the time span of this study. The decreasing trend is statistically significant[1] with a p-value[2] of 0.0001. There was insufficient information to determine what caused the decreasing trend in CCF events, but there were several regulatory initiatives by the NRC and industry initiatives by utilities, INPO, and EPRI involving improved operation, maintenance, testing, and inspection during the 21 years of improving performance. Examples of these initiatives include improvements in testing, inspection, and maintenance associated with Generic Letter 89-13, *Problems with Service Water Systems Affecting Safety-Related Components*[5], and Generic Letter 89-04, *Guidance on Developing Acceptable Inservice Testing Programs*[6]. Additionally, the testing and examination code for pumps has been improved significantly since 1980.

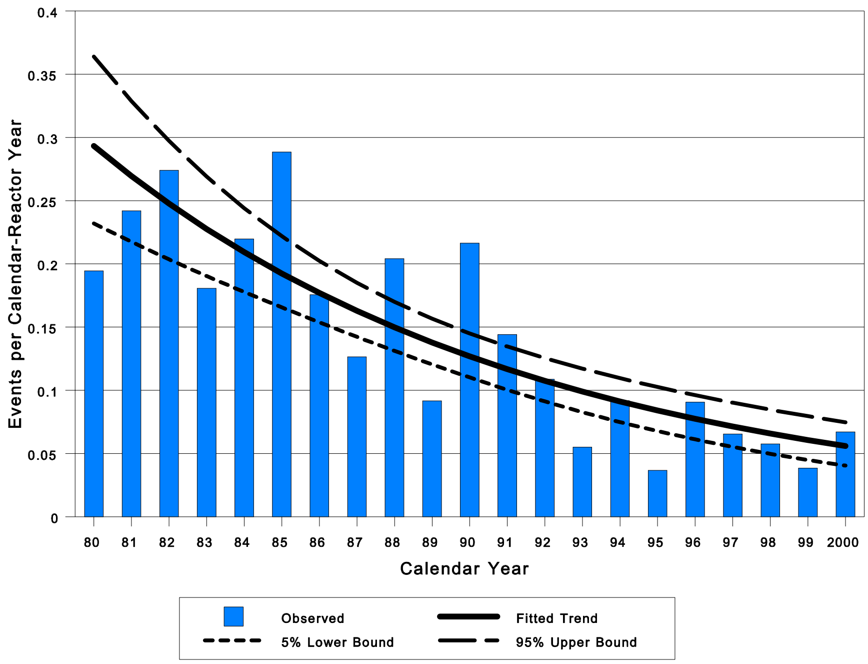

Figure 1-1. Trend for all pump CCF events. The decreasing trend is statistically significant with a p-value = 0.0001.

Figure 1-2 through Figure 1-4 show trends for subsets of the pump CCF events contained in Figure 1-1. Figure 1-2 shows the trend for Complete pump CCF events. The overall trend for Complete pump CCF events from 1980 to 2000 is also statistically significant with a p-value of 0.0001. This indicates a dramatic decrease of Complete pump CCF events, especially since the mid-1980's. Figure 1-3 and Figure 1-4 show similar statistically significant decreasing trends for

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1. The term "statistically significant" means that the data are too closely correlated to be attributed to chances and consequently have a systematic relationship. A p-value of less than 0.05 is generally considered to be statistically significant.

2. A p-value is a probability, with a value between zero and one, which is a measure of statistical significance. The smaller the p-value, the greater the significance. A p-value of less than 0.05 is generally considered statistically significant. A p-value of less than 0.0001 is reported as 0.0001.

both the fail-to-start and the fail-to-run failure modes for all pump CCF events, both with p-values of 0.0001.

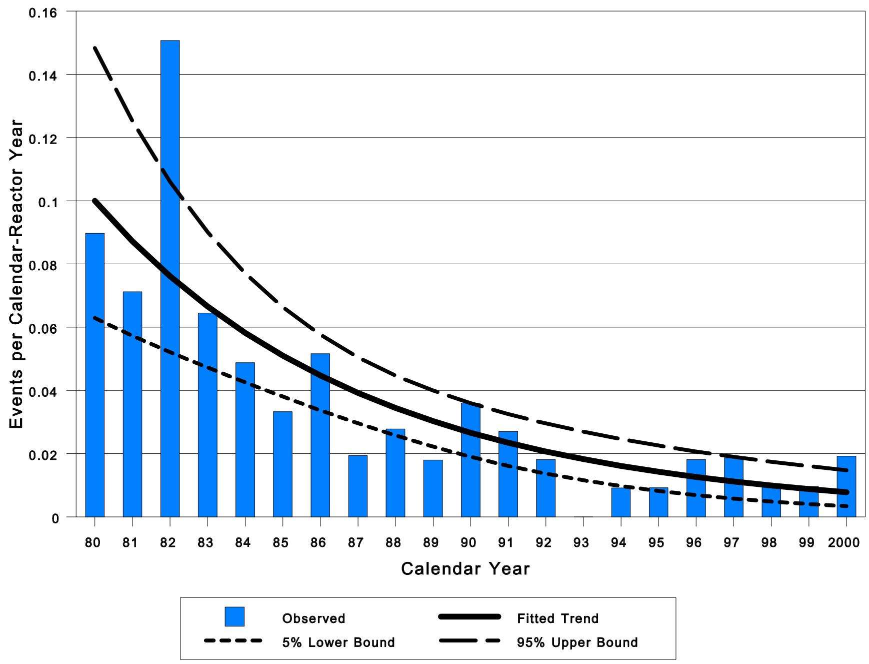

Figure 1-2. Trend for Complete pump CCF events. The decreasing trend is statistically significant with a p-value = 0.0001.

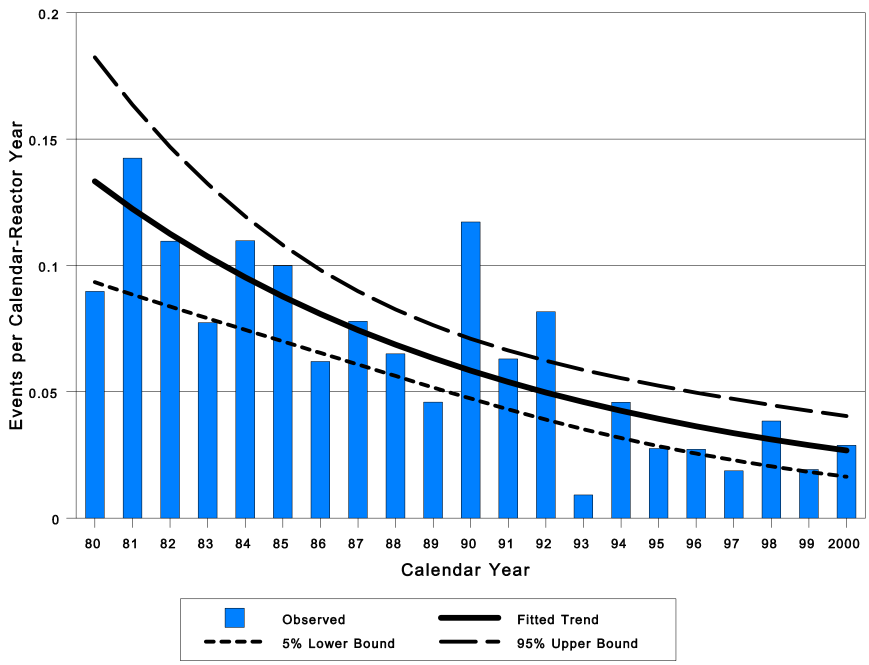

Figure 1-3. Trend for all pump CCF events for the fail-to-start failure mode. The decreasing trend is statistically significant with a p-value = 0.0001

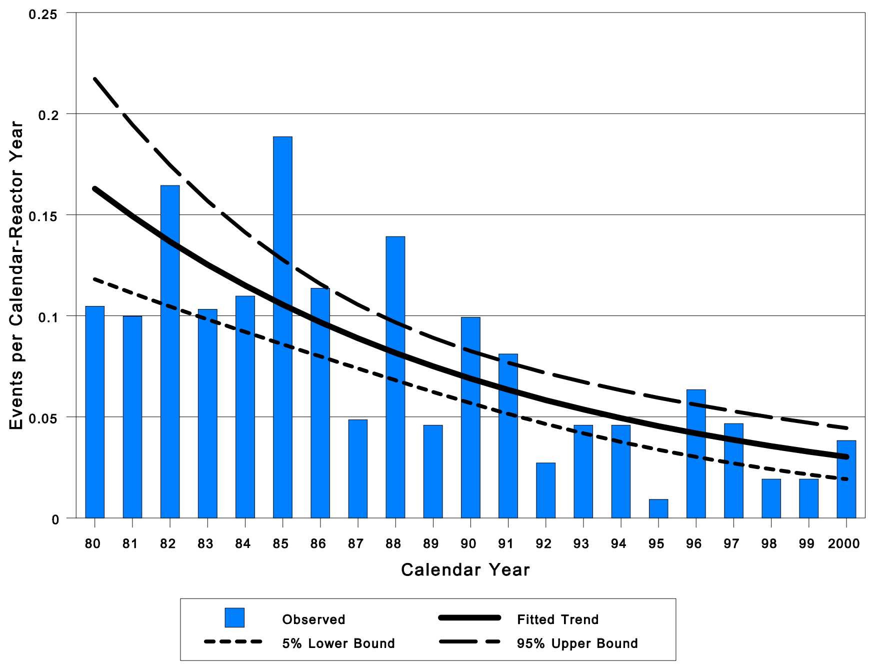

Figure 1-4. Trend for all pump CCF events for the fail-to-run failure mode. The decreasing trend is statistically significant with a p-value = 0.0001.

1.3 CCF Segment Overview

Pumps are complex machines and can easily be thought of as a collection of segments, each with many components. The pump CCF data were reviewed to determine the affected segment and the affected piece part in that segment. This was done to provide insights to the most vulnerable areas of the pump component to common-cause failure events.

Figure 1-5 shows the distribution of the CCF events by pump segment. Overall, for all pumps, the highest number of events occurred in the pump segment (106 events or 39 percent). The driver and suction segments were also significant contributors (32 and 24 percent, respectively), while relatively few events involved the discharge segment. These statistics vary by system. For the ESW and SLC systems, most of the failures occurred in the pump segment. However, for the AFW, HPI, and RHR-B systems, most of the failures occurred in the driver segment, and for the RHR-P system, most of the failures occurred in the suction segment. Events involving the driver and suction segments were more likely to be Complete. Ninety-two percent of all Complete events occurred in these two segments.

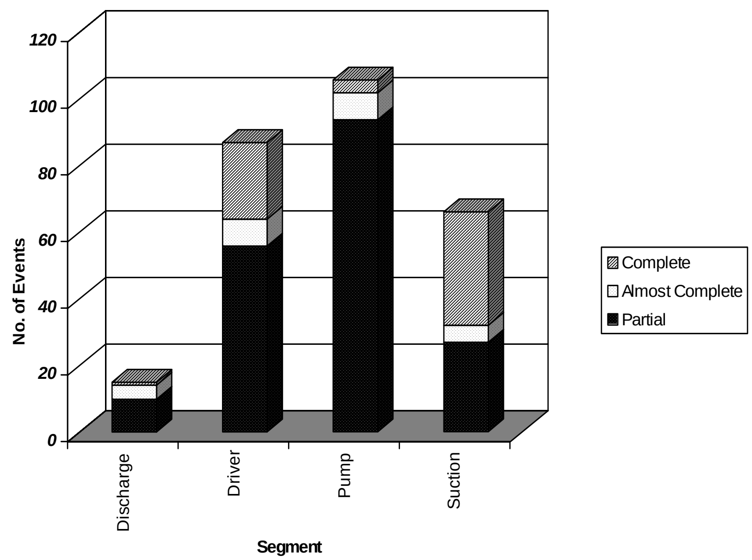

Figure 1-5. Segment distribution for all pump CCF events.

1.4 CCF Proximate Cause

It is evident that each component fails because of its susceptibility to the conditions created by the root cause, and the role of the coupling factor is to make those conditions common to several components. In analyzing failure events, the description of a failure in terms of the most obvious "cause" is often too simplistic. The sequence of events that constitute a particular failure mechanism is not necessarily simple. Many different paths by which this ultimate reason for failure could be reached exist. This chain can be characterized by two useful concepts—proximate cause and root cause.

A **proximate cause** of a failure event is the condition that is readily identifiable as leading to the failure. The proximate cause can be regarded as a symptom of the failure cause, and it does not in itself necessarily provide a full understanding of what led to that condition. As such, it may not be the most useful characterization of failure events for the purposes of identifying appropriate corrective actions.

The proximate cause classification consists of six major groups or classes:

- Design/Construction/Installation/Manufacture Inadequacy
- Operational/Human Error
- Internal to the component, including hardware-related causes and internal environmental causes
- External environmental causes
- Other causes
- Unknown causes.

The causal chain can be long and, without applying a criterion identifying an event in the chain as a "root cause," is often arbitrary. Identifying proximate causes in relation to the implementation of defenses is a useful alternative. The proximate cause is therefore the most basic reason or reasons for the component failure, which if corrected, would prevent recurrence. Reference 3 contains additional details on the proximate cause categories, and how CCF event proximate causes are classified.

Figure 1-6 shows the distribution of CCF events by proximate cause. The leading proximate cause was Internal to Component, which accounted for about 39 percent of the total events; however, none of these events were Complete. Design/Construction/Installation/Manufacture Inadequacy and Human error accounted for 24 and 20 percent of the total events, respectively. The Other and External Environment proximate causes were attributed to a small fraction of the pump CCF events.

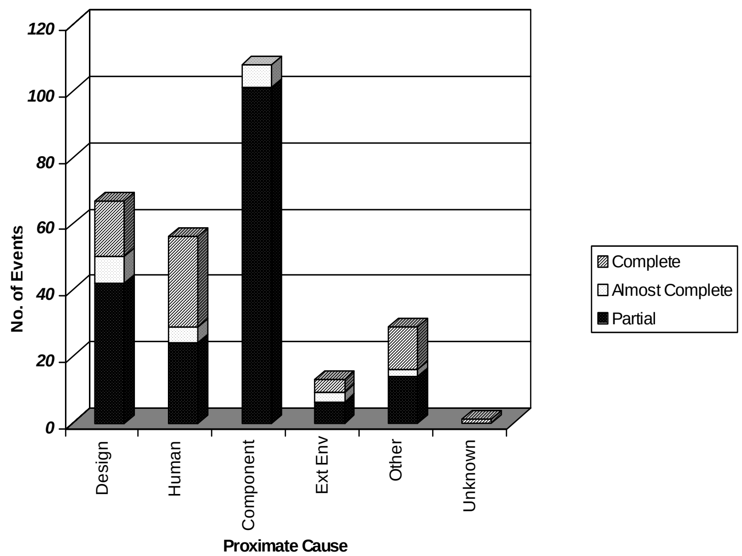

Figure 1-6. Proximate cause distribution for all pump CCF events.

The **Internal to Component** proximate cause category is dominant for pump events and involves the failure or malfunction of parts internal to the pump. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms that are influenced by the ambient environment of the component. Specific mechanisms include erosion, corrosion, internal contamination, fatigue, wear-out, and end of life. Internal to Component failures resulted in 108 events. Of these, 61 events were classified as fail-to-run and 47 were fail-to-start. Although this is the dominant proximate cause group, there were no Complete failure events attributed to the Internal to Component proximate cause. This is because most failure mechanisms in this group are gradual in nature; infrequently causing all system components to fail at once. In addition, the lack of a large number of Complete events may be due to the method of discovery. The majority of events in this cause group were discovered by Testing. These data suggest that the testing programs are succeeding in finding and fixing gradual failures of pumps before full failure is observed.

The **Design/Construction/Installation/Manufacture Inadequacy** proximate cause category is the next most likely for pump events and encompasses events related to the design, construction, installation, and manufacture of components, both before and after the plant is operational. Included in this category are events resulting from errors in equipment and system specifications, material specifications, and calculations. Events related to maintenance activities are not included. Design/Construction/Installation/Manufacture Inadequacy errors resulted in 67 events. The failure mode for 42 of these events was fail-to-run, and 25 events had fail-to-start as the failure mode. There were 17 Complete CCF events in this proximate cause group: 13 Complete events were fail-to-run and 4 were fail-to-start. The majority of these Complete events (11 out of 17) occurred in the Suction segment. Typically, these events were due to a lack of adequate NPSH due to design discrepancies. Instead of the loss of suction events being distributed over a large number of NPP units, two stations account for approximately 65 percent of the Suction segment CCF events with the Design, Construction, and Manufacturer proximate. The rest of the CCF events were relatively evenly distributed between the Driver segment and the Pump segment.

The **Operational/Human Error** proximate cause category is also likely for pump CCF events. This proximate cause category represents causes related to errors of omission or commission on the part of plant staff or contractor staff. Included in this category are accidental actions, failures to follow the correct procedures or following inadequate procedures for construction, modification, operation, maintenance, calibration, and testing. This proximate cause group may also include deficient training. Operational/Human Error was assigned to 56 pump CCF events. The majority of these events involved inadequate procedures and accidental action. The failure mode for 24 events was fail-to-run and 32 events had fail-to-start as the failure mode. Almost half (48 percent) of the pump CCF events in this cause category were Complete. This highlights the importance of maintenance and operations in the availability of the pump component. The majority of CCF events were discovered by either Demand or Inspection. The high number of events discovered by Demand is explained by the fact that human errors are prone to occur during operations involving system demands. In addition, maintenance personnel errors also show up when the system is called upon to function. However, for those events not discovered by system demands, Inspection discovered more events than Maintenance and Testing. Many of these events involved problems such as system misalignments, improper circuit breaker operations, Technical Specification violations (non-allowed combinations of systems/components out of service at the same time) that were discovered by plant operators. It is expected that routine Inspection would discover more of these events than Testing and Maintenance, which are conducted only periodically.

The **Other** proximate cause category is comprised of events that were caused by instrumentation and control circuit setpoint drift or failure components outside the defined pump component boundary. There were 29 events assigned to this cause category. The failure mode for 13 events was fail-to-run and 16 events had fail-to-start as the failure mode. Again, almost half (45 percent) of the pump CCF events in this cause category were Complete. The most common Complete events in this category involved an interlock dependent on either a temperature or pressure sensor that prevented pump start or an actual low level in the suction source. Therefore, this cause category is important although the total number of events was relatively small. Most of the events were discovered by Demand in lieu of Testing, Maintenance, and Inspection. This is expected due to the nature of CCF events in this proximate cause group. The dependencies outside the pump component that initiate these CCF events may not be the specific target of system component testing; therefore, it is reasonable that more events would be discovered during system operation than by less-frequent test surveillance. In addition, because CCF events that occur due to the state of other components typically are indirectly initiated by failure of other components, they may not be readily apparent during routine inspections and maintenance. Fourteen events (48 percent) affected the Driver segment. This is reasonable to expect because the pump Drivers are dependent on a large number of other components, such as circuit breakers, instruments, interlocks and controls. The other important segment is Suction, with 11 events. This is a reflection of the number of events in the RHR-P system related to loss of suction due to system configuration.

The **External Environment** proximate cause category represents causes related to a harsh environment that are not within the component design specifications. Specific mechanisms include chemical reactions, electromagnetic interference, fire or smoke, impact loads, moisture (sprays, floods, etc.), radiation, abnormally high or low temperature, vibration load, and acts of nature (high wind, snow, etc.). There were 13 pump CCF events in this cause category. The failure mode for eight events was fail-to-run, and five events had fail-to-start as the failure mode. There were four Complete CCF events in attributed to External Environment.

The **Unknown** proximate cause category is used when the cause of the component state cannot be identified. There was one Complete, fail-to-run event in this cause category that occurred in the Suction segment.

1.5 CCF Coupling Factor

Closely connected to the proximate cause is the concept of **coupling factor**. A coupling factor is a characteristic of a component group or piece parts that links them together so that they are more susceptible to the same causal mechanisms of failure. Such factors include similarity in design, location, environment, mission, and operational, maintenance, design, manufacturer, and test procedures. These factors have also been referred to as examples of coupling mechanisms, but because they really identify a potential for common susceptibility, it is preferable to think of these factors as characteristics of a common-cause component group. Reference 3 contains additional detail about the coupling factors.

The coupling factor classification consists of five major classes:

- Hardware Quality based coupling factors,
- Design-based coupling factors,
- Maintenance coupling factors,
- Operational coupling factors, and
- Environmental coupling factors.

Figure 1-7 shows the coupling factor distribution for the pump CCF events. Maintenance was the leading coupling factor with 111 events (40 percent). The next leading coupling factor was Design with 76 events (28 percent). While not the leading coupling factor, over half (51 percent) of the Design, coupled events were either Complete or Almost Complete. The Environmental and Operational coupling factors account for the majority of the remaining events (44 and 28 events, respectively). Only a small fraction of the events coupled by Environmental were Complete; however, over half (57 percent) of the events coupled by Operational were Complete. These Complete events were almost all coupled by inadequate operations procedures.

Only 15 events were coupled by Quality, and three of these were Complete and affected the Driver segment.

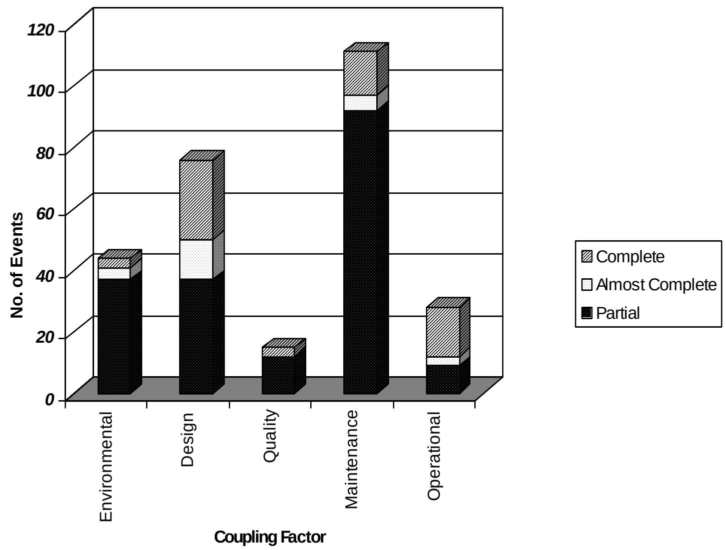

Figure 1-7. Coupling factor distribution for all pump CCF events.

The **Maintenance** coupling factor indicates that the maintenance frequency, procedures, or personnel provided the linkage among the events. Most of the pump CCF events with this coupling factor were coupled by maintenance/test schedules (74 out of 111) and maintenance/test procedures (23 out of 111). Internal to Component was the most prevalent proximate cause to be linked by maintenance (75 events). The maintenance linkage to the component failure proximate cause usually indicated that maintenance that is more frequent could have prevented the CCF mechanism. Very few of these events actually resulted in Complete CCF events, and most were detected as incipient failures. Examples of these are:

- The circuit breakers associated with the Auxiliary Feedwater Pumps failed to close as required. The cause of the failure was the binding in the operating mechanism due to accumulated dirt and lack of lubrication.

- The AFW pumps failed to start due to steam binding. The cause of the steam binding was determined to be leakage past the downstream AFW system check valves.

- Two of three ESW pumps failed to start on demand. The cause was determined to be bad couplings between the pumps and drivers. The cause was determined to be lack of periodic maintenance and inspection.

- The two gland seal retaining bolts inside the centrifugal charging pump speed increaser lube oil pump were found to be backed out allowing the gland seal to loosen. This resulted in reduced oil flow to the speed increaser causing significant damage. Other centrifugal charging pumps (CCPs) were inspected, and the same gland seal bolts as on the first pump were found loosened. The cause of the bolts backing out was determined to be lack of a periodic adjustment of the gland seal bolts.

The **Design** coupling factor indicates that the failures were linked by the components having the same design and component parts or by the system configuration. Design/Construction/Installation/ Manufacture was the most prevalent proximate cause to be linked by Design (45 events). This means that design errors and inadequacies were both the cause and the link between the events. Examples of these events are:

- A modification design error removed a start permissive interlock contact. This flaw de-energized the auxiliary lube oil pump; consequently, when one AFW pump was started it ran for 2.5 seconds and tripped on low oil pressure. Further investigation showed that both units AFW pumps would be affected in the same way.

- Both RHR-P pumps failed to run due to high bearing temperatures caused by inadequate bearing clearances and using the wrong lubricating oil, which had too high a viscosity. Inadequate vender design information resulted in the higher viscosity oil being used.

- During the performance of a special test to determine the available net positive suction head of the SLC Pumps, the pumps began to cavitate unexpectedly. The causes of this event were determined to be inadequate modification testing and errors in the original design calculations.

- During a unit load shed test, the service water pumps lost suction and tripped. The loss of suction pressure was caused by a loss of prime in the condenser circulating water siphon flow system. The event was attributed to poor system design.

The **Environmental** coupling factor propagates a failure mechanism via identical external or internal environmental characteristics. Internal to Component was the most prevalent proximate cause to be linked by Environmental (29 events). Examples of these events are:

- Failure of the HPI Pumps due to clam and sludge fouling of the pump lube oil coolers.

- A CCP seized during surveillance testing. Subsequent inspection revealed resin particles and metal shavings in the pump casings and suction lines for all the charging pumps.

The **Operational** based coupling factor links the CCF events via inadequate operations procedures and operations staff errors. Human Error was the dominant proximate cause for events linked by Operational factors (25 events). Examples of these events are:

- HPI pumps not restored to service before a mode change as required by Technical Specifications due to a procedural inadequacy.

- The CCPs were erroneously placed in pull-to-lock when required to operable.

- During a routine Control Board walk-down it was discovered that the AFW pump discharge MOVs were closed. Subsequent investigation revealed the AFW system had not been previously placed in standby readiness per the operating procedure after the system was secured.

The **Quality** based coupling factor propagates a failure mechanism among several components by manufacturing and installation errors. Design was the dominant proximate cause for events linked by Quality based coupling factors (12 events). Examples of these events are:

- During surveillance testing, neither motor-driven AFW pump would start. The pump control circuit was found with auto-start defeat switches labeled backwards, causing all auto-starts except the low-low steam generator level to be defeated. This was an original installation error resulting from an inadequate design change process.

- Both motor-driven AFW pumps failed to start when the operator tried to start them manually. While preparing a design change, the designer failed to review all the unit specific documentation associated with the motor-driven AFW pump wiring and made the erroneous assumption that both units switchgear compartment internal wiring was identical. In fact, the wiring for each unit was different. Consequently, when the design change was installed, it was installed in accordance with the erroneous design.

1.6 CCF Discovery Method Overview

An important facet of these CCF events is the way in which the failures were discovered. Each CCF event was reviewed and categorized into one of four discovery categories: Test, Maintenance, Demand, or Inspection. These categories are defined as:

Test	The equipment failure was discovered either during the performance of a scheduled test or because of such a test. These tests are typically periodic surveillance tests, but may be any of the other tests performed at nuclear power plants, e.g., post-maintenance tests and special systems tests.
Maintenance	The equipment failure was discovered during maintenance activities. This typically occurs during preventative maintenance activities.
Demand	The equipment failure was discovered during a demand for the equipment. The demand can be in response to an automatic actuation of a safety system or during normal system operation.
Inspection	The equipment failure was discovered by personnel, typically during system tours or by operator observations.

Figure 1-8 shows the distribution of how the events were discovered or detected. Testing accounted for 95 events, (35 percent), 83 events (30 percent) were discovered during Demand, Inspection accounted for 69 events (25 percent), and 27 events (10 percent) were detected during Maintenance activities. Considering the extensive and frequent surveillance test requirements for pumps contained in Technical Specifications, it is expected that a majority of the pump CCF events would be detected by Testing. The intent of testing programs is to detect degradation and initiate corrective actions before total failure. The failures detected by testing tended to be Internal to Component causes attributed to wear and aging and only a small percentage of these failures resulted in Complete CCF events. It was expected that fewer failures would be detected by Demand. Analysis of events showed that over half of the events discovered by Demand were Complete or Almost Complete. The majority of events detected by Demand were attributed to design errors, human errors, and the Others. These causes were also dominant for all Complete CCF events. This implies that testing may be effective at detecting normal wear and aging problems, but less effective at detecting failures related to design and human errors.

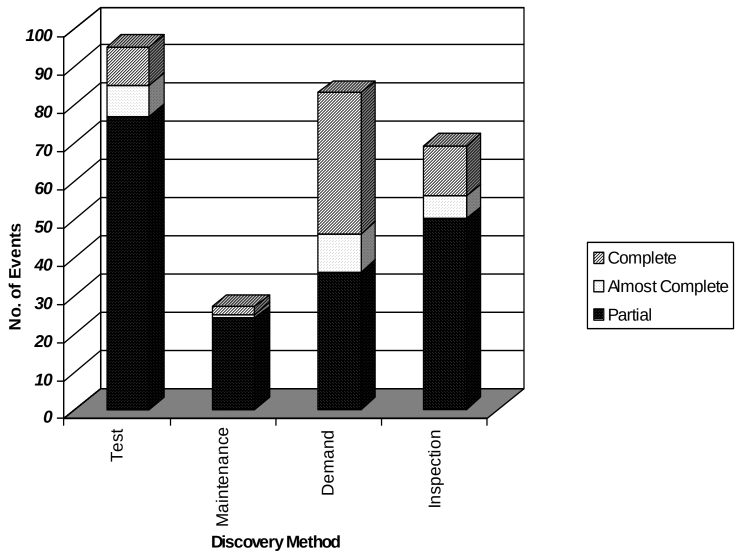

Figure 1-8. Discovery method distribution for all pump CCF events.

1.7 Pump CCF System Observations

Figure 1-9 shows the distribution of pump CCF events by system and the degree of failure. The ESW system had the most events. Most pump CCF events in the ESW system involved problems with the pump impellers and wear rings. The RHR-P system had the largest fraction of Complete CCF events (92 percent). Most of the RHR-P system events involved loss of suction, usually during refueling outages with reduced water level in the RCS.

1.8 Other Pump CCF Observations

Figure 1-10 shows the distribution of pump CCF events among the NPP units. The data are based on 109 NPP units represented in the insights CCF studies. Eighty-eight of the NPP units included in this study (81 percent) experienced at least one pump CCF event, and 55 NPP units had more than one pump CCF event. While only 38 NPP units experienced more than two pump CCF events, these 38 NPP units account for 76 percent of the total number of pump CCF events.

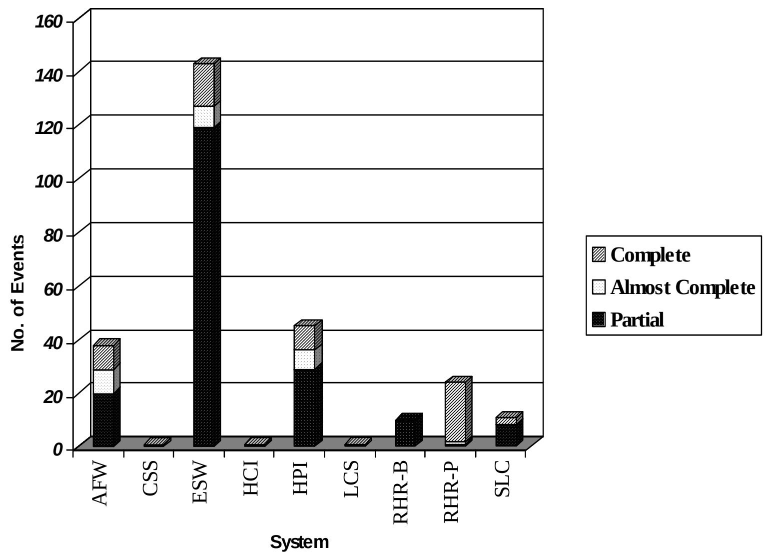

Figure 1-9. Distribution of pump CCF events by system.

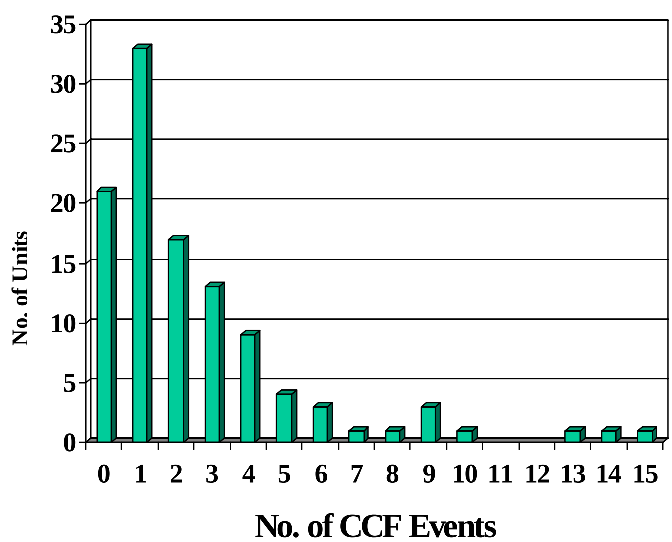

Figure 1-10. Distribution of NPP units experiencing a multiplicity of CCFs for all pump CCF events.

2 REFERENCES

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