1 CIRCUIT BREAKER INSIGHTS

1.1 Introduction

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

Not all circuit breaker CCF events included in this study resulted in observed failures of multiple circuit breakers. Many of the events included in the database, in fact, describe degraded states of the circuit breakers where, given the conditions described, the circuit breakers may or may not perform 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 circuit breaker 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 because they show 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 circuit breaker CCF events contained in this study. The majority of the circuit breaker CCF events were fail-to-close (55 percent). The Complete degree of failure makes up a small fraction (3 percent) of the circuit breaker CCF events. The small fraction of Complete and Almost Complete events is mainly due to the large populations of circuit breakers in plants and the large number of minor events such as slow closing times, trip voltage out-of-specification, etc.

Table 1-1. Summary statistics of circuit breaker data.

Failure Mode	Degree of Failure			Total
	Partial	Almost Complete	Complete	
Fail-to-Open (FTO)	48	2	4	54
Fail-to-Close (FTC)	65			65
Total	113	2	4	119

1.2 CCF Trends Overview

Figure 1-1 shows the yearly occurrence rate, the fitted trend, and its 90 percent uncertainty bounds for all circuit breaker CCF events over the time span of this study. The decreasing trend is statistically significant[1] with a p-value[2] of 0.0001. Based on the review of failure data for this study, the improved maintenance and operating procedures as well as the improved testing and inspection requirements have facilitated the observed reduction of the occurrence of CCF events over the 21 years of experience included in this study.

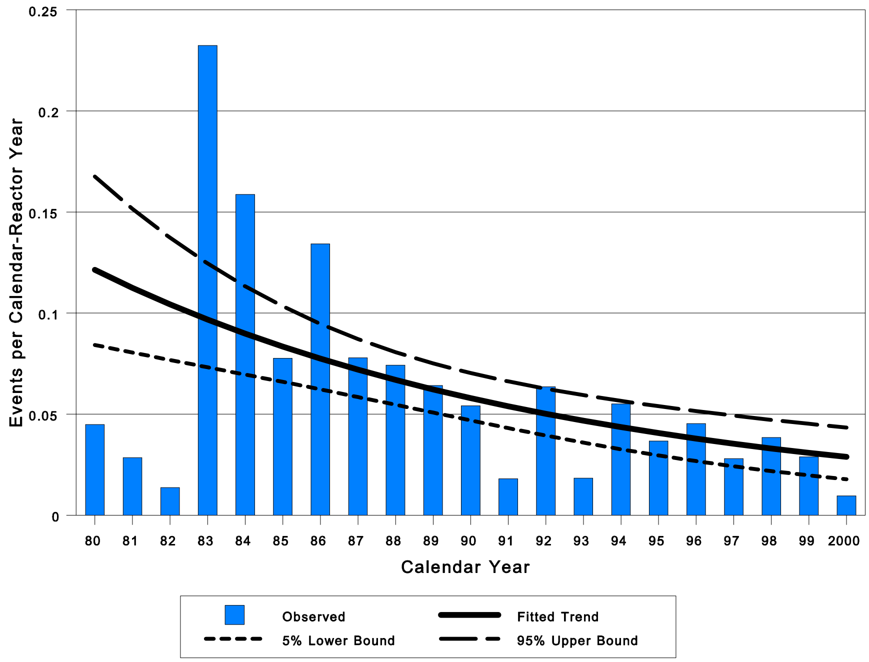

Figure 1-1. Trend for all circuit breaker CCF events. The decreasing trend is statistically significant with a p-value = 0.0001.

Figure 1-2 and Figure 1-3 show similar statistically significant decreasing trends for both the fail-to-close and the fail-to-open failure modes for all circuit breaker CCF events, with p-values of 0.0099 and 0.0001, respectively. Figure 1-2 shows a significant increase after 1983 followed by a noticeable decease in the number of total failures beginning in 1990. Figure 1-3 shows a large step increase in 1983, followed by a rapid decrease from 1983 through 1987. The increase in circuit breaker unreliability was noted in a study performed for the NRC's Nuclear Plant Aging Research Program (NPAR)[5]. The study noted that this increase was due to utility response to IE Bulletins (IE 83-01 & IE 83-08) that were issued subsequent to the RTB failures at Salem Unit 1 in February 1983. In addition to more frequent and detailed inspections, the IE Bulletins required independent testing of the operation of the undervoltage trip device, leading to the discovery of multiple undervoltage trip device failures, some of which had occurred well before the time of detection. The 1987 study utilized data through March 1985 and therefore did not extend to the time when the failure rates began to decrease.

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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.

The NRC originally required licensees to qualify all safety-related electrical equipment in accordance with the 1974 Edition of IEEE Standard 323 (Reference 10). However, concerns with the industry methods developed to qualify equipment in accordance with the standard were not resolved to the satisfaction of the NRC. This issue was originally identified in 1978 and later was determined to be an unresolved safety issue (USI). The Code of Federal Regulations (CFR) was amended in January of 1983, requiring implementation of the rules contained in 10 CFR 50.49, *Environmental Qualification of Electric Equipment Important to Safety for Nuclear Power Plants*. This rule required licensees to determine performance requirements for electrical equipment under design-basis accident conditions considering both environmental conditions and the affects of aging, and to implement a qualification program to assure that the specified performance can be attained. Requirements included evaluation of the aging effects on component piece parts due to normal environmental conditions, determination of the end-of-installed life, and corresponding preventative maintenance program provisions to assure part replacement prior to the end-of-installed life. While the final rule required implementation of the 10 CFR 50.49 requirements by May 1983, inspections revealed significant instances of non-compliance into the late 1980s.

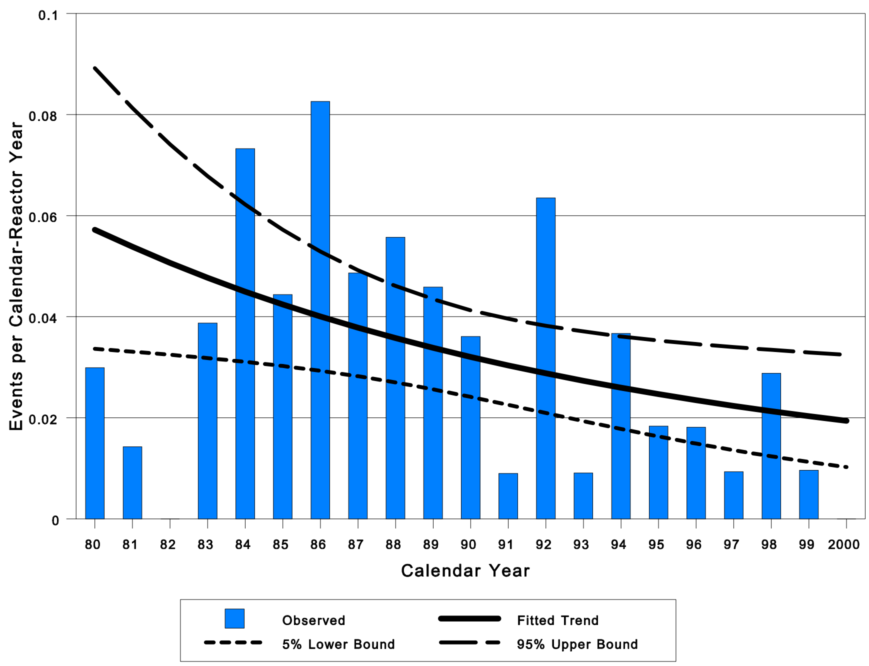

Figure 1-2. Trend for all circuit breaker CCF events for the fail-to-close failure mode. The decreasing trend is statistically significant with a p-value = 0.0099.

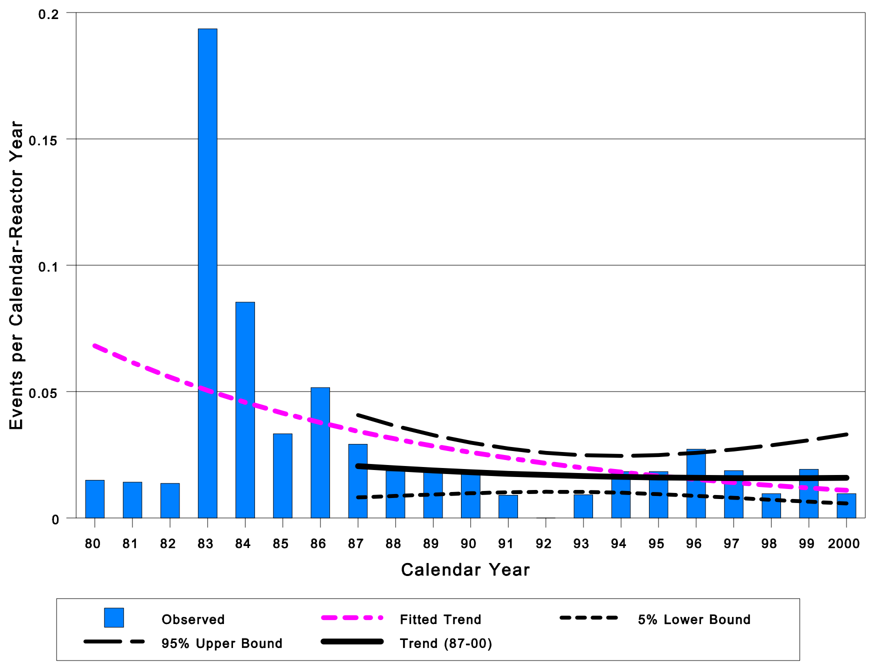

Figure 1-3. Trend for all circuit breaker CCF events for the fail-to-open failure mode. The decreasing trend is statistically significant with a p-value = 0.0001. P-value is 0.6746 for 1987-2000 data.

1.3 CCF Circuit Breaker Type Overview

The circuit breaker CCF data were reviewed to determine the affected circuit breaker type and the affected piece part in that circuit breaker type. This was done to provide insights into what are the most vulnerable areas of the circuit breaker component with respect to common-cause failure events.

Figure 1-4 shows the distribution of the CCF events by circuit breaker type. The highest number of events occurred in the RPS trip breaker type (50 events or 42 percent). The Complete RTB events are fail-to-open, and all occurred in 1983 at two NPP units. The Medium Voltage (34 events, 29 percent) and 480 Vac circuit breakers (31 events, 26 percent) are also significant contributors. Together, these three circuit breaker types comprise over 97 percent of the circuit breaker CCF events studied.

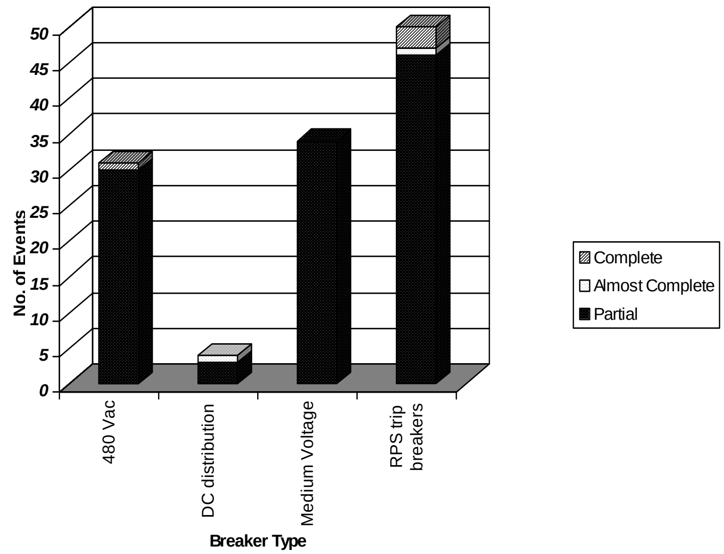

Figure 1-4. Circuit breaker type distribution for all circuit breaker CCF events.

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 root causes in relation to the implementation of defenses is a useful alternative. The root 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 1-5 shows the distribution of CCF events by proximate cause. The leading proximate cause was Internal to Component and accounted for about 61 percent of the total events. Design/ Construction/Installation/Manufacture Inadequacy faults accounted for 18 percent of the total. Human error accounted for 13 percent of the total events. To a lesser degree, External Environment and the Other proximate cause categories were assigned to the circuit breaker component.

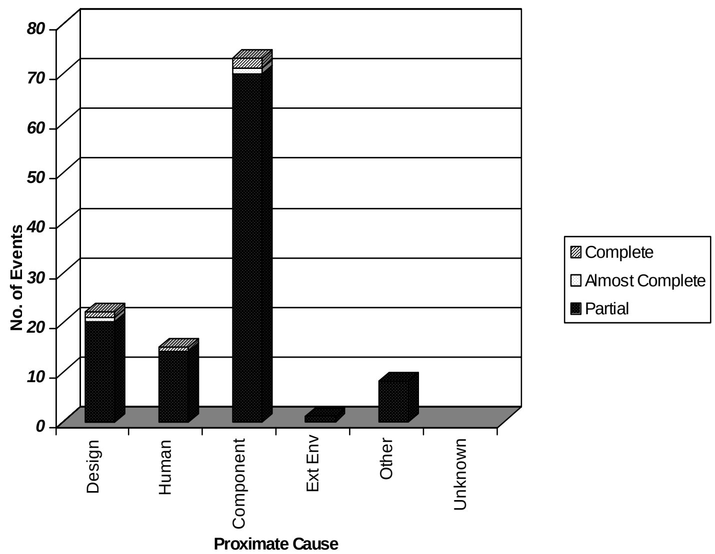

Figure 1-5. Proximate cause distribution for all circuit breaker CCF events.

Table A-1 in Appendix A presents the entire circuit breaker data set, sorted by the proximate cause. This table can be referred to when reading the following discussions to see individual events described.

The **Internal to Component** proximate cause category is the most important for the circuit breakers and encompasses the malfunctioning of hardware internal to the component. Internal to Component causes result from phenomena such as normal wear or other intrinsic failure mechanisms. Specific mechanisms include corrosion of internal parts, lack of lubrication or lubricant hardening, internal contamination (dust/dirt), fatigue, wear-out, and end of life. Internal to Component errors resulted in 73 events.

Although the majority of circuit breaker CCF events were determined to have Internal to Component as the proximate cause, there were only two Complete failures in this category. Most failure mechanisms in this group are gradual in nature; therefore, complete failure of all circuit breakers in a group should not occur frequently. 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 detected by Testing. Effective testing programs should discover gradual degradation of the breakers prior to failure of all the circuit breakers in the group.

The most common types of events in this category involved wear, dirt, and inadequate lubrication inside the circuit breaker. This finding is supported by a study performed for the NRC's NPAR.[6] The study identified dust, dirt, and deterioration of lubrication of the trip mechanism as significant causes of some circuit breaker failures. The lubricant evaporates in the bearing of the trip mechanism, leaving the soap base behind. The force required to operate the trip mechanism increases to the point where the trip coil cannot cause the trip latch to operate.

The **Design/Construction/Installation/Manufacture Inadequacy** proximate cause group is the second most likely for circuit breakers 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 22 events. There was one Complete circuit breaker CCF event in this proximate cause group. The coupling factors affecting most of the events are Quality and Design, accounting for 86 percent of the events.

Compared to the overall distribution of circuit breaker types, the Medium Voltage circuit breakers have a higher contribution under the Design/Construction/Installation/Manufacture Inadequacy proximate cause and the 480 Vac circuit breakers and RTBs have lower contributions.

The **Operational/Human Error** proximate cause group is the next most likely for the circuit breaker and 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 also includes deficient training.

Operational/Human Error resulted in 15 circuit breaker CCF events. There was one Complete circuit breaker CCF event with Operational/Human Error as the proximate cause. These Operational/Human Errors include disabling all circuit breakers, not restoring circuit breakers to the correct position following tagouts, and procedure inadequacies that result in incorrect circuit breaker actuation. Inadequate maintenance procedures, inattention to work practices, and operator error were the most common coupling factors cited in the event narratives. Many of these events involved the observation of an incorrect system alignment (circuit breakers left open is one common observation). The Operational/Human Error proximate cause group appears randomly throughout the time frame of this study.

The **External Environment** proximate cause category represents causes related to a harsh environment that is 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.). This proximate cause had one event assigned to it.

The **Other** proximate cause group is comprised of events that include setpoint drift and the state of other components as the basic causes. Eight events were attributed to this category. However, none of the circuit breaker CCF events in this cause group were Complete. All of the events were attributed to setpoint drift, which tends to be a minor failure mode. Half of these events were in the RTBs and involved failure of the undervoltage trip mechanism to trip the breakers within the required time or voltage tolerances.

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. Figure 1-6 shows the coupling factor distribution for the events.

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.

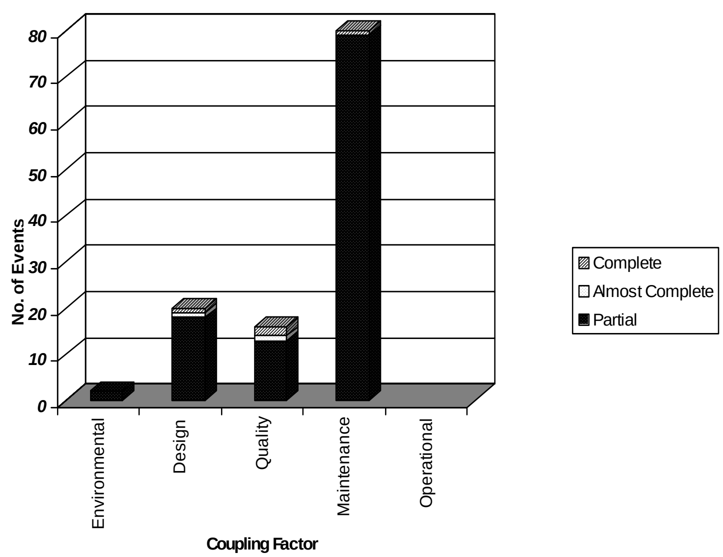

Figure 1-6. Coupling factor distribution for all circuit breaker CCF events.

Table A-2 in Appendix A presents the entire circuit breaker data set, sorted by the coupling factor. This table can be referred to when reading the following discussions to see individual events described.

The **Maintenance** coupling factor indicates that the maintenance frequency, procedures, or personnel provided the linkage among the events. The single largest coupling factor is Maintenance and it is strongly associated with the Internal to Component proximate cause. The Maintenance coupling factor indicates that the frequency of maintenance, the maintenance procedures, or the maintenance staff coupled the circuit breaker CCF events. The actual link for most of these events was maintenance and test schedules, indicating that more frequent maintenance could have prevented the CCF mechanism. Only one event coupled by Maintenance actually resulted in a Complete CCF event; most were detected as incipient failures. An example of this is a RTB failing its trip time requirements. The circuit breakers have historically been noted to be lacking in lubrication and worn.

The **Design** coupling factor is most prevalent in the Design/Construction/Installation/ Manufacture Inadequacy and Internal to Component proximate cause categories. This means that the design was inadequate and was the link between the events. The link for most of these events was that the breakers shared the same design and internal parts. Examples of this include loose operating springs, interference between piece-parts, cracked and bent piece-parts, and part location.

Quality based coupling factors are factors that propagate a failure mechanism among several components due to manufacturing and installation faults. The Quality coupling factor indicates that either the quality of the construction or installation or the quality of the manufacturing provided the linkage. The Quality coupling factor is also prevalent in the Design/Construction/Installation/Manufacture Inadequacy proximate cause category. Examples of this include defective undervoltage coils installed at the manufacturer, incorrect relay type for the application, and an incorrect lug size on the trip coil pigtail. The two Complete events in this group were due to incorrect relay installation in the circuit breaker trip circuit and mechanical binding of the latch mechanism.

The **Environment** based coupling factors are the coupling factors that propagate a failure mechanism via identical external or internal environmental characteristics. Two minor events occurred in this category.

The **Operational** based coupling factors indicate that operational procedures or staff provided the linkage among events. For example, two 4160-vac circuit breakers were racked-out because of operator error. No Operational based coupling factors were noted for the circuit breaker CCF events.

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 an actual 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 1-7 shows the distribution of how the events were discovered or detected. Testing accounts for 71 events, (60 percent), Demand for 25 events (21 percent), Maintenance for 11 events (9 percent), and Inspection for 12 events (10 percent). The importance of Testing indicates the success of testing in detecting common-cause failures. Testing is designed to detect faults before they occur. The testing program has shown that it is successful in accomplishing this goal.

Table A-3 in Appendix A presents the entire circuit breaker data set, sorted by the discovery method. This table can be referred to when reading the following discussions to see individual events described.

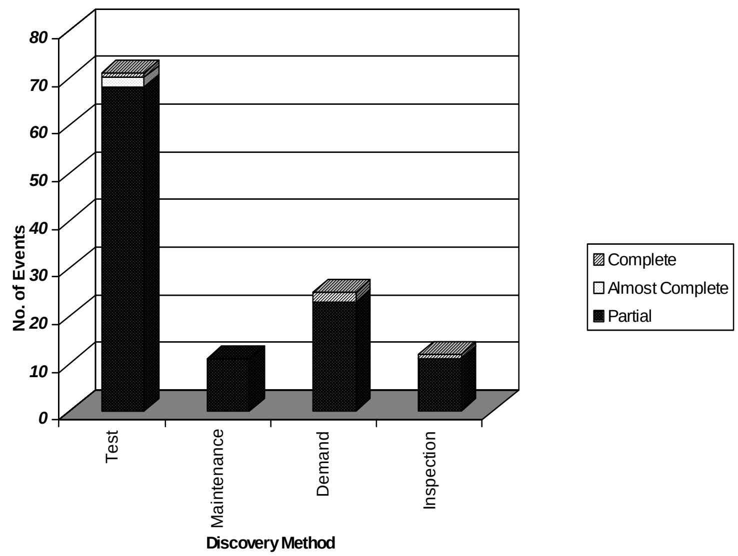

Figure 1-7. Discovery method distribution for all circuit breaker CCF events.

1.7 Other Circuit Breaker CCF Observations

Figure 1-8 shows the distribution of breaker CCF events among the NPP units. The data are based on 109 NPP units represented in the insights CCF studies. The largest contribution (76 percent) consists of NPP units with either zero or one CCF event. This may indicate that the majority of the NPP units have maintenance and testing programs to identify possible circuit breaker CCF events and work towards preventing either the first event or any repeat events. Seventy-four percent of the total circuit breaker CCF events occurred at 51 of the NPP units.

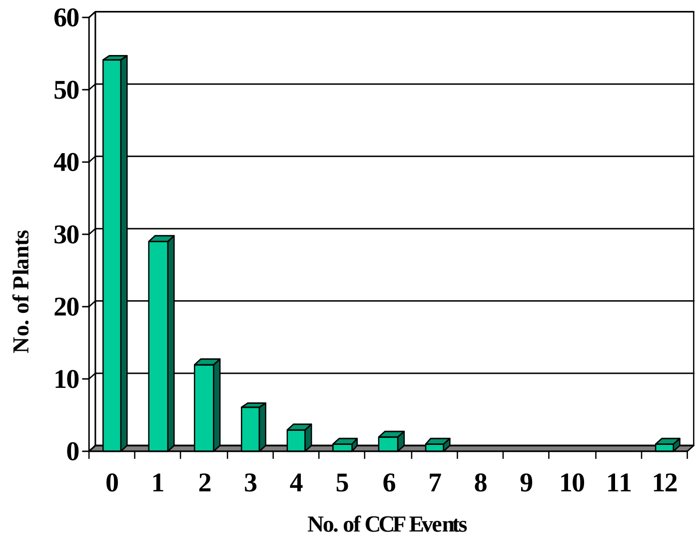

Figure 1-8. Distribution of NPP units experiencing a multiplicity of CCFs for all circuit breaker CCF events.

Figure 1-9 shows the distribution of the failed piece-parts for all breaker types. The mechanical assembly had 31 events (26 percent). The mechanical assembly was identified for all breaker types. Most of these events were coupled by inadequate maintenance. The UV trip assembly had 28 events (24 percent). The UV trip assembly was identified mostly for the RPS trip breakers. Table A-4 in Appendix A presents the entire circuit breaker data set, sorted by the piece-part. This table can be referred to when reading the following discussions to see individual events described.

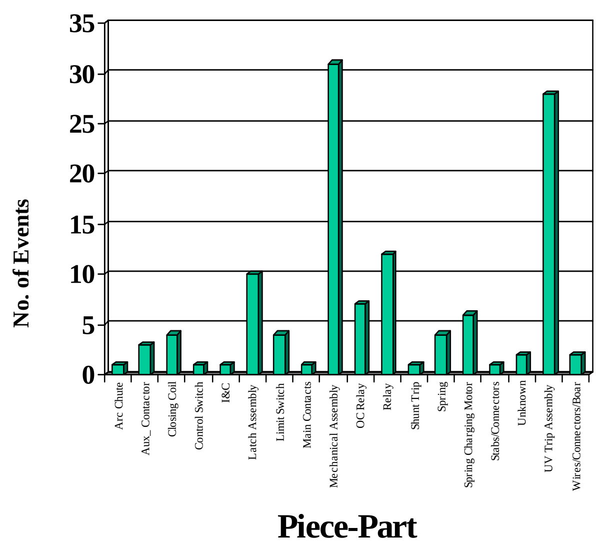

Figure 1-9. Distribution of the failed piece-parts for all circuit breaker CCF events.

2 REFERENCES

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