# 1 EMERGENCY DIESEL GENERATOR INSIGHTS

## 1.1 Introduction

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

Not all EDG CCF events included in this study resulted in observed failures of multiple EDGs. Many of the events included in the database, in fact, describe degraded states of the EDGs where, given the conditions described, the EDGs 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 EDG 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 EDG CCF events contained in this study. The majority of the EDG CCF events were fail-to-run (57 percent). The review of the data suggests that many failures require the EDG to be running to develop failures and for those failures to be detected. The Complete degree of failure makes up a small fraction (16 percent) of the EDG CCF events. However, almost half (46 percent) of the events are classified as either Complete or Almost Complete.

**Table 1-1. Summary statistics of EDG data.**

| Failure Mode | Degree of Failure | | | Total |
|---|---|---|---|---|
| | Partial | Almost Complete | Complete | |
| Fail-to-start (FTS) | 29 | 20 | 10 | 59 |
| Fail-to-run (FTR) | 45 | 22 | 12 | 79 |
| Total | 74 | 42 | 22 | 138 |

## 1.2 CCF Trends Overview

Figure 1-1 shows the yearly occurrence rate, the fitted trend, and its 90 percent uncertainty bounds for all EDG 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.

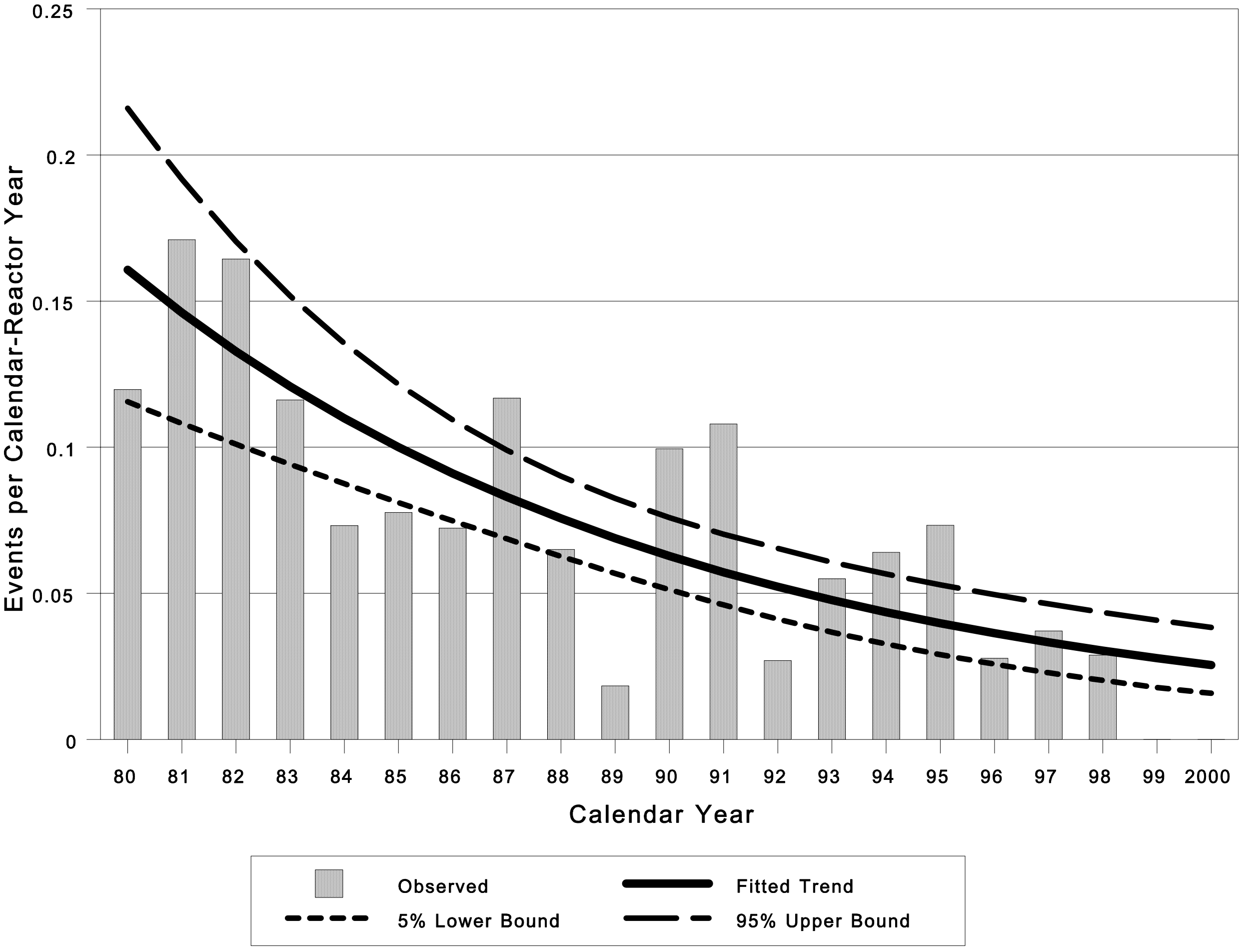

**Figure 1-1. Trend for all EDG CCF events. The decreasing trend is statistically significant with a p-value = 0.0001.**

Figure 1-2 through Figure 1-4 show trends for subsets of the EDG CCF events contained in Figure 1-1. Figure 1-2 shows the trend for Complete EDG CCF events. The overall trend from 1980 to 2000 is also statistically significant with a p-value of 0.0001. This indicates a dramatic decrease of Complete

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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.

EDG CCF events, especially since the mid-1980's. However, since 1985, the occurrence rate of Complete EDG CCFs is essentially flat with a p-value of 0.4874. Figure 1-3 and Figure 1-4 show similar statistically significant decreasing trends for both the fail-to-start and the fail-to-run failure modes for all EDG CCF events, both with p-values of 0.0001.

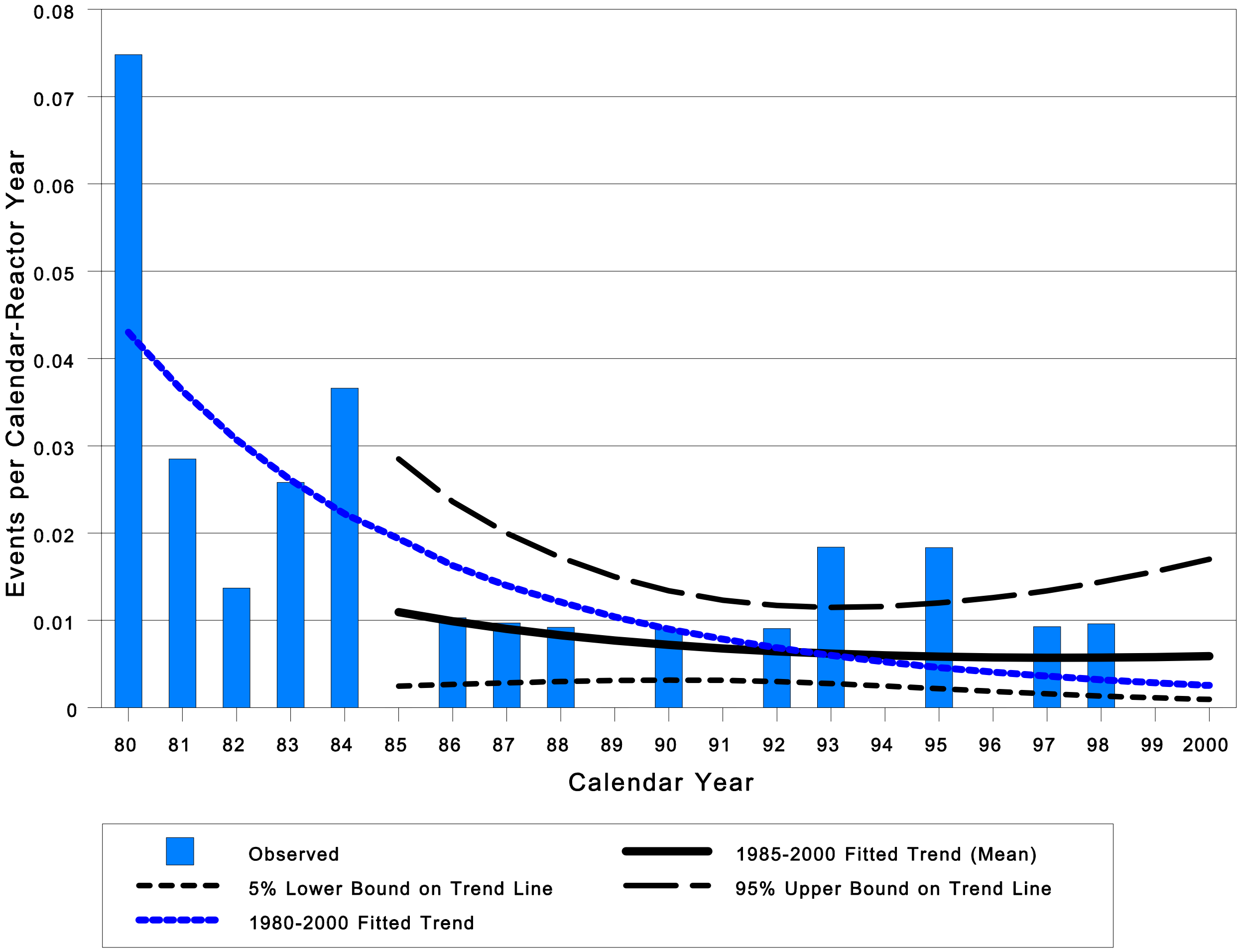

**Figure 1-2. Trend for Complete EDG CCF events. The decreasing trend is statistically significant with a p-value = 0.0001. The trend from 1985-2000 is not statistically significant (p-value = 0.4874).**

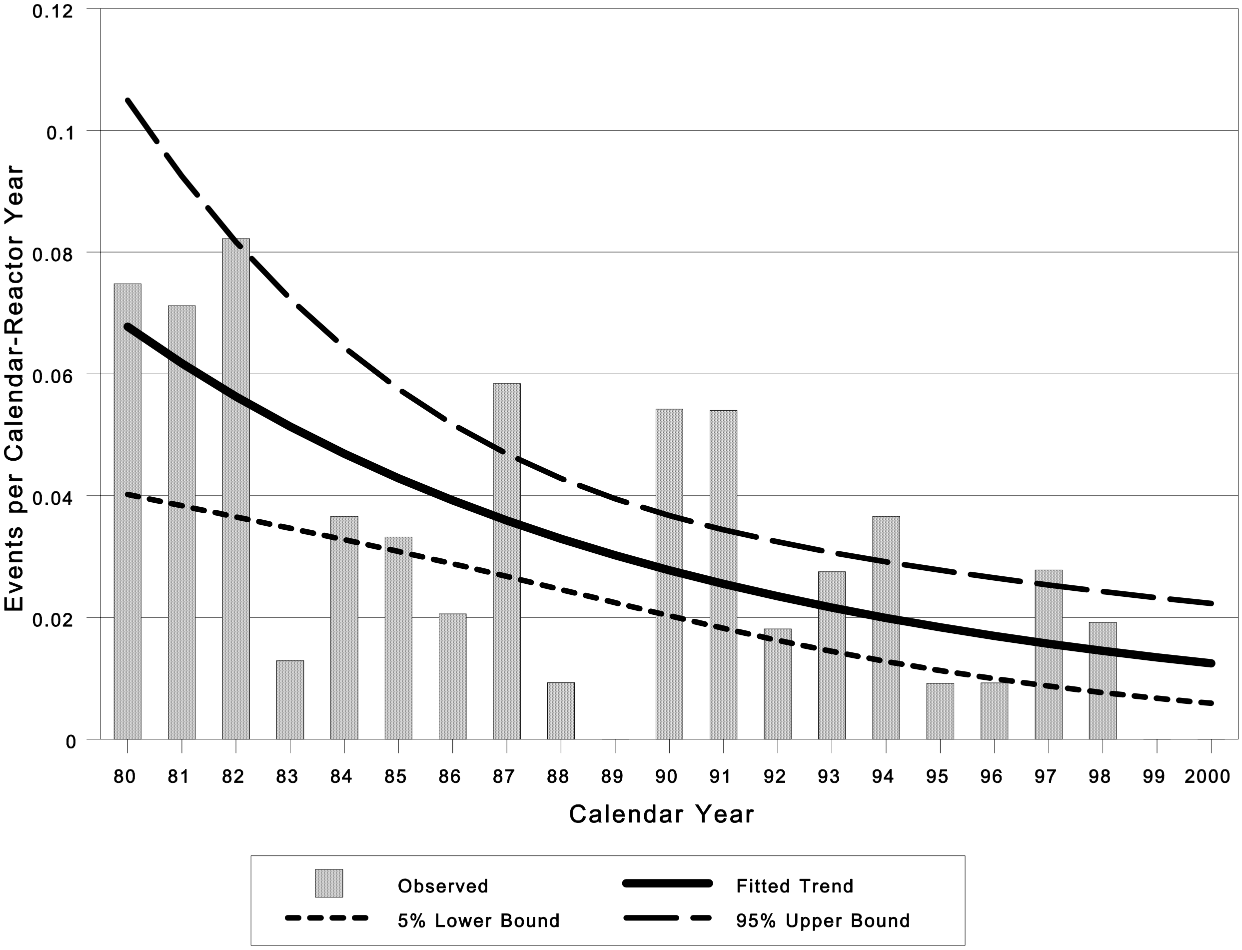

**Figure 1-3. Trend for all EDG CCF events for the fail-to-start failure mode. The decreasing trend is statistically significant with a p-value = 0.0001**

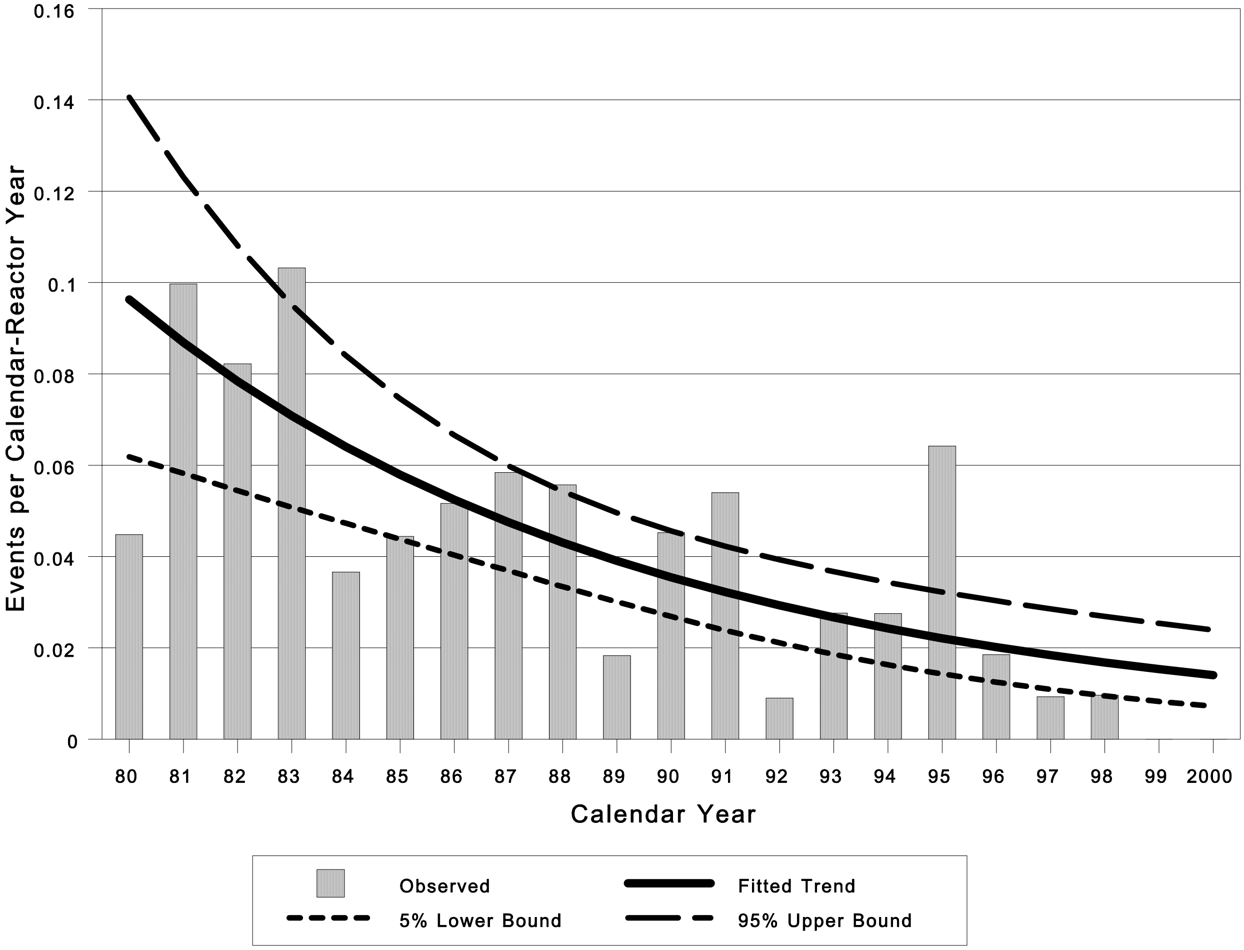

**Figure 1-4. Trend for all EDG CCF events for the fail-to-run failure mode. The decreasing trend is statistically significant with a p-value = 0.0001.**

In 1980, the NRC designated the issue of station blackout (SBO), which is a loss of all ac off-site and on-site power concurrent with a reactor trip, as Unresolved Safety Issue (USI) A-44. The goal of USI A-44 was to determine the need for additional safety requirements since SBO can be a significant contributor to core damage frequency. In 1988, the Commission concluded that additional SBO safety requirements were justified and issued the SBO rule (10 CFR 50.63).[5]

The SBO rule established an EDG reliability program that was to maintain the reliability of the EDG at or above 0.95. The EDG CCF data in this study suggest that the nuclear industry started improving the reliability of the EDGs prior to the final issue of the SBO rule in 1988. This effort appears to have significantly improved the CCF aspect of EDG reliability. A study on EDG reliability from 1987 to 1993[6] also found no increasing or decreasing trend in EDG failure rates over the period of that study.

In Figure 1-2, the bars at approximately 0.01 events per calendar-reactor year correspond to a single Complete EDG CCF event in the year and the bars at approximately 0.02 correspond to two Complete EDG CCF event in the year. To show a statically significant decrease in the occurrence of Complete EDG CCF events, there would have to be many years without any Complete EDG CCF events.

Since 1985, the majority of the Complete EDG CCF events have been in the instrumentation and control sub-system. However, the affected sub-component is different in all cases. Testing was the most common method of discovery and the proximate cause was evenly distributed among Internal to Component, Design/Construction/Installation/Manufacturer Inadequacy, and Operation/Human Error. The EDG is a complex machine and instrumentation and control is the most complex sub-system in the EDG. The instrumentation and control sub-system has the capability to shutdown or render inoperable the EDG component. The most recent Complete EDG CCF events have these characteristics.

EDG Complete CCF events mostly occur in the instrumentation and control sub-system and are discovered by testing. The attributes of proximate cause and coupling factor are random with respect to the completeness of the CCF event.

## 1.3 CCF Sub-System Overview

The EDGs are complex machines and can easily be thought of as a collection of sub-systems, each with many components. The EDG CCF data were reviewed to determine the affected sub-system and the affected sub-component in that sub-system. This was done to provide insights into what are the most vulnerable areas of the EDG component with respect to common-cause failure events.

Figure 1-5 shows the distribution of the CCF events by EDG sub-system. The highest number of events occurred in the instrumentation and control sub-system (41 events or 30 percent). The cooling, engine, fuel oil, and generator sub-systems are also significant contributors. Together, these five sub-systems comprise over 80 percent of the EDG CCF events. The battery, exhaust, and lubricating oil sub-systems are minor contributors.

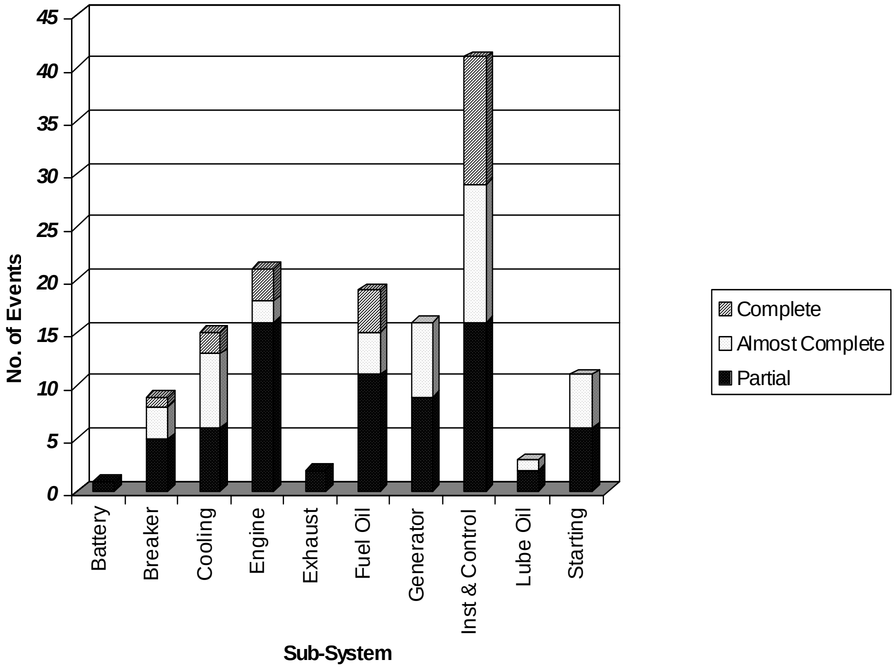

**Figure 1-5. Sub-system distribution for all EDG CCF events.**

## 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 Design/Construction/Installation/Manufacture Inadequacy and accounted for about 33 percent of the total events. Internal to Component faults accounted for 30 percent of the total. Human error accounted for 22 percent of the total events. To a lesser degree, External Environment and the Other proximate cause categories were assigned to the EDG component.

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

The **Design/Construction/Installation/Manufacture Inadequacy** proximate cause group is the most likely for the EDGs 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 46 events. The failure mode for 28 of these events is fail-to-run, and the remaining 18 events have fail-to-start as the failure mode. There were six Complete CCF events in this proximate cause group: three Complete events were fail-to-run and three were fail-to-start. Five of the six Complete events were in the Instrumentation and control sub-system. One of these events was a Complete failure at one unit and the design flaw was detected at the other unit before failure. Except for this one event, the affected sub-component was different for each event.

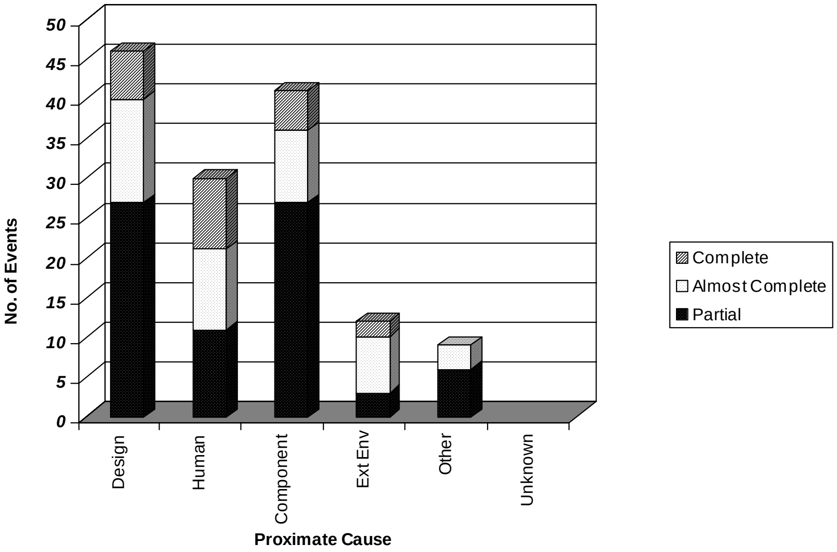

**Figure 1-6. Proximate cause distribution for all EDG CCF events.**

The **Internal to Component** proximate cause category is important for the EDGs and encompasses the malfunctioning of hardware internal to the component. 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 errors resulted in 41 events. Of these, 20 were classified as fail-to-run and 21 were fail-to-start. There were five Complete failure events. The Engine and the Instrumentation and Control sub-systems each had two Complete events and the fifth Complete event was in the Cooling sub-system.

The **Operational/Human Error** proximate cause group is the next most likely for the EDG 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 30 EDG CCF events. These events included eight occurrences of accidental action, six occurrences of following the wrong procedure, and 16 occurrences due to use of inadequate procedures. The failure mode for 18 events is fail-to-run and 12 events have fail-to-start as the failure mode. There were nine Complete CCF events: seven were linked by maintenance and two were linked by system design. There are disproportionately more Complete events in this proximate cause category than in any other. This highlights the importance of maintenance and operations in the availability of the EDG component.

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 12 events assigned to it. The failure mode for eight events is fail-to-run, and four events have fail-to-start as the failure mode. There were two Complete CCF events, both resulting in fail-to-run. The two Complete events were due, in part, to engine vibration and were discovered by testing. This distribution of failure modes is not similar to the overall set of data, mostly because the environmental factors are more likely to affect the EDG during running time. For example, high temperature cooling water will not likely be too hot when the EDG starts, but after some amount of running time, due to the higher than average initial temperature, the cooling water temperature will increase above the acceptable limit.

The **Other** proximate cause group is comprised of events that indicated setpoint drift and the state of other components as the basic causes. Nine events were assigned to this category. The failure mode for five events is fail-to-run and four events have fail-to-start as the failure mode. There were no Complete CCF events in this category, and many of the events in this category are weak (i.e., small degradation values, weak coupling factors, and long time intervals among events).

## 1.5 CCF Coupling Factors

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 events. Design is the leading coupling factor with 66 events (48 percent). Design coupling factors result from common characteristics among components determined at the design level. Maintenance with 39 events (28 percent) accounts for the majority of the remaining events. Maintenance also has a higher proportion of Complete events than any other coupling factor. Again, highlighting the importance of maintenance in the EDG CCFs. These two coupling factors account for the top 76 percent of the events.

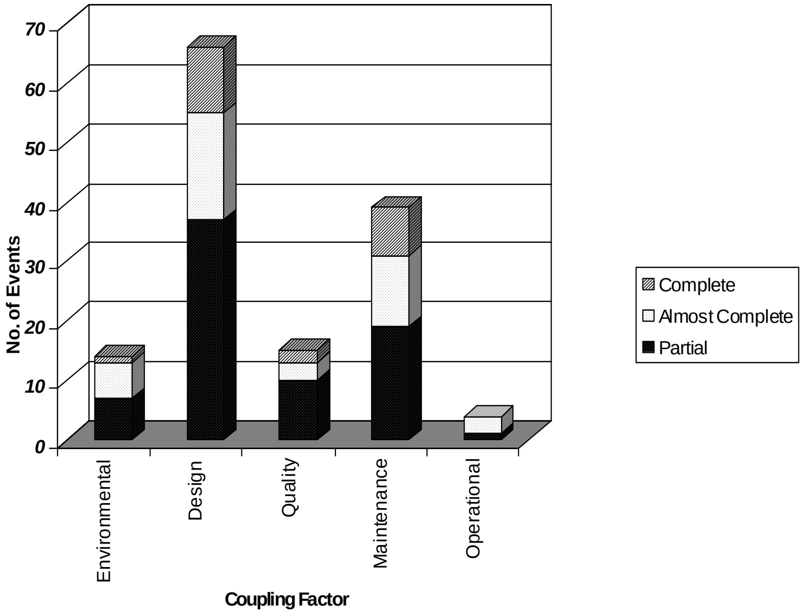

**Figure 1-7. Coupling factor distribution for all EDG CCF events.**

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

The design coupling factor is most prevalent in the Design/Construction/Installation/Manufacture Inadequacy proximate cause category. This means that the design was inadequate and was the link between the events. Examples of this follow:

- a single fault in a fire detection system caused all three EDGs to be unavailable,
- a modification was made to the load sequencers and the EDGs would not load during subsequent testing, and
- low lube-oil pressure sensors were replaced with modified sensors on all EDGs at both units and within 5 days all EDGs at both NPP units experienced failures due to a large calibration shift in the sensors.

The next most prevalent proximate cause under the Design coupling factor is Internal to Component. This means that the component failures, while not necessarily related to the original design, occurred in multiple components because all had the same design. Examples of these types of events are:

- damage to all lockout relays during an attempt to shutdown the EDGs resulting in the EDGs failing to restart,
- both EDGs failed due to failure of their electrical governor caused by a burnt resistor in the power supply of the control unit, and

- a service water valve to EDG coolers was mispositioned due to a faulty positioner, resulting in the EDGs overheating.

The **Maintenance** coupling factor indicates that the maintenance frequency, procedures, or personnel provided the linkage among the events. Operational/Human Error is the most prevalent proximate cause to be linked by maintenance. Examples of this are:

- misaligned breakers during an automatic start test,
- dirty contacts in the load sequencers, painted fuel rack pivot points, fuel oil isolated from EDGs,
- drained fuel oil day tanks,
- service water isolated to all EDGs during maintenance, and
- incorrect setpoints on a newly installed phase differential over-current relay in both EDGs.

The maintenance linkage to the component failure proximate cause usually indicated that more frequent maintenance could have prevented the CCF mechanism. Very few of these events actually resulted in Complete CCF events, but were detected as incipient failures. An example of this is timing devices, which failed due to aging, and were replaced. These devices had a history of an excessive need for calibration, yet were allowed to fail before being replaced. This event occurred in 1980 and since then, all CCFs in this category have been detected before complete failure.

The **Environment** based coupling factors propagate a failure mechanism via identical external or internal environmental characteristics. Examples of environmental based coupling factors are:

- degraded relay sockets caused by vibration and
- sticking limit switches caused by low temperatures.

**Quality** based coupling factors propagate a failure mechanism among several components due to manufacturing and installation faults. An example of a Quality based coupling factor is the failure of several RHR pumps because of the failure of identical pump air deflectors due to improper installation.

The **Operational** based coupling factors propagate a failure mechanism because of identical operational characteristics among several components. For example, failure of three redundant HHSI pumps to start because the breakers for all three pumps were racked-out because of operator error.

## 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 the 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 1-8 shows the distribution of how the events were discovered or detected. Testing accounted for 90 events (65 percent), Inspection for 28 events (20 percent), 12 events (9 percent) were discovered during an actual Demand, and eight events (6 percent) were discovered during Maintenance activities. These results are as expected considering the extensive and frequent surveillance test requirements for EDGs contained in the Technical Specifications.

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

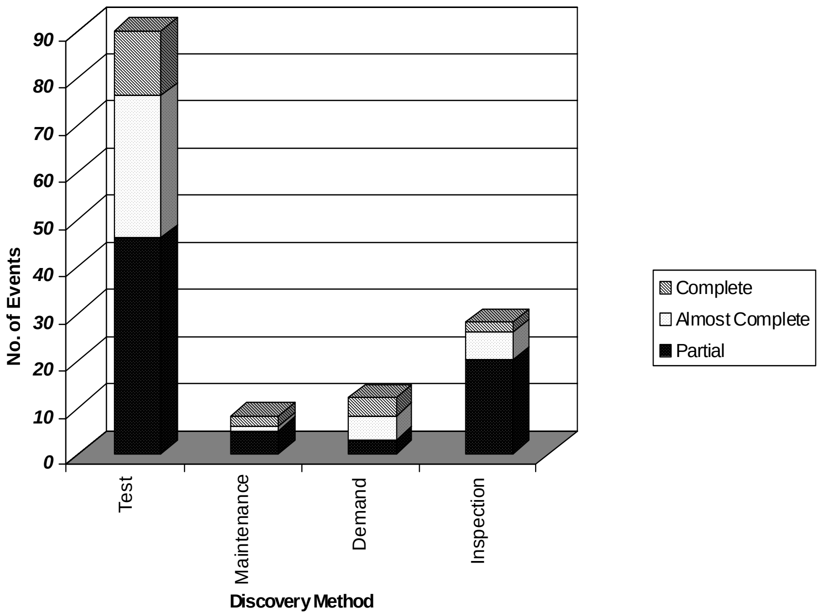

**Figure 1-8. Discovery method distribution for all EDG CCF events.**

## 1.7 Other EDG CCF Observations

Figure 1-9 shows the distribution of CCF events grouped by EDG manufacturers and graphically demonstrates the data in Table 1-2. EDG manufacturer data in Table 1-2 was taken from *Emergency Diesel Generator Power System Reliability 1987-1993.* A statistical test was performed to determine whether the occurrence of CCF events was independent of the manufacturer. There is no evidence that the number of CCF events differs among manufacturers (p-value = 0.365).

**Table 1-2. EDG manufacturer and CCF event distribution.**

| Manufacturer Name | Total EDGs Installed | Percent Installed | No. CCFs | Percent CCF |
|---|---|---|---|---|
| Other | 1 | 0.4% | 0 | 0.0% |
| Worthington Corp | 4 | 1.7% | 4 | 2.9% |
| Nordberg Mfg | 8 | 3.4% | 6 | 4.3% |
| Transamerica Delaval | 22 | 9.3% | 16 | 11.6% |
| ALCO Power | 23 | 9.7% | 18 | 13.0% |
| Cooper Bessemer | 36 | 15.3% | 23 | 16.7% |
| Fairbanks Morse/Colt | 67 | 28.4% | 28 | 20.3% |
| Electro Motive | 75 | 31.8% | 43 | 31.2% |
| Total | 236 | 100.0% | 138 | 100.0% |

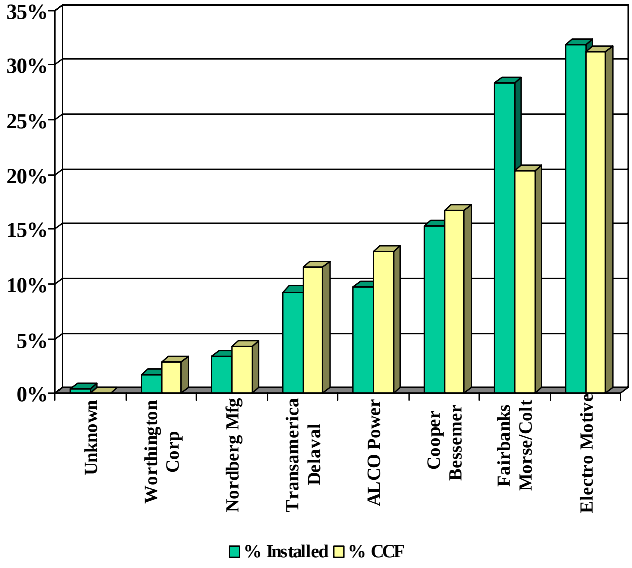

**Figure 1-9. Comparison of EDG manufacturer population and occurrence of CCF events.**

Figure 1-10 shows the distribution of EDG CCF events among the NPP units. The data are based on 109 NPP units represented in the insights CCF studies. Forty-two NPP units each had one CCF event during the period; 34 NPP units did not experience a CCF event. The zero and one CCF event counts account for about 70 percent of the NPP units. Seventeen percent of the NPP units have experienced three or more EDG CCF events. This may indicate that the majority of the NPP units have maintenance and testing programs to identify possible EDG CCF events and work towards preventing either the first event or any repeat events. Less than 6 percent of the NPP units have experienced four or more EDG CCF events.

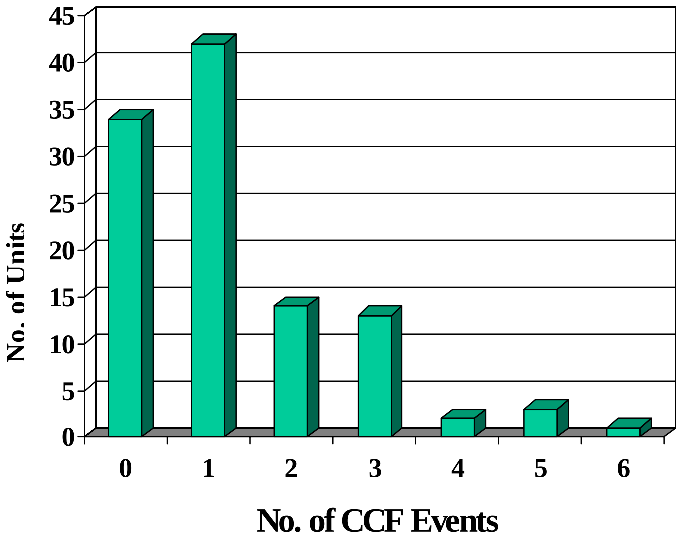

**Figure 1-10. Distribution of NPP units experiencing a multiplicity of CCFs for all EDG CCF events.**

# 2 REFERENCES

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