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ABSTRACT

This report documents an analysis of the reliability of emergency diesel generator (EDG) power systems at U.S. commercial nuclear plants during the period 1987–1993. To evaluate EDG power system performance, estimates are given of individual EDG train reliability to supply emergency ac power to the safety-related bus. The estimates are based on EDG train performance data that would be typical of an actual response to a low-voltage condition on a safety-related bus for averting a station blackout event. A risk-based analysis and an engineering analysis of trends and patterns are performed on data from EDG operational events to provide insights into the reliability performance of EDGs throughout the industry and at a plant-specific level. Comparisons are made to EDG train statistics from Probabilistic Risk Assessments, Individual Plant Examinations, and NUREG reports, representing 40% of the U.S. commercial nuclear power plants. In addition, EDG train reliability estimates and associated uncertainty intervals are compared to station blackout target reliability goals.

Job Code: E8246—Technical Assistance in Reliability and Risk Analysis

EXECUTIVE SUMMARY

This report presents an evaluation of the performance of emergency diesel generator (EDG) trains at U.S. commercial nuclear power plants. The study is based on the operating experience from 1987 through 1993, as reported in Licensee Event Reports (LERs) and Special Reports. The data extracted from LERs and Special Reports for plants reporting under Regulatory Guide 1.108 requirements were analyzed in three ways (referred to in this report for simplicity as RG-1.108 data). First, the EDG train unreliability was estimated, and the factors affecting unreliability were determined. The estimates were analyzed to uncover trends and patterns within EDG train reliability. The trend and pattern analysis yielded insights into the performance of the EDG train on plant-specific and industry-wide bases. Second, comparisons were made between the estimates calculated in this report and EDG train unreliabilities reported in the selected PRAs, IPEs, and NUREGs (PRA/IPEs). The objective of the comparisons was to indicate where RG-1.108 data support or fail to support the assumptions, models, and data used in the PRA/IPEs. Third, plant-specific estimates of EDG train reliability derived from the RG-1.108 data were calculated. These estimates were compared to the station blackout (SBO) target reliability goals. For the non-RG-1.108 population of EDGs, the results of a cursory analysis and comparisons derived solely from LER data associated with unplanned demands were presented.

Twenty-nine plant risk source documents, PRA/IPEs, were used for comparison with the EDG reliability results obtained in this study. The information extracted from the source documents contain relevant EDG train statistics for 44 plants comprising 97 EDGs. The data represent approximately 40% of the plants and EDGs at operating nuclear power plants. Of the 44 plants, 29 report in accordance with the requirements identified in Regulatory Guide 1.108.

EDG train unreliabilities were estimated using a fault tree model to combine broadly defined train failure modes such as failure to start or failure to run into an overall EDG train unreliability. The failure probabilities for the individual failure modes were calculated by reviewing the failure information, categorizing each failure event by failure-mode, and then estimating the corresponding number of demands (both successes and failures). Approximate PRA/IPE-based unreliabilities were calculated from the failure data documented in the respective PRA/IPE for the start, load, run, and maintenance phases of the EDG train operation.

The estimated EDG train unreliability derived from unplanned and cyclic test demand data for the RG-1.108 plants was 0.044. The EDG train unreliability was estimated from 50 failures observed during 181 unplanned demands and 682 cyclic (18 month) surveillance tests. The observed failures were classified as either failure to start, failure to run, or maintenance out of service. Maintenance out of service was further classified as to whether or not the plant was in a shutdown condition at the time of the demand. In addition, recovery of EDG trains from failures during unplanned demands were identified. The unreliability estimate includes consideration of recovery of EDG train failures, maintenance out of service while the plant is not in a shutdown condition, and assumes an 8-hour mission time. Maintenance out of service is the major contributor to EDG train unreliability. Approximately 70% of the unreliability is attributed to maintenance being performed on an EDG train at the time of an unplanned demand. If recovery is excluded, the estimate of an EDG train unreliability is 0.069. The causes of unreliability were primarily electrical in nature and typically the result of hardware malfunctions.

The EDG train failures observed during an unplanned demand which contributed to EDG unreliability appeared to be difficult for operators to diagnose and recover. These EDG train failures were caused by problems associated with instrumentation and controls, and electrical subsystems. The failures associated with the instrumentation and controls subsystem were difficult for plant personnel to diagnose, and were the result of intermittent actuation of the temperature and pressure switches in the automatic shutdown circuits. In approximately 50% of these failures, troubleshooting activities failed to find a cause for the EDG failure and the EDG was restarted without performing any corrective maintenance. In one case the troubleshooting lasted 2.5 hours with the safety-related bus de-energized throughout the troubleshooting. The failures associated with the electrical subsystem were the result of a personnel error in operation of a running EDG, and a hardware-related problem in the timer for the sequencer.

The EDG train failures that occurred during cyclic surveillance tests which contributed to unreliability were either the result of electrical-related failures, or leaking/loose components. The electrical-related failures primarily contributed to the failure to start probability. These failures were primarily the result of blown fuses and the malfunction of relays, potentiometers, contacts, solenoids and resistors associated with the voltage regulator, governor, and sequencer. The failures that resulted from either leaking or loose components dominated the failure to run probability. The leaking or loose category of failures was associated with a broad variety of components. However, the leaking or loose components were typically the result of errors associated with maintenance (improper assembly of the components) and either vibration or wear-induced fatigue failure. A significant number of the leaking or loose components appeared over an hour after the EDG was running, and therefore may not be detected in the monthly test due to the short run time of the monthly test, compared to the cyclic test's endurance run.

The average of the plant-specific RG-1.108-based estimates of EDG train unreliability is in agreement (approximately 13% higher) with the average of the PRA/IPE estimates, assuming an 8-hour run time of the EDG. Generally, the RG-1.108-based estimate for failure to start and maintenance out of service probabilities agree with their respective PRA/IPE counterparts. However, for a 24-hour mission time for the EDG train, the average PRA/IPE estimate of failure to run is approximately a factor of 30 higher than the corresponding RG-1.108-based estimate. Figure ES-1 provides a plot of PRA/IPE and RG-1.108 estimates of EDG train unreliabilities and uncertainties for RG-1.108 reporting plants.

Based on the mean reliability, all of the RG-1.108 plants (44) with an EDG target reliability goal of 0.95 attain the SBO target goal provided that the unavailability of the EDG due to maintenance is ignored. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.95 SBO target goal is 0.987, with a corresponding uncertainty interval of 0.96, 0.99. For the RG-1.108 plants with a EDG target reliability goal of 0.975, eighteen of the nineteen RG-1.108 plants, based on the mean reliability, attain the reliability goal provided that the unavailability of the EDG due to maintenance is ignored. The EDGs associated with the plant not achieving the 0.975 reliability goal had a mean reliability of 0.971. However, when uncertainty is accounted for, these EDGs have approximately a 0.54 probability of meeting or exceeding the 0.975 reliability goal. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.975 target goal is 0.985, with a corresponding uncertainty interval of 0.95, 0.99.

The effect of maintenance unavailability on EDG reliability is significant based on the RG-1.108 data. The technical basis for the Station Blackout Rule assumes that such unavailability is negligible (0.007). The estimate derived from the RG-1.108 data for maintenance out of service is 0.03. Forty of the 44 RG-1.108 plants with a 0.95 target reliability attain the goal when comparing mean estimates. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.95 target goal is 0.956, with a corresponding uncertainty interval of 0.92, 0.99. For the RG-1.108 plants with an EDG target reliability goal of 0.975, none of the EDGs meet the target reliability goal. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.975 target goal is 0.954, with a corresponding uncertainty interval of 0.91, 0.98.

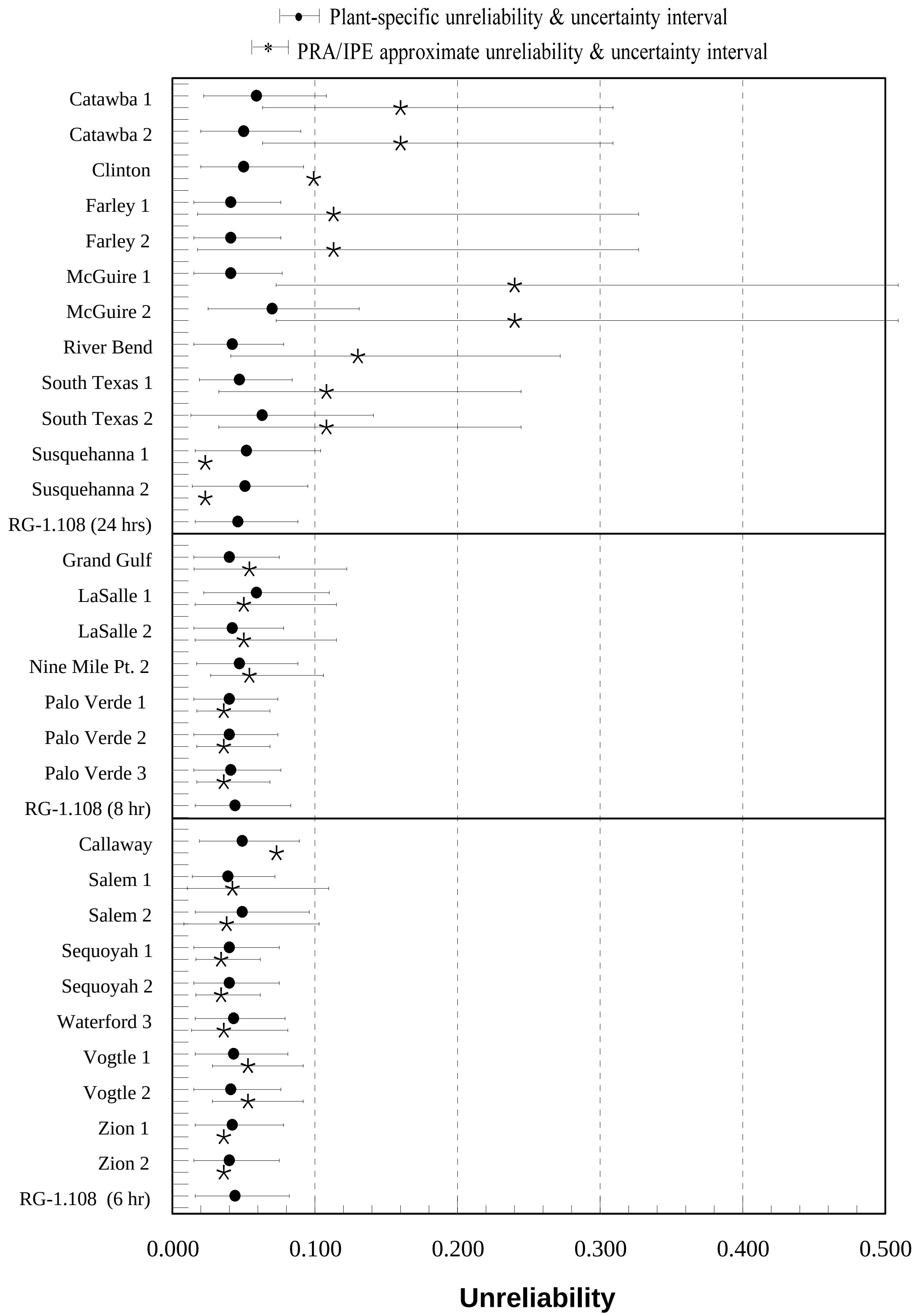

Figure ES-1. Plot of PRA/IPE and RG-1.108 estimates of EDG train unreliabilities and uncertainties with recovery for Regulatory Guide 1.108 reporting plants. The FTR contribution is based on the mission time stated in the PRA/IPE (with the exception of Susquehanna and Palo Verde).

Based on the limited failure data (i.e., unplanned demand data only) for the non-RG-1.108 plants, reliability parameters estimated for this population of EDGs tend to agree with those generated for the RG-1.108 plants. The reliability estimate (without maintenance unavailability) for the overall population of EDGs at the non-RG-1.108 plants is 0.984, with a corresponding uncertainty interval of 0.97, 0.99. This unreliability is attributed to hardware-related failures of the output breaker that were not observed in the RG-1.108 reporting plants. Owing to the sparseness of the non-RG-1.108 data, the reliability estimates apply to either SBO target reliability goal. The reliability estimate for the overall population of EDGs at the non-RG-1.108 plants with maintenance unavailability included is 0.958, with a corresponding uncertainty interval of 0.92, 0.98.

Trending analysis of the failure rate, unplanned demand rate and unreliability data by year indicates no statistically significant trend over the 7 years of the study period. However, the smallest number of events for any given year did occur in 1993. The analysis of plant-specific unreliability by low-power license date indicates no statistically significant trend. However, analysis of plant-specific EDG failure rate by low-power license date identifies a statistically significant trend. The trend indicates that the plants with low-power license dates from 1980–1990 typically had an EDG failure rate greater than those plants with a low-power license date prior to 1980. The trend observed by low-power license date for the EDG failure rate requires further investigation as to the cause of the trend. Information in the LERs was not sufficient to determine the reason for the trend. Each of the trending analyses are provided in Figures ES-2 through 6.

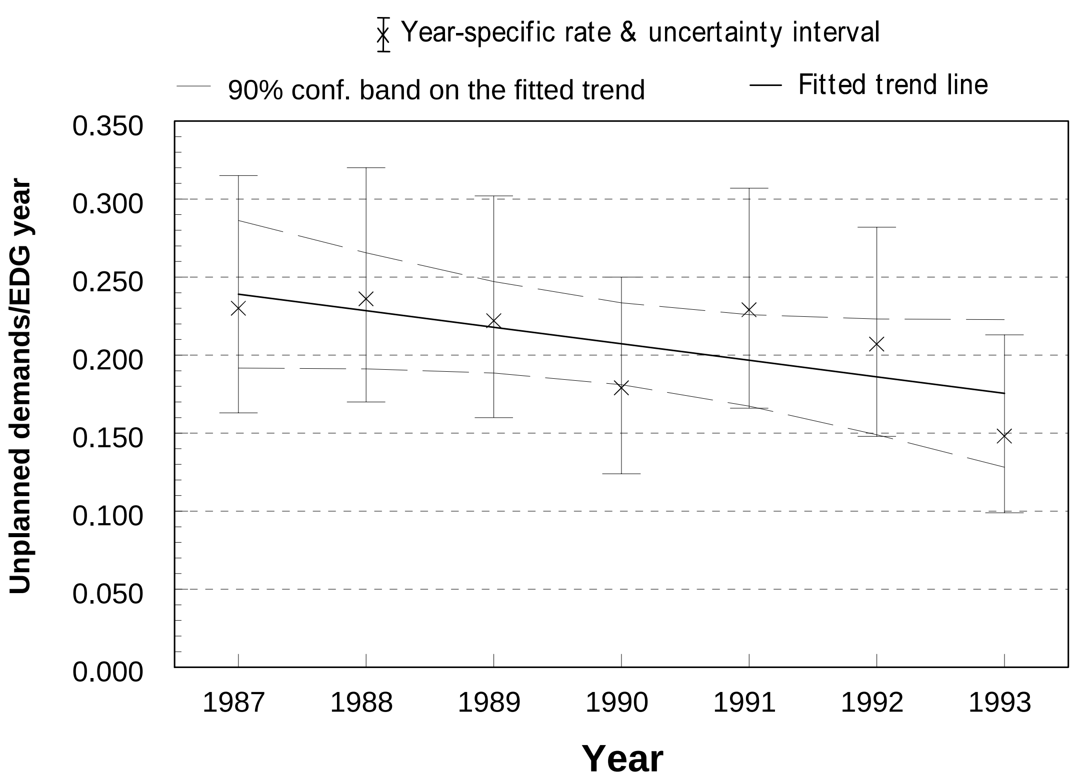

Figure ES-2. EDG unplanned demands per EDG-year with 90% confidence intervals and fitted trend. The trend is not statistically significant (P-value=0.08).

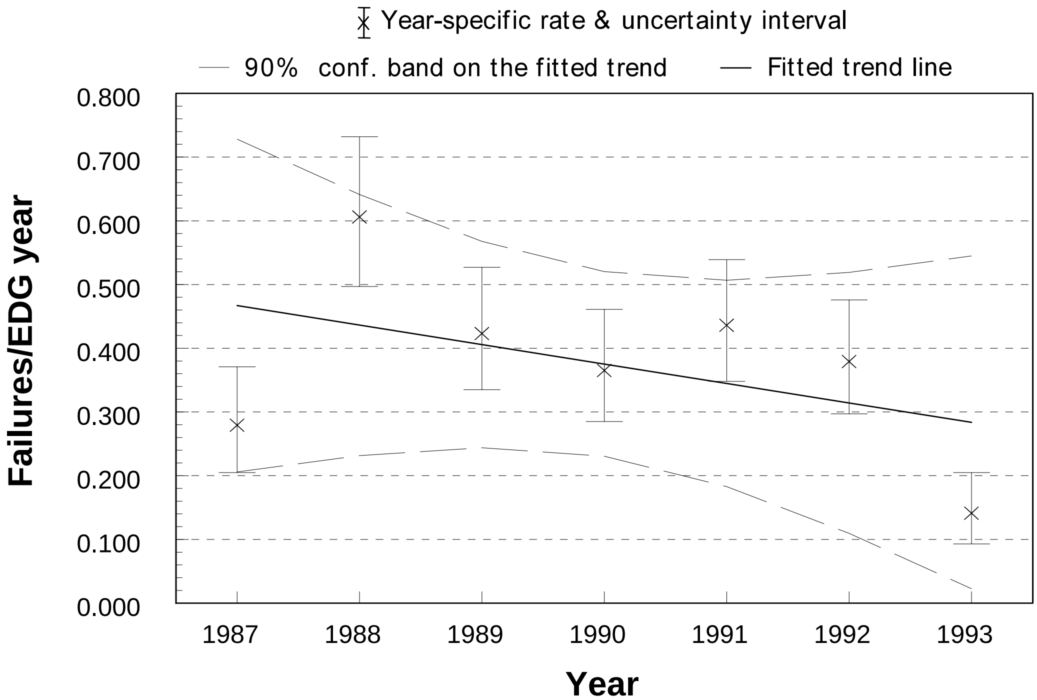

Figure ES-3. EDG failures per EDG-year with 90% confidence intervals and fitted trend. The trend is not statistically significant (P-value=0.30).

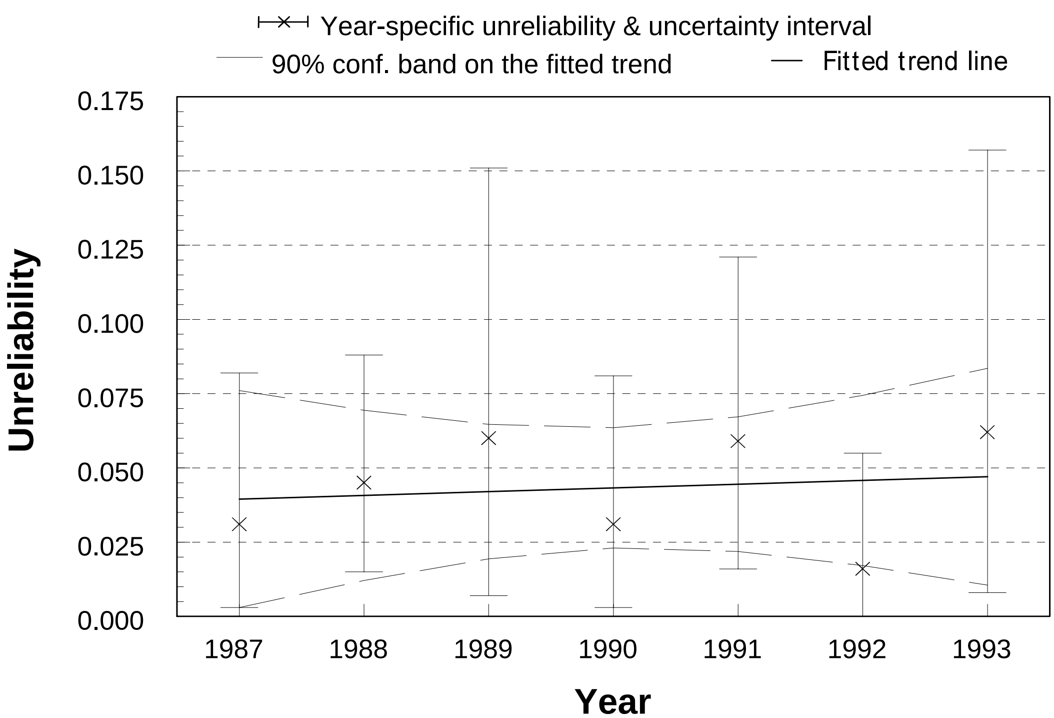

Figure ES-4. EDG train unreliability by calendar year, based on a constrained noninformative prior and annual data. Ninety percent Bayesian intervals and a fitted trend are included. The trend is not statistically significant (P-value=0.75).

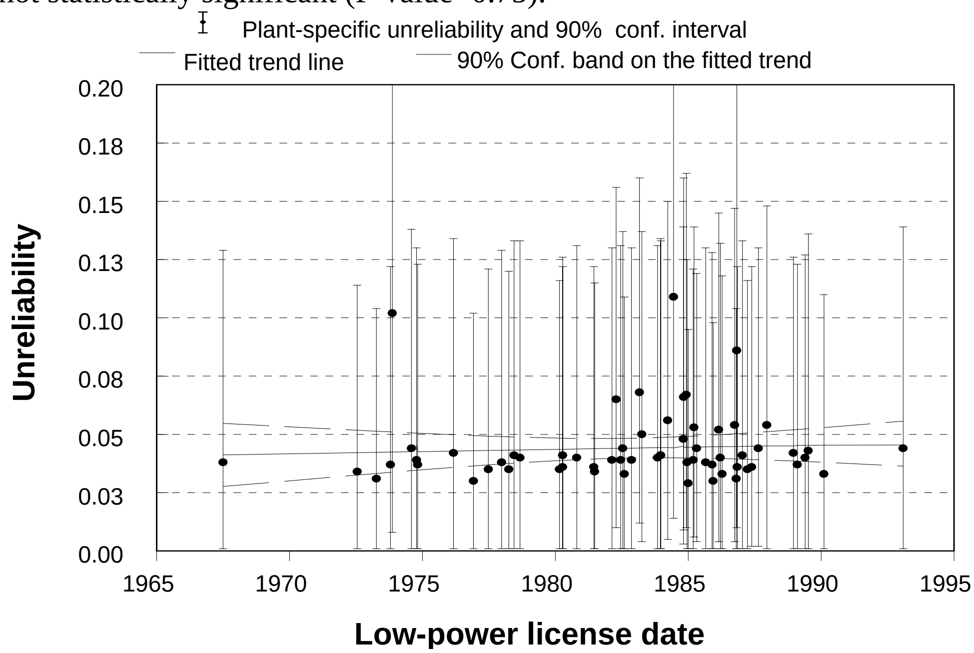

Figure ES-5. Plant-specific unreliability based on constrained noninformative prior distributions and an 8-hour mission, plotted against low-power license date. Ninety percent Bayesian intervals and a fitted trend are included. The trend is not statistically significant (P-value=0.62).

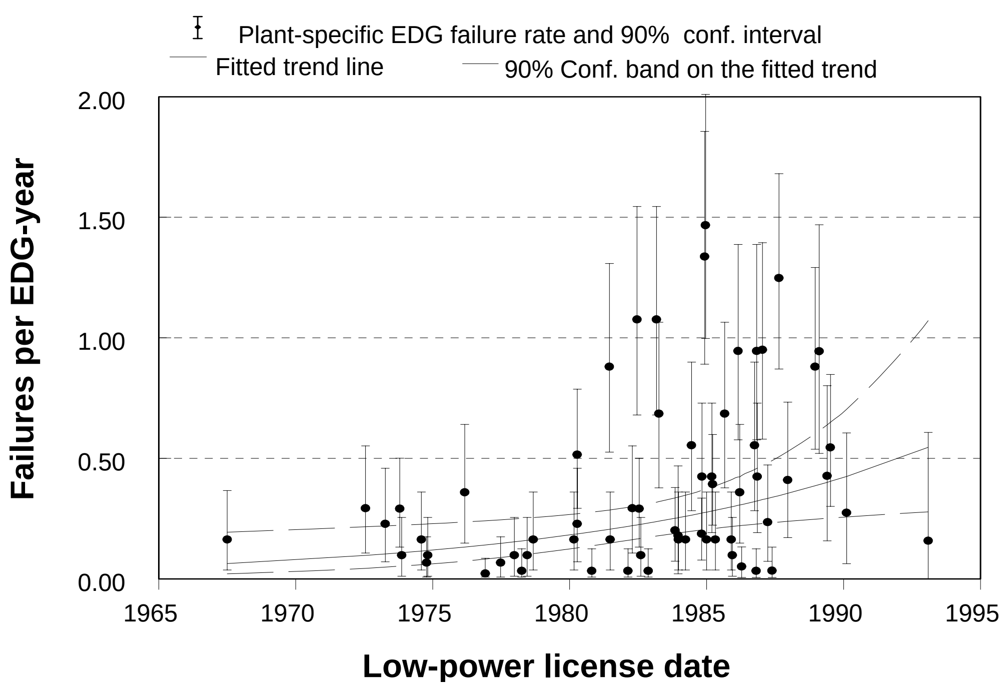

Figure ES-6. Plant-specific EDG failures per EDG-year, plotted against low-power license date. Ninety percent Bayesian intervals and a fitted trend are included. The trend, based on a fit of the logarithms of the rates as a function of low-power license date, is statistically significant (P-value=0.007).

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Technical contributions by F. M. Marshall, D. A. Prawdzik, and P. H. McCabe of the INEL contributed to the final report.

CONTENTS

FIGURES

TABLES

ACRONYMS

AEOD	Analysis and Evaluation of Operational Data (NRC Office)
AP	ALCO Power (EDG manufacturer)
ASP	accident sequence precursor
BWR	boiling water reactor
CB	Cooper Bessemer (EDG manufacturer)
CCDP	conditional core damage probability
CCF	common cause failure
CFR	Code of Federal Regulations
CL	SACM/Compair Luchard (EDG manufacturer)
ECCS	emergency core cooling system
EDG	emergency diesel generator
ESF	engineered safety feature
EM	Electro Motive General Motors (EDG manufacturer)
FC	Fairbanks Morse/Colt (EDG manufacturer)
FRFTR	failure to recover from failure to run
FRFTS	failure to recover from failure to start
FTR	failure to run
FTS	failure to start
HVAC	heating, ventilating, and air conditioning
IPE	individual plant examination
INEL	Idaho National Engineering Laboratory
LER	Licensee Event Report

LOCA	loss-of-coolant accident
LOOP	loss of offsite power
MCC	motor-control center
MOOS	maintenance out of service
NM	Nordberg Mfg. (EDG manufacturer)
NPRDS	Nuclear Plant Reliability Data System
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
OUTINFO	a database of plant outages
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RF	restoration failure
RFP	restoration failure, power
RFR	restoration failure, reset
RG	Regulatory Guide
SAS	SAS Institute, Inc.'s commercial software package
SBO	station blackout
SCSS	Sequence Coding and Search System
SIF	self-initiated failure
TD	Transamerica Delaval (EDG manufacturer)
WC	Worthington Corp. (EDG manufacturer)

DEFINITION OF TERMS

Common cause failure (CCF)—A set of dependent failures resulting from a common mechanism in which more than one EDG train exists in a failed state at the same time, or within a small time interval.

EDG Train—An EDG train is a single diesel engine, electrical generator, and the associated support subsystems necessary to power and sequence the electrical loads on the vital ac bus. Typically, two or more EDG trains constitute the onsite emergency ac power system.

Failure—A malfunction of the EDG train or associated support subsystems that prevents the EDG train from starting and running when a demand has occurred. An administrative inoperability, such as a missed surveillance test, does not constitute a failure.

Failure to run (FTR)—A failure of the EDG train to continue to supply power to its respective safety-related electrical bus given the EDG train successfully started.

Failure to start (FTS)—A failure of the EDG train to either manually or automatically start on a bus under-voltage condition, reach rated voltage and speed, close the output breaker, or sequence safety-related electrical loads onto the respective safety-related bus.

Demand—An event requiring the EDG to start and supply power to the safety-related bus. This event may be the result of a scheduled (i.e., cyclic surveillance test) or an unscheduled (i.e., unplanned) demand. An unscheduled demand is an under-voltage condition on the EDG's safety-related bus thereby requiring the EDG to supply power to the affected bus. A safety injection signal is not considered an unscheduled demand for this report, since the EDG is not required to supply power to the safety-related bus for this plant condition.

Inoperability—An occurrence where one or more EDG trains were not fully operable as defined by applicable plant technical specifications or Regulatory Guide 1.108. Inoperabilities may or may not be an actual failure of the EDG train.

Load shedding—Automatic removal of all electrical equipment powered on an electrical bus.

Maintenance out of service (MOOS)—Failure of the EDG train caused by the EDG train being out of service for either preventative or corrective maintenance at the time of an unplanned demand.

Maintenance unavailability—Probability that the EDG train is unavailable due to MOOS.

Mission time—The elapsed clock time during which the EDG train is required to provide power to the safety-related electrical bus. For an under-voltage condition on the safety-related bus, it is the length of time to successfully recover offsite power. For EDG train testing, it is the required test run time as specified in the testing program (RG-1.108).

Operational Data—A term used to represent the industry operating experience reported in LERs, Special Reports, or monthly operating reports. It is also referred to as operational experience or industry experience.

PRA/IPE—A term used to represent the data found in the PRAs, IPEs, and NUREGs.

P-value—The probability that the data set would be as extreme as it is, assuming the model or hypothesis is correct. It is the significance level (0.05 for this study) at which the assumed model or hypothesis would be statistically rejected.

Recovery—An act that enables the EDG train to be recovered from either an FTS or FTR failure. Recovery of an EDG was only considered in the unplanned demand events, because these are the types of events where recovery of power to the vital bus is necessary. Each failure reported during an unplanned demand was evaluated to determine whether recovery of the EDG train by operator actions had occurred. Some events identified recovery of power to the vital bus using off-site power when the EDG failed to respond to the bus low-voltage condition. These events were not considered a successful recovery of the EDG train because the EDG train was left in the failed state. In these events, the initiator of the bus low-voltage condition was actually corrected.

Restoration failure—An incipient failure condition of the EDG train that results from a failure to restore the EDG to a standby operating condition. A restoration failure reset (RFR) condition occurs when emergency actuations are reset and a protective trip signal (e.g., low cooling water flow/discharge pressure, high vibration, etc.) of the EDG is present. This condition would result in tripping the EDG and a potential station blackout if offsite power was not previously restored. A restoration failure of offsite power (RFP) condition occurs during a parallel operation of the EDG with offsite power. During parallel operations, failure mechanisms exist (e.g., performance of the voltage and speed regulators) for the EDG that are not present when operating independent of offsite power. These failure mechanisms can trip the EDG and/or cause electrical disturbances on the electrical bus, potentially resulting in a station blackout condition.

Safety function—The requirement that an EDG train starts and loads its associated vital bus for the duration of its mission time.

Sequencer—A system device that controls the order and timing of emergency loads that are automatically loaded onto the safety-related bus. It can be *distributed*, with various devices located throughout the electrical system, or *discrete*, that is, contained in a single cabinet/panel, and is generally a solid state device.

Self-Initiated Failure (SIF)—A special class of EDG train failure to successfully start. These failures are differentiated from the FTS events because the demand for the EDG train also causes the EDG train to fail to start. The demand and failure of the EDG train is typically the result of a sequencer fault that strips the vital bus and subsequently prevents the bus from loading from the EDG train.

Unreliability—Probability that the EDG train will fail to perform its required mission (e.g., provide power to a bus for the required time).

Emergency Diesel Generator Power System Reliability, 1987–1993

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC), Office for Analysis and Evaluation of Operational Data (AEOD), in cooperation with other NRC Offices, has undertaken an effort to ensure that the stated NRC policy to expand the use of probabilistic risk assessment (PRA) within the agency can be implemented consistently and predictably. As part of this effort, the AEOD Safety Programs Division is reviewing the functional reliability of risk-important systems in commercial nuclear power plants. The approach is to compare the estimates and associated assumptions found in PRAs and Individual Plant Examinations (IPEs) to actual operating experience. The first phase of the review involves the identification of risk-important systems from a PRA perspective and the performance of reliability and trending analysis on these identified systems. As part of this review, a risk-related performance evaluation of emergency diesel generator (EDG) power systems at U.S. commercial reactor plants was performed.

The evaluation measures EDG power system performance using actual operating experience under conditions most representative of circumstances that would be found in a response to a postulated loss-of-offsite-power event. To perform this evaluation and make comparisons to the relevant information provided in the PRA/IPEs, it was necessary to evaluate system reliability on the individual train level. Therefore, the reliability estimates presented in this study are based on the individual EDG trains in performing their risk-significant function. These estimates of EDG train reliability were based on data from unplanned demands as a result of an actual safety-related bus low-voltage condition, and surveillance tests that best simulate an EDG train response to a safety-related bus low-voltage condition. Data were not used from component failures that did not result in the loss of the risk-significant function of the EDG train. Also, partial demands, whether unplanned and not in response to a low-voltage condition or tests that did not simulate a complete EDG response to a low-voltage condition, were not used to estimate reliability. These partial demands were not used to estimate reliability because they do not represent the same stresses the EDG train would experience during a loss-of-offsite-power event.

As a result of the focus of this study, the classifications of the various failure modes found in this report are based on the criteria identified in NUREG/CR-2989, *Reliability of Emergency AC Power Systems at Nuclear Power Plants.*[1] NUREG/CR-2989 contains the results of a reliability analysis of the onsite ac power system relative to calculating the expected frequency of a station blackout. Because of this focus, NUREG/CR-2989 was chosen as the reference for classifications of the various EDG train failure modes. These criteria are different from those found in Regulatory Guide 1.108, *Periodic Testing of Diesel Generator Units Used as Onsite Electrical Power Systems,*[2] Regulatory Guide 1.9, *Selection, Design, and Testing of Emergency Diesel Generator Units Used as Class 1E Onsite Electrical Power Systems,*[3] and other studies such as NSAC-108, *The Reliability of Emergency Diesel Generators at U.S. Nuclear Power Plants.*[4] The regulatory guides and the NSAC-108 study present criteria for evaluating EDG train performance during testing that do not always simulate a complete EDG train response as would be observed during a loss-of-offsite-power event. In addition, the NSAC study and regulatory guides present different and conflicting definitions of demands, failures, and failure modes than those that would be used in a risk-based assessment.

The EDG train performance study was based upon the operating experience during the period from 1987 through 1993, as reported in Licensee Event Reports (LERs) and Special Reports. The objectives of the study were to:

1. Estimate unreliability based on operational data and compare the results with the assumptions, models, and data used in selected probabilistic risk assessment and individual plant examinations.

2. Compare the plant-specific estimates of EDG train reliability to EDG target reliability goals for station blackout concerns.

3. Provide an analysis of the factors affecting unreliability and determine if trends and patterns are present in the operational data.

This report is arranged as follows. Section 1 provides an introduction. Section 2 describes the scope of the study, which includes a description of the EDG train and brief descriptions of the data collection and analysis methodologies. Section 3 presents the results of the risk-based analysis of the operational data. Section 4 presents the results of the engineering analysis of the operational data. Section 5 contains the references.

Appendix A explains in detail the methods used for data collection, characterization, and subsequent analysis. Appendix B presents summary lists of the data. Appendix C summarizes the detailed statistical analyses used to determine the results presented in Sections 3 and 4 of the body of the report.

2. SCOPE OF STUDY

This study documents an analysis of the EDG train operational experience during 1987–1993 at U.S. commercial nuclear power plants. The analysis focused on the ability of the EDG train to start and load its associated safety-related bus for a specified mission time. For the purposes of this study, an EDG train is a diesel engine, electric generator, and the associated support subsystems necessary to power and sequence the electrical loads on the safety-related bus. Typically, two or more EDG trains constitute the onsite emergency ac power system. The EDG train boundaries, data collection, failure categorization, selection of PRAs and/or IPEs for risk-based comparison, and limitations of the study are described in this section.

The data used in this report are limited to the set of plants listed in Appendix B, Table B-1. However, among these plants, exclusions occurred as follows. For the newer plants, data started from the low-power license date. Several plants were excluded due to atypical EDG trains, lack of EDGs, or because the plants were not operational during the study period; these are identified in Appendix B. Table B-1 presents for each plant the operating utility, the EDG manufacturer, model number, the number of EDGs, and event reporting criteria.

All but one of the plant designs in this study include the capability for at least two EDG trains to supply power to the plant using independent safety-related buses. The one exception is at Millstone 1 where one EDG train and a gas turbine generator train supply ac power to the emergency ac power system. In some cases, a *swing* EDG train is used that can supply power to more than one plant (but not simultaneously) such that two plants will have a total of only three EDG trains: one EDG train dedicated to each specific plant and the third, a swing EDG system, capable of powering either plant. There are other EDG train configurations, as indicated in Table B-1. Each EDG train uses combinations of one or two diesel engines powering one ac electrical generator. The typical EDG train comprises one diesel engine per generator. In this study, two diesel engines powering one generator were considered as one EDG train.

Diesel engines used for fire pumps, specific Appendix R purposes, or non-class 1E backup generators, were not included in the study. Neither were the high-pressure core spray (HPCS) EDGs included in this study. The HPCS EDGs are a dedicated power source for the HPCS system and do not have load/shed sequencers. Because sequencers are absent in the HPCS EDG system and they have a special function, these data were not included in the study. HPCS EDGs will be included in a separate HPCS reliability report.

2.1 EDG Train

2.1.1 EDG Operating Characteristics

The EDG train is part of the standby emergency onsite ac power system and is required to be available as a reliable source of ac power in the event of a loss of normal ac power during all plant modes (operating or shutdown). Normally, each plant has two safety-related buses that power the electrical loads required for safe shutdown and emergency conditions. These buses typically receive power from either the auxiliary or startup transformers, which are powered from the main generator or offsite power. In the event of the loss of offsite power or the failure of the normal power to the individual safety-related buses, an EDG train will provide a backup source of power to its associated safety-related bus. The EDG train has sufficient capacity to power all the loads required to safely shut the plant down or supply emergency core cooling system (ECCS) loads on a loss-of-coolant accident (LOCA). Plant-specific technical specifications identify the requirements for the emergency ac power system operability under various plant conditions.

Instrumentation is provided in the control room to monitor EDG operation following an automatic start signal. Control switches are also available to control EDG operation or manually start the EDG if necessary. In addition, local manual controls are available in or near the EDG room. Generally, any automatic start of the EDG train is considered an emergency start regardless of whether the start was planned (i.e., surveillance test) or unplanned (i.e., low-voltage condition). An EDG train is required to automatically start upon indication of the following:

- A loss-of-coolant accident (safety injection signal)

- A low-voltage condition on the safety-related bus.

A safety injection signal without a loss of offsite power will automatically start the EDG; however, the EDG output breaker will not close. The EDG train will not supply power to the safety-related bus for safety injection events unless a low-voltage condition exists. The EDG will remain at rated speed and voltage with the output breaker open until manually stopped. Should a LOCA occur during loss of offsite power, the bus is first stripped of all loads (automatic load shedding), except for selected feeds for motor-operated valves, and isolated from offsite power sources before the loading sequence begins. After the bus is stripped of loads, the EDG output breaker automatically closes, and the load sequencer automatically restarts selected equipment at a preset time interval onto the affected safety-related bus.

A low-voltage condition on the safety-related bus requires automatic starting of the EDG and closing of the output breaker to supply electrical power to designated equipment on the affected bus. Should a loss of offsite power on any safety-related bus occur, the bus is stripped of loads by a load-shedding scheme. Automatic loading of the safety-related bus begins after the EDG has obtained rated speed and voltage and the EDG output breaker has closed. During an under-voltage condition, the EDG train operates independently without being in parallel with any other electrical power source. When normal power again becomes available, the EDG train can then be paralleled with the grid, unloaded, secured, and returned to standby condition.

For most testing purposes, the EDG train is manually started, brought up to speed, synchronized to the plant power system, and loaded. Normally, voltage is regulated automatically. If offsite power is lost during parallel operation with the plant electrical system, the EDG output breaker will open automatically via an under-frequency relay. The under-frequency relay protects the EDG from an over-load condition during parallel operation. The under-frequency relay opens only the output breaker and is interlocked to operate only in parallel operation. Once the output breaker has been opened by the under-frequency relay, an under-voltage condition on the affected bus will exist, causing the output breaker to reclose automatically. Operation of the EDG train from this point is similar to the loss-of-offsite-power or under-voltage condition discussed earlier.

2.1.2 EDG Support Subsystems

Support subsystems are necessary for successful EDG train operation. Instrument and control subsystems function to start, stop, and provide operational control and protective trips for the EDG. Heating and ventilation subsystems maintain the EDG room environment and supply engine combustion air. Controls for the diesel engines are a mix of pneumatic and electrical devices, depending on the manufacturer. These function to control the voltage and speed of the EDG. Various safety trips for the engine and generator exist to protect the EDG. During the *emergency start* mode of operation, some of these protective trips associated with the diesel engine are bypassed.

The cooling subsystem is a closed-loop water system integral to the engine and generator and has some external cooling medium, generally emergency service water. The lubrication oil subsystem is a closed-loop system integral to the engine and generator consisting of a sump, various pumps, and a heat exchanger. The fuel subsystem provides fuel oil from large external storage tanks, having a capacity for several days of system operation, to a smaller *day* tank for each engine. The day tank typically has capacity to operate the engine for 4 to 6 hours. Day tank fuel oil is supplied to the cylinder injectors, which inject the fuel to each individual cylinder for combustion. The engine governor maintains correct engine speed by metering the fuel oil to each cylinder injector. An air start subsystem provides compressed air to start the engine. The generator, exciter, and output breaker all function to deliver electrical power to the safety-related bus.

Automatic load shedding and sequencing controls the order and timing of emergency loads that are loaded onto the safety-related bus. The purpose of this equipment is to prevent instantaneous full loading (ECCS loads during a LOCA event) of the engine when the output breaker is closed. The load sequencer consists of at least two redundant, physically separated, and electrically isolated sets of circuitry, one set for each EDG train. Each sequencer functions independently and is associated with the sensors and safety equipment of a particular division. Each EDG train has its own independent automatic load sequencing equipment to load the generator. The load sequencer can either be a centrally located solid state configuration or a distributed sequencer with associated relays and timers located in the respective load centers on the safety-related buses. The solid state sequencer is normally used in plants designed after 1980. However, some older plants may have been backfitted with this type of sequencer. The pre-1980 plants typically have the distributed sequencer.

2.1.3 EDG Train Boundaries

The EDG train boundaries selected for this study are shown in Figure 1. These boundaries are consistent with the boundaries identified in similar studies: NUREG-1032, *Evaluation of Station Blackout Accidents at Nuclear Power Plants*[5] and NUREG-2989 (Reference 1).

The boundary of the EDG train includes the diesel engine, electrical generator, generator exciter, output breaker, load shedding and sequencing controls, EDG room heating/ventilating subsystems (including combustion air), the exhaust path, lubricating oil (with the device that physically controls the cooling medium, i.e., the nearest isolation/control valve to the EDG boundary that is actuated on a start signal), fuel oil subsystem (including all storage tanks permanently connected to the engine supply), and the starting compressed air subsystem. All pumps, valves, valve operators, the power supply breakers for the powered items, and associated piping for the above support subsystems are inside the boundary of the EDG train.

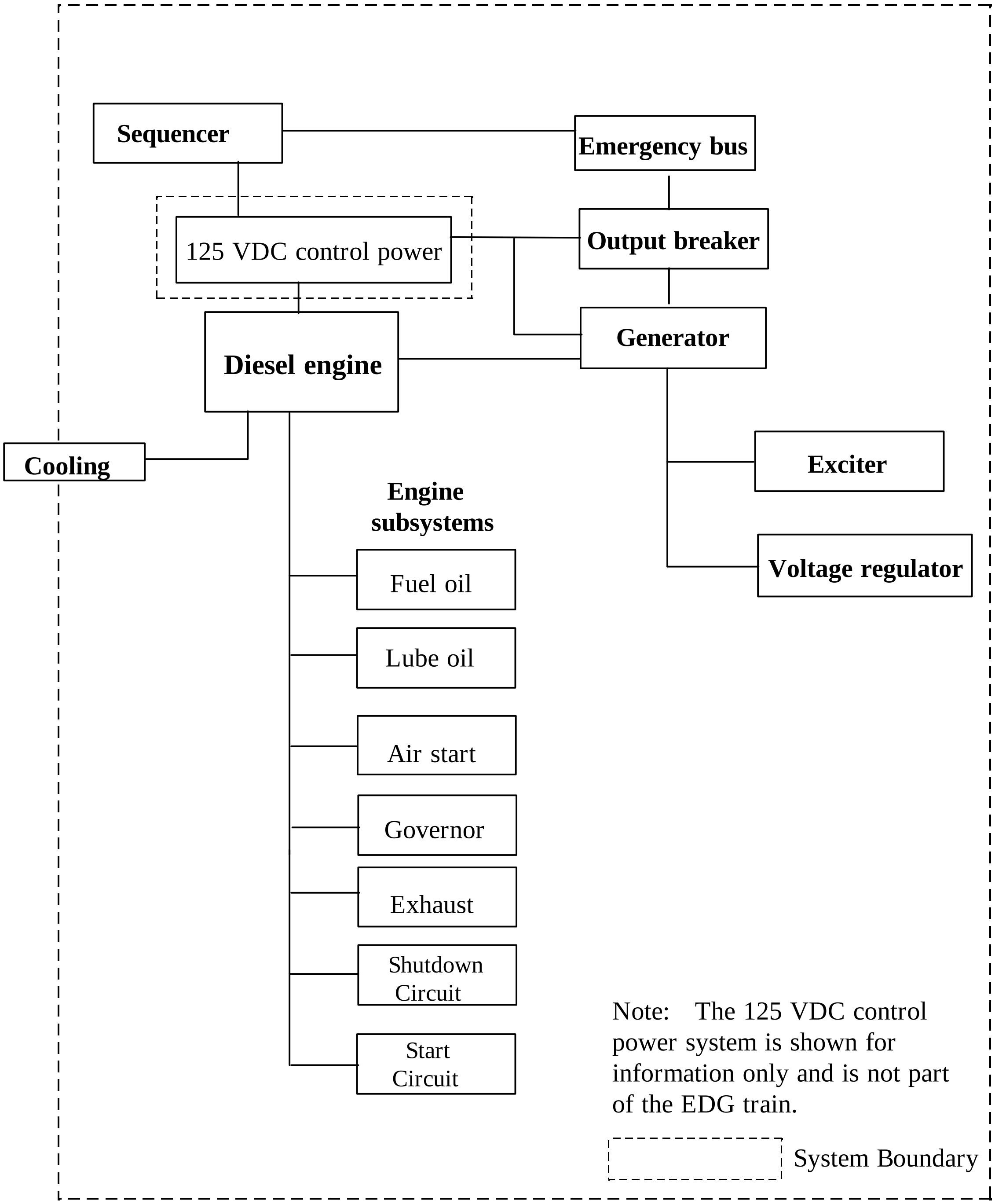


Figure 1. Simplified EDG train schematic.

2.2 Operational Data Collection

The sources of EDG train operational data used in this report are based on the LERs found using the Sequence Coding and Search System (SCSS) database, and the Special Reports found in the NRC's Nuclear Documents System (NUDOCS) database.

The SCSS database was searched for all records for the years 1987 through 1993 that identified any failure of an EDG or its associated subsystems within the system boundary defined previously in Section 2.1.3. The SCSS database was also searched for all unplanned engineered safety feature (ESF) actuations associated with the EDGs during the study period. The information encoded in the SCSS database and included in this study encompasses both actual and potential EDG failures during all plant operating conditions and testing. Differences that may exist between the plants in reporting EDG ESF actuations and failures were not considered in this report. It was assumed that every plant was reporting EDG ESF actuations and failures as required by the LER rule, 10 CFR 50.73, and in the guidance of NUREG-1022, *Event Reporting Systems 10 CFR 50.72 and 50.73.*[6] EDG events that were reported in accordance with the requirements of 10 CFR 50.72 were not used in this report because of the uncertainty associated with the completeness of the data provided in the 10 CFR 50.72 report compared to the information provided in the LER. The LER data provide a more detailed account of the event needed to determine successful operation or failure of the EDG, the associated failure mode, and the failure mechanism and cause. The 10 CFR 50.72 report generally only provides a brief description of the event and does not always contain enough data to determine failure modes or other important reliability- and risk-related information.

In addition to the LER-based SCSS data, some plants are required by Regulatory Guide 1.108 to report EDG train failures detected during testing in a Special Report. Approximately 60% of the plants are required to report EDG failures during a test in accordance with requirements provided in Regulatory Guide 1.108. The specific plants reporting in accordance with the regulatory guide are identified in Table B-1. The Special Reports provide information that is not available in the LERs. Therefore, the NUDOCS database was searched for all records that identified an EDG Special Report for the 1987–1993 study period.

Because a significant number of plants identified in Table B-1 are not required to report EDG failures in accordance with the reporting requirements identified in Regulatory Guide 1.108, not all EDG data were available for this report. The data available from the plants not reporting to Regulatory Guide 1.108 requirements result from unplanned ESF actuations and any associated failures observed during the ESF actuations [10 CFR 50.73(a)(2)(iv)], and failures that occurred as the result of a common cause mechanism [10 CFR 50.73(a)(2)(vii)]. As a result of the reporting differences, the plants reporting in accordance with Regulatory Guide 1.108 and 10 CFR 50.73 provide the most complete data source for this study; see Appendix A, Section A-2, for more details.

The information encoded in the above databases were only used to identify LERs and Special Reports for screening of EDG train failure data. The information necessary for determining reliability, such as classification of EDG failures, unplanned demands, failure modes, failure mechanisms, causes, etc., were based on an independent review, from a risk and reliability perspective, of the data provided in the LERs and Special Reports.

2.2.1 Methodology for Data Characterization

Failure Classifications—As stated above, not all EDG train events contained in the SCSS or NUDOCS databases resulted in actual failures. The term *inoperability* is used here to describe any occurrence in which the plants reported an EDG train problem either in accordance with the requirements of 10 CFR 50.73, or Regulatory Guide 1.108. The term *failure*, which is also an inoperability, is an event for which the safety function of the EDG train was lost, i.e., the EDG train did not or could not supply electrical power to safety-related loads for the required mission time. That is, the condition reported in the LER or Special Report was such that the EDG train would not have been capable of responding to a low-voltage condition on its safety-related bus.

The EDG train events identified as failures in this study represent actual malfunctions that prevented the successful operation of the EDG train. Slow engine starting times that exceeded technical specification requirements were not considered failures since facility analyses stated that a sufficient safety margin was present to preclude core damage even with a slow engine starting time. No starts greater than 19 seconds were observed in the data. Most late starts, were generally 10 or 12 seconds in duration, and were within a few seconds of the technical specification required start time. EDG train events reported as potential failures because of inadequate seismic design, environmental qualification, or other similar concerns were not considered failures. Administrative inoperabilities, such as late performance of a surveillance test, did not constitute a failure for the purposes of this report. In addition, EDG train events related to trouble-shooting activities, such as immediately after major maintenance and prior to the post-maintenance test, were not considered failures. Also, equipment malfunctions used solely for the purposes of testing the EDG and which did not affect the EDG's ability to operate, were not considered failures.

The classification of events as failures in this report differs from the failure criteria defined by Regulatory Guide 1.108. Regulatory Guide 1.108 differentiates the EDG failures by either valid or non-valid failures based on the criteria provided in the regulatory guide. Both the non-valid and valid failures are required to be reported in the Special Reports. As discussed above, the failure classification used in this report was based on the EDG train's ability to supply electrical power to safety-related loads for the required mission time. If the EDG train was capable of responding to the bus low-voltage condition, then the event reported in the Special Report was classified as an inoperability. However, if the EDG train was not capable of responding, then the event was classified as a failure.

To estimate unreliability of the EDG train, classification of the failure events by failure mode was necessary. The review of the operational data identified that when the EDG receives an automatic start signal as a result of a low-voltage condition, the EDG is required to start, obtain rated speed and voltage, close the output breaker to the affected safety-related bus, sequence required loads onto the bus, and maintain power to the bus for the duration of the mission. Failure may occur at any point in this process. As a result, the following failure modes were observed in the operational data:

- Maintenance out of service (MOOS) occurred if, because of preventative or corrective maintenance, the EDG was prevented from starting.

- Failure to start (FTS) occurred if the EDG failed to automatically start, reach rated speed and voltage, close the output breaker, or sequence the loads onto its respective safety-related bus.

- Self-initiating failure (SIF) is a special type of failure to successfully start the EDG. These failures were differentiated from the FTS events because the event that caused the demand for the EDG train also caused the EDG train to fail.

- Failure to run (FTR) occurred if at any time after the EDG successfully started delivering electrical power to its safety-related bus, the EDG failed to maintain electrical power while it was required.

- Restoration failure, reset (RFR) is an incipient failure, which occurs when emergency actuation signals are reset and a protective trip signal (e.g., low cooling water flow/discharge pressure, high vibration, etc.) to the EDG is present. This condition would result in tripping the EDG and creating a potential interruption of power. This mode does not apply to all EDGs and depends on the design of the trip reset function.

- Restoration failure, power (RFP) is an incipient failure, which occurs while attempting to restore the EDG to standby with the EDG operating in parallel with offsite power. During parallel operations, failure mechanisms exist (e.g., relevant to the performance of the voltage and speed regulators) for the EDG that are not present when the EDG is operating independent of offsite power. These failure mechanisms have the potential to trip the EDG and/or cause electrical disturbances on the electrical bus, potentially resulting in an interruption of power to the bus.

- Common cause failure (CCF) is a set of dependent failures resulting from a common mechanism in which more than one EDG train exists in a failed state at the same time, or within a small time interval.

The operational data used for this report contain events relating to the recovery of a failed EDG train or restoring ac power to the safety-related bus. Recovery of an EDG train was only considered in the unplanned demand events, since these are the types of events where recovery of power to the safety-related bus is necessary. To recover an EDG train from an FTS event, operators have to recognize that the EDG was in a failed state, manually start the EDG, and restore EDG electrical power to the safety-related bus. Recovery from an FTR was defined in a similar manner. Each failure reported during an unplanned demand was evaluated to determine whether recovery of the EDG train by operator actions had occurred. Some events identified recovery of power to the safety-related bus using off-site power when the EDG failed to respond to the bus low-voltage condition. These events were not considered a successful recovery of the EDG train because the EDG train was left in the failed state. In these events, the initiator of the bus low-voltage condition was all that was actually corrected. Further details of the failure characterization, including additional measures taken to ensure completeness and correctness of the coded data, are also included in Section A-1 of Appendix A.

Demand Classifications—For the purposes of estimating reliability, demand counts must be associated with failure counts. The first issue is the determination of what types of demands and associated failures to consider. Two criteria are important. First, each unplanned demand must reasonably approximate conditions observed during a bus low-voltage condition. Any surveillance test selected to estimate reliability needs to be at least as stressful on the train as a demand in response to a bus low-voltage situation. For this study, this requirement meant that the entire EDG train must be exercised in the test. Second, counts or estimates of the number of the demands and associated failures must be reliable. Because the criteria used for estimating the reliability of the EDG train was the ability of the EDG train to supply power to safety-related loads, unplanned demands as a result of a bus low-voltage condition and cyclic surveillance test demands (18-month or refueling outage testing) were used to estimate EDG train reliability.

For this study, an EDG unplanned demand is defined as a low-voltage condition existing on the safety-related bus that requires the EDG to provide electrical power to the affected bus with all required loads sequenced onto the bus. The mission time for the unplanned demand is the time from the start of the low-voltage condition to restoring normal electrical power to the safety-related bus. Even though an EDG may not be at design rated load for an unplanned demand, the EDG mission was assumed to be successful if it carried the required load for the given plant conditions. For example, if loss of normal power occurred on a safety-related bus and the EDG train restored ac power to the bus at 25% of full load (which is the load that was required based on plant conditions), then the EDG train was considered as successfully completing its mission.

Plant technical specifications and Regulatory Guide 1.108 require a variety of surveillance tests. The frequency of the tests are generally monthly and every operating or refueling cycle (18 months). The latter tests are referred to in this report as cyclic tests. Cyclic testing, as defined in Section C.2 of Regulatory Guide 1.108, is intended to completely demonstrate the safety function capability of the EDG train. Cyclic testing requirements simulate automatic actuation of the EDG train up through completion of the sequencer actions to load the safety-related bus. The cyclic test's 24-hour loaded run segment does not simulate an actual emergency demand, since it is performed with the EDG train paralleled with the grid rather than being in a totally independent mode. However, the data do provide important insights into the ability of the EDG train to run for extended periods of time.

A partial demonstration (e.g., monthly surveillance testing) of the EDG train's capability was not considered representative of the EDG train's performance under actual accident conditions. Surveillance testing information that does not demonstrate the EDG train's safety function completely, as would be observed during a bus low-voltage condition, was not used in the assessment of EDG train reliability. For example, the monthly testing requirements identified in Regulatory Guide 1.108 do not test the sequencer and automatic start circuitry. Because of the guidance provided in Regulatory Guide 1.108, monthly test demands do not represent the type of demand that the EDG train would experience during a low-voltage condition. As a result, monthly testing data were not used to estimate the reliability of the EDG train.

Another type of partial demonstration was identified in some unplanned ESF actuations of the EDG. Some ESF actuations resulted in starting and obtaining rated speed and voltage; however, the EDG train was not required to supply electrical power to the safety-related bus (the EDG was not loaded). These ESF actuations may have occurred either as a result of a valid or spurious safety injection signal, or human error. Events of this nature did not constitute a complete demonstration of the EDG train's safety function. Therefore, these events were excluded from the count of EDG unplanned demands.

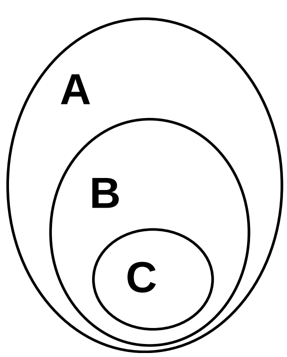
For additional details on the counting of unplanned demands and surveillance test demands, see Appendix A.

2.3 Methodology for Analyzing Operational Data

The risk-based and engineering analyses of the operational data were based on two different data sets. The Venn diagram presented as Figure 2 illustrates the relationship between these data sets. Data set A represents all the LERs and Special Reports that identified an EDG train inoperability from the above-mentioned SCSS and NUDOCS database searches. Data set B represents the inoperabilities that resulted in a loss of the safety function (failure) of the EDG train. Data set B is the basis for the engineering analysis. Data set C represents the actual failures identified from LERs and Special Reports for which the corresponding demands (both failures and successes) could be counted. As a result, data set C represents the data used in the risk-based analysis. As discussed in Section 2.2, the test demands must reasonably approximate the stress on the system that would be experienced during a bus low-voltage condition. Therefore, only the cyclic test demands and associated failures were used in data set C.

To eliminate any bias in the analysis of the failure and demand data in data set C and to ensure a homogeneous population of data, three additional selection criteria on the data were imposed: (1) the data from the plants must be reported in accordance with the same reporting requirements, (2) the data from each plant must be statistically from the same population, and (3) the data must be consistent (i.e., from the same population) from an engineering perspective. Each of these three criteria must be met or the results of the analysis could be incorrectly influenced.

As a result of these three criteria, the failure and demand data that constitute data set C were not analyzed exclusively on the ability to count the number of failures and associated demands for a risk-based mission, but also to ensure each of the above three criteria were met. Because the cyclic test data would provide a larger data set and additional run time information of the EDG, only the plants reporting EDG train failures in accordance with the requirements of Regulatory Guide 1.108 were used to provide plant-specific estimates of EDG train reliability. Therefore, the reliability analysis contained in Section 3 was performed separately for the plants reporting in accordance with Regulatory Guide 1.108. Only population estimates are calculated for those plants not reporting in accordance with Regulatory Guide 1.108.



A The EDG train was inoperable as defined by applicable technical specifications.

B The safety function of the EDG train was lost (failure).

C The safety function of the EDG train was lost (failure) and the demand count could be determined or estimated.

Figure 2. Illustration of the relationship between inoperability and failure data sets.

The purpose of the engineering analysis was to provide qualitative insights into EDG train performance, not to calculate quantitative estimates of reliability. Therefore, the engineering analysis used all the EDG train failures appearing in the operational data. That is, the engineering analysis focused on data set B which includes data set C with an engineering analysis of the factors affecting EDG train reliability. For the trending analysis and the data comparisons (e.g., between the plants, between EDG manufacturers, failure causes/mechanisms, etc.) considered in the engineering analysis, only the data from the plants reporting in accordance with Regulatory Guide 1.108 were used to ensure a consistency in the results. The only data excluded in the engineering analysis were the failures attributed to MOOS. Although the MOOS events result in the inability of the EDG train to supply power, they do not always involve an actual failure of the EDG train. However, an unplanned demand of an EDG train while maintenance was being performed on that EDG train during power operating conditions was considered in estimating unreliability.

2.4 Criteria for Selecting PRAs and IPEs for Risk Comparison

In order to put the operational performance of the EDG trains into a risk perspective, a comparison of the operational data with a representative sample of the various PRAs and IPEs was made. To ensure a representative sample of the nuclear power plant population was chosen, the following guideline elements were used to select the sample:

- A cross section of pressurized water reactors (PWRs) and boiling water reactors (BWRs)
- A cross section of nuclear steam supply system (NSSS) vendors within PWRs
- A cross section of reactor and containment design within the NSSS vendors
- A cross section of plants with respect to annual core damage frequency due to internal events
- A cross section of the major EDG manufacturers:

ALCO Power	AP
Cooper Bessemer	CB
Electro Motive (General Electric)	EM
Fairbanks Morse/Colt	FC
Nordberg Mfg.	NM
Transamerica Delaval	TD

The plants selected and the information used to make the selections are shown in Table 1. Overall, 44 plants were selected and used in the risk/reliability insights comparisons. The reliability statistics relevant to EDG train performance were extracted from the PRA/IPE reports[7-37] and comparisons to the operational information were performed. Section 3 of this report presents the results of that analysis.

Table 1. Plants selected for PRA/IPE comparison.

Plant (EDG mfg.)	NSSS	Design	Containment	CDF	Report
RG-1.108 reporting plants					
Callaway (FC)	WEST	4 Loop	Dry (3)	5.8E-5	IPE
Catawba 1 and 2 (TD)	WEST	4 Loop	Ice Cond.	4.3E-5	PRA
Clinton (EM)	GE	BWR/6	Type 5h Mark 3	2.6E-5	IPE
Farley 1 and 2 (FC)	WEST	3 Loop	Dry (3b)	1.3E-4	IPE
Grand Gulf (TD)	GE	BWR/6	Type 5h Mark 3	1.7E-5	NUREG/CR-4550
LaSalle 1 and 2 (EM)	GE	BWR/5	Type 5g Mark 2	4.4E-5	NUREG/CR-4832
McGuire 1 and 2 (NM)	WEST	4 Loop	Ice Cond.	4.0E-5	IPE
Nine Mile Point 2 (CB)	GE	BWR/5	Type 5g Mark 2	3.1E-5	IPE
Palo Verde 1, 2, and 3 (CB)	CE	2 Loop	Dry (3b)	9.0E-5	IPE
River Bend (TD)	GE	BWR/6	Type 5h Mark 3	1.6E-5	IPE
Salem 1 and 2 (AP)	WEST	4 Loop	Dry (3)	4.0E-5	IPE
Sequoyah 1 and 2 (EM)	WEST	4 Loop	Ice Cond.	1.7E-4	NUREG/CR-4550
South Texas 1 and 2 (CB)	WEST	4 Loop	Dry (3b)	4.4E-5	PRA/IPE
Susquehanna 1 and 2 (CB)	GE	BWR/4	Type 5g Mark 2	1.1E-7	IPE
Vogtle 1 and 2 (TD)	WEST	4 Loop	Dry (3b)	4.9E-5	IPE
Waterford 3 (CB)	CE	2 Loop	Dry (2e)	1.7E-5	PRA
Zion 1 and 2 (CB)	WEST	4 Loop	Dry (3b)	4.0E-6	IPE
Non-RG-1.108 reporting plants					
Arkansas 1 (EM)	B&W	2 Loop	Dry (3b)	4.7E-5	PRA summary
Beaver Valley 2 (FC)	WEST	3 Loop	Sub. Atm.	1.9E-4	IPE
Brunswick 1 and 2 (NM)	GE	BWR/4	Type 5g Mark 1	2.7E-5	IPE/PRA
Calvert Cliffs 1 and 2 (FC)	CE	2 Loop	Dry (3b)	3.0E-4	IPE
FitzPatrick (EM)	GE	BWR/4	Type 4g Mark 1	1.9E-6	IPE/PRA
Indian Point 2 (AP)	WEST	4 Loop	Dry (3)	3.1E-5	IPE
Indian Point 3 (AP)	WEST	4 Loop	Dry (3)	4.4E-5	IPE
Kewaunee (EM)	WEST	2 Loop	Dry (2e)	6.7E-5	IPE
Millstone 1 (FC)	GE	BWR/3	Type 4g Mark 1	1.1E-5	IPE
Oyster Creek (EM)	GE	BWR/2	Type 4g Mark 1	3.7E-6	PRA
Peach Bottom 2 (FC)	GE	BWR/4	Type 4g Mark 1	5.5E-5	NUREG/CR-4550
Surry 1 and 2 (EM)	WEST	3 Loop	Sub. Atm.	7.4E-5	NUREG/CR-4550

3. RISK-BASED ANALYSIS OF THE OPERATIONAL DATA

In this section, the data extracted from LERs and Special Reports for plants reporting under Regulatory Guide 1.108 requirements were analyzed in three ways. First, the EDG train unreliability is estimated for those plants reporting under Regulatory Guide 1.108 requirements. (The descriptor used to identify the failure data and estimates calculated for the Regulatory Guide 1.108 plants in this study is "RG-1.108.") The RG-1.108 estimates are analyzed to uncover trends and patterns within EDG train reliability in U.S. commercial nuclear power plants. The trend and pattern analysis provides insights into the performance of the EDG train on plant-specific and industry-wide bases. Second, comparisons are made between the RG-1.108 estimates and EDG train unreliabilities reported in the selected PRAs, IPEs, and NUREGs. The objective of the comparisons is to indicate where RG-1.108 data support or fail to support the assumptions, models, and data used in the PRAs, IPEs and NUREGs. Third, RG-1.108 plant-specific estimates are made of EDG train reliability. These estimates are compared to the plant-specific station blackout target reliabilities. For the non-RG-1.108 population of EDGs, the results of a cursory analysis and comparisons derived solely from the unplanned demand data are presented.

Twenty-nine plant risk source reports (i.e., PRAs, IPEs and NUREGs) were used for comparison with the EDG reliability results obtained in this study. For the purposes of this study, the source documents will be referred to collectively as “PRA/IPEs.” Distinctions between reference reports are noted where necessary. The information extracted from the source documents contain relevant EDG train statistics for 44 plants comprising 97 EDGs. The data represent approximately 40% of the plants and EDGs at operating nuclear power plants. Of the 44 plants, 29 plants report according to Regulatory Guide 1.108 requirements. The analysis presented in this section primarily focuses on the 29 RG-1.108 plants. The 15 non-RG-1.108 plants are evaluated in the context of the unplanned demand data reported by these plants under 10 CFR 50.73 reporting requirements.

EDG train unreliabilities were estimated using a fault tree model to combine broadly defined train failure modes such as failure to start or failure to run into an overall EDG unreliability. The probabilities for the individual failure modes were calculated by reviewing the failure information, categorizing each failure event by failure-mode and then estimating the corresponding number of demands (both successes and failures). Approximate PRA/IPE-based unreliabilities were calculated from the failure data for the start, load, run, and maintenance phases of the EDG train. The EDG train-level unreliabilities and failure probabilities extracted from the PRA/IPEs are compared to the RG-1.108 and non-RG-1.108 results. A summary of the major findings are presented here:

- The estimate of EDG train unreliability derived from unplanned demand and cyclic test data for plants reporting under Regulatory Guide 1.108 requirements was determined to be 0.044. This estimate includes recovery of EDG train failures that did not require repair and assumes an 8-hour run time of the EDG. If recovery is excluded, the estimate of an EDG train unreliability is 0.069.

- No yearly trends in EDG unreliability were apparent in the data for the 1987–1993 time frame.

- The average of the plant-specific RG-1.108-based estimates of EDG train unreliability is in agreement (approximately 13% higher) with the average of the PRA/IPE estimates assuming an 8-hour run time of the EDG. Generally, the RG-1.108-based estimate for failure-to-start and maintenance out of service probability agree with their respective PRA/IPE counterparts. However, for a 24-hour mission time for the EDG train, the PRA/IPE estimate of failure to run is approximately a factor of 30 higher than the corresponding RG-1.108-based estimate.

- Based on the mean reliability, all of the RG-1.108 plants (44) with a EDG target reliability goal of 0.95 attain the target goal, provided that the unavailability of the EDG due to maintenance is ignored. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.95 target goal is 0.987, with a corresponding uncertainty interval of

0.96, 0.99. For the RG-1.108 plants with a EDG target reliability goal of 0.975, eighteen of the nineteen RG-1.108 plants, based on the mean reliability, attain the reliability goal, provided that the unavailability of the EDG due to maintenance is ignored. The EDGs associated with the plant not achieving the 0.975 reliability goal had a mean reliability of 0.971. When uncertainty is accounted for, the EDGs at the plant not meeting the SBO target reliability have approximately a 0.54 probability of meeting or exceeding the 0.975 reliability goal. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.975 target goal is 0.985, with a corresponding uncertainty interval of 0.95, 0.99.

- The effects of maintenance unavailability on the EDG reliability is significant based on the RG-1.108 plant data. The technical basis for the Station Blackout Rule assumes that such unavailability was negligible (0.007). The estimate derived from the RG-1.108 for maintenance out of service is 0.03. Forty of the 44 RG-1.108 plants with a 0.95 target reliability attain the goal when comparing mean estimates. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.95 target goal is 0.956, with a corresponding uncertainty interval of 0.92, 0.99. For the RG-1.108 plants with a EDG target reliability goal of 0.975, none of the EDGs meet the target reliability goal. The reliability estimate for the overall population of EDGs at RG-1.108 plants with a 0.975 target goal is 0.954, with a corresponding uncertainty interval of 0.91, 0.98.

- Based on the limited failure data (i.e., unplanned demand data only) for the non-RG-1.108 plants, reliability parameters estimated for this population of EDGs tend to agree with those generated for the RG-1.108 plants. The reliability estimate (without maintenance unavailability) for the overall population of EDGs at the non-RG-1.108 plants is 0.984, with a corresponding uncertainty interval of 0.97, 0.99. Due to the sparseness of these data, the reliability estimates apply to both target reliability goals for the non-RG-1.108 plant group. The reliability estimate for the overall population of EDGs at the non-RG-1.108 plants with maintenance unavailability included is 0.958, with a corresponding uncertainty interval of 0.92, 0.98.

3.1 Unreliability Estimates Based on RG-1.108 Data

Estimates of EDG train unreliability were calculated using the unplanned demands and cyclic tests reported in the LERs and Special Reports for plants reporting under Regulatory Guide 1.108 requirements. The RG-1.108 data were used to develop failure probabilities for the observed failure modes defined in Section 2. The types of data (i.e., cyclic test and unplanned demands) used for estimating probabilities for each of the EDG failure modes are identified in Table 2.

In calculating failure rates for individual failure modes, the RG-1.108 failure data were analyzed and tested (statistically) to determine if significant variability was present in the data. All data were initially analyzed by failure mode, by plant, by year, and by source (i.e., unplanned and cyclic demands). Each data set was modeled as a binomial distribution with confidence intervals based on sampling uncertainty. Various statistical tests (Fisher's exact test, Pearson chi-squared test, etc.) were then used to test the hypothesis that there is no difference between the types and sources of data.

Table 2. RG-1.108 failure data sources used for estimating EDG-train failure mode probabilities.

	Regulatory Guide 1.108 reporting			
	Unplanned Demands		Cyclic tests	
Failure mode	failures	demands	failures	demands
Failure to start (FTS)	2	181	17	1364
Failure to run (FTR)	—	—	—	—
Early (FTR_E)	1	179	11	665
Middle (FTR_M)	—	—	15	654
Late (FTR_L)	—	—	1	639
Failure to recover from an FTS (FRFTS)	2	2	—	—
Failure to recover from an FTR (FRFTR)	0	3	—	—
Maintenance out of service (MOOS)[a] while not in a shutdown condition	3	112	—	—
Maintenance out of service (MOOS)[a] while in a shutdown condition	8	83	—	—

a. In this report, MOOS contribution to train unreliability was determined using those unplanned demand failures that resulted from the EDG being unavailable because it was in maintenance at the time of the demand.

Because of concerns about the appropriateness and power of the various statistical tests and an engineering belief that there are real differences between groups, an empirical Bayes method was used regardless of the results of the statistical tests for differences. The simple Bayes method was used if no empirical Bayes could be fitted. [For more information on this aspect of the data analysis, see Appendices A and C (Sections A-2.1 and C-1.1) for the details of the statistical approach to evaluate the RG-1.108 data]. If the uncertainty in the calculated failure rate was dominated by random or statistical uncertainty (also referred to as sampling uncertainty), then the data were pooled. If, on the other hand, the uncertainty was dominated by the plant-to-plant (or year-to-year, between unplanned and cyclic demands, etc.) variability, then the data were not pooled, and individual plant-specific failure rates were calculated based on the factor that produced the variability.

The RG-1.108 failure data from cyclic testing and unplanned demands were used to estimate the FTS and FTR probabilities. Plant-to-plant variability (i.e., statistically significant) was detected in both the FTS and FTR failure modes.

The EDG train run-time information reported in the unplanned demands generally lacked sufficient detail to make an accurate determination of run times. The available data in the unplanned demand information were not sufficient in determining if a constant failure rate existed for the EDG train. EDG train run times were generally greater than one-half hour, but the information did not allow an assessment to be made of when the EDG was secured. Therefore, one-half hour was assumed for the minimum run time during an unplanned demand. To provide better accuracy in the estimation of hourly failure rates for the FTR failure mode, data from cyclic tests were used. Even though the cyclic test data may not totally represent the EDG train start sequence during an unplanned demand, the run period of the test represents EDG train performance after a successful start. The run time information identified with the cyclic test data is the best available source of EDG run times without surveying individual plants and searching records. The run times extracted from the cyclic tests allow for better resolution of hourly failure rate estimates. Three distinct FTR failure rate regimes were identified in the RG-1.108 failure data. The corresponding run time intervals associated with these regimes were 0 to ½ hour, ½ hour to 14 hours, and 14 to 24 hours. The intervals are labeled early(FTR_E), middle(FTR_M), and late(FTR_L), respectively. An hourly failure rate estimate is calculated for the early, middle, and late run time intervals. A constant failure rate was assumed for each of these intervals. Data from the unplanned demands were used only in the early time frame.

The run times associated with the unplanned and cyclic tests vary, as do those associated with the assumptions presented in the PRA/IPEs. To allow for comparisons between unreliability estimates based on RG-1.108 data with those generated from PRA/IPEs, the hourly FTR rates derived for the three time regimes were time integrated over the mission time specified in the plant-specific PRA/IPE. This mission time adjustment normalizes the EDG train unreliability to the risk perspectives presented in the various PRA/IPEs.

For the MOOS failure mode, pooling of the unplanned demand data with cyclic test data was illogical when estimating unreliability, since the plant is unlikely to initiate an EDG test if the EDG is out of service for maintenance. Only MOOS events that occurred while the plant was not shutdown are included in the unreliability estimates. No statistical plant-to-plant variability exists for the MOOS failure mode. For this reason, only a single estimate of the mean and associated uncertainty for the overall RG-1.108 data are calculated.

Four events were identified as CCF events in the RG-1.108 failure data. All four CCF events were detected during cyclic testing. One of the CCF events occurred during the start sequence. The start sequence CCF event is included in the FTS estimates. Two CCF events occurred during the load/run segment of the test. The load/run CCF events are included in the FTR estimates. The remaining CCF event occurred while restoring the EDG to its standby condition. This CCF event that occurred after successful operation is not included in the reliability estimates. Additional discussion of the CCF events is found in Section 3.3.4 and Section 4.

Table 3 contains the probabilities and associated uncertainty intervals calculated from the RG-1.108 data for each of the failure modes. As indicated in Table 3, the probabilities of failing to recover from an FTS and FTR were quite high. Recovery probabilities were based only on the unplanned demand data. The high probabilities may be the result of the criteria used in this study. Recovery was only considered possible if the EDG could be used to restore electrical power and not offsite or normal power. The estimates are based on sparse data; therefore, only weak inferences can be made. Due to the sparseness of the recovery data, one must make conclusions about the ability to recover a failed EDG train with caution.

3.1.1 EDG Train Unreliability

The unreliabilities of the EDG train were estimated using the simple fault tree model depicted in Figure 3. The unreliability is estimated on a per EDG train or per safety-related bus basis. The train estimate is based on failure data consistent with the EDG train boundary definition defined in Section 2. The estimates of EDG train unreliability do not represent failure probability of complete loss of emergency ac power at the plant, but of an individual train. Because these calculations are for a single train, the contribution from CCFs are included in the appropriate failure mode. No system level results

Table 3. Failure mode data and Bayesian probability information based on plants reporting under Regulatory Guide 1.108 requirements.

Failure mode	Failures	Demands	Modeled variation	Distribution	Bayes mean and 90% interval
Failure to start (FTS)	19	1545	Plant to plant	Beta 0.9, 70.2	5.0E-4, 1.2E-2, 3.9E-2[a]
Failure to recover from FTS (FRFTS)	2	2	Sampling	Beta 2.5, 0.5	4.3E-1, 8.3E-1, 1.0E-0[a]
Failure to run 0–0.5 hr (FTR_E)	12	844	Plant to plant	Gamma 0.25, 9.7	4.2E-7, 2.5E-2, 1.2E-1[b]
Failure to run 0.5–14 hr (FTR_M)	15	654	Plant to plant	Gamma 0.26, 143	5.0E-8, 1.8E-3, 8.7E-3[b]
Failure to run 14–24 hr (FTR_L)	1	639	Sampling	Gamma 1.45, 5706	2.8E-5, 2.5E-4, 6.7E-4[b]
Failure to recover from FTR (FRFTR)	0	3	Sampling	Beta 0.5, 3.5	6.0E-4, 1.3E-1, 4.4E-1[a]
Maintenance out of service (MOOS) while not shutdown	3	112	Sampling	Beta 3.5, 109.5	9.7E-3, 3.1E-2, 6.2E-2[a]
Maintenance out of service (MOOS) while shutdown	8	83	Sampling	Beta 8.5, 75.5	5.3E-3, 1.0E-1, 1.6E-1[a]

a. Estimates are in units of failures per demand.

b. Estimates are in units of failures per hour.

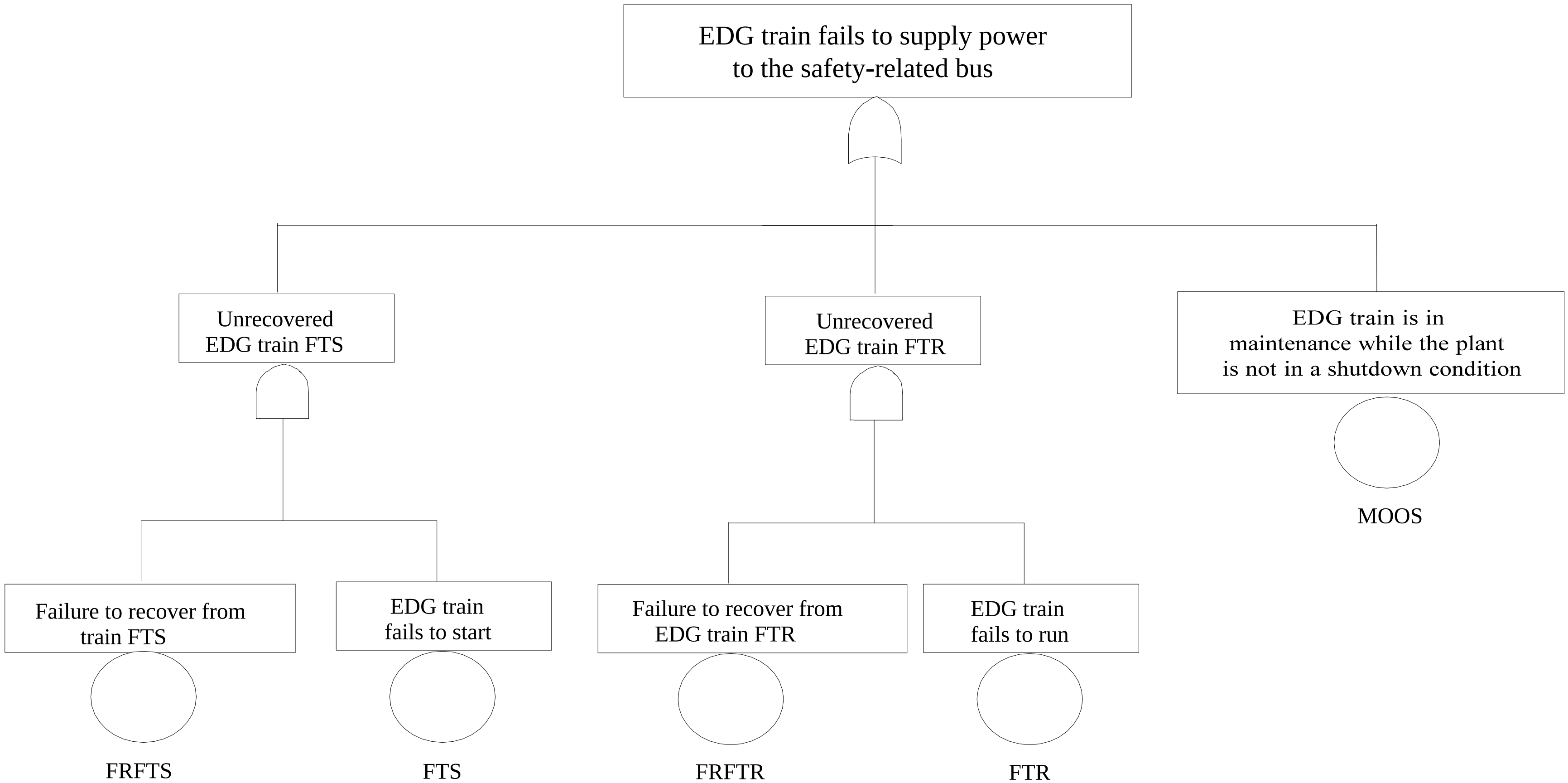


Figure 3. EDG train unreliability model with recovery actions.

are provided within this report. Therefore, the reader is cautioned to use appropriate CCF quantification techniques when calculating emergency ac power system unreliability.

Table 4 contains the estimated EDG train (safety-related bus) unreliability and associated uncertainty intervals resulting from quantifying the fault tree using the data in Table 3. Included in Table 4 are the probabilities for the logical combinations of failures resulting in an inoperable EDG train. Generally, there were three mission times assumed in the PRA/IPEs: 6, 8, and 24 hours. The FTR estimate in Table 4 is based on a mission time of 8 hours, since the 6- and 24-hour estimates of EDG train unreliability resulted in no significant change from the train unreliability estimate based on an 8-hour mission. The corresponding 6-hour estimate of EDG train unreliability and uncertainty are 0.016, 0.044, 0.082. The 24 estimates of EDG train unreliability and uncertainty are 0.16, 0.046, 0.088. Due to the *non-sensitivity* of the EDG train estimates (based on the RG-1.108 data) to the various mission times assumed in the PRA/IPEs, and to avoid reporting a voluminous amount of similar reliability information, only the 8-hour estimates are discussed in this report.

3.1.2 Investigation of Possible Trends

No trend of EDG train reliability performance by year is evident, based on the RG-1.108 data (P-value=0.75). Estimates of unreliability by year were used to identify any possible trend in EDG train reliability performance. The statistical details for the evaluation of possible trends based on time are presented in Section A-2.1.4 of Appendix A and in Appendix C. The data were normalized to calendar years to identify possible year-to-year differences. The annualized unreliabilities include the probability of recovering failed EDG trains (i.e., operator recovery of EDG train from FTS or FTR). Figure 4 trends the unreliability by calendar year.

Table 4. EDG train unreliability and uncertainty based on RG-1.108 plant data, an 8-hour mission time, and includes recovery.

Contributor	Contributor probability	Percentage contribution
FTS*FRFTS	0.01	23
MOOS	0.03	68
FTR*FRFTR	0.004	9
EDG Train Unreliability (mean)	0.044	100
90% Uncertainty Interval	0.016, 0.083	

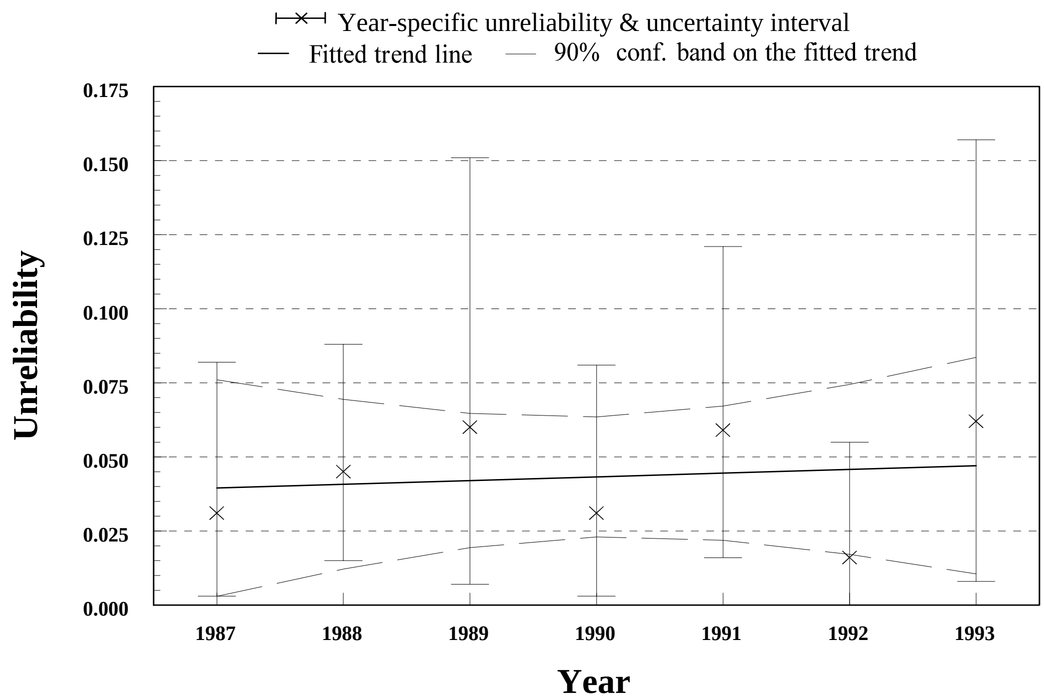


Figure 4. EDG train unreliability by calendar year, based on a constrained noninformative prior and annual data. Ninety percent Bayesian intervals and a fitted trend are included. The trend is not statistically significant (P-value=0.75).

3.2 Comparison of PRAs

The RG-1.108-based unreliabilities were compared to the results documented in the PRA/IPEs selected for this study. The PRA/IPEs encompass all EDG manufacturers as well as a cross section of PWRs and BWRs. The EDG train unreliabilities were estimated from the RG-1.108 data using the fault tree depicted in Figure 3 and include the FRFTS and FRFTR recovery events. Due to the nature of the IPE reports, fault tree models were not readily available for all plants. However, the failure data associated with quantifying the EDG unavailability were readily available in the IPEs. The fault tree models documented in the PRA/IPEs typically include explicit modeling of EDG train failures resulting from hardware faults, human errors, support systems failures, and maintenance or test unavailabilities. However, these PRA/IPE models are not consistent among themselves in explicitly defining potential failure mechanisms. For example, one PRA models human error for failing to restore an EDG train after a test, another does not. To allow comparison of PRA/IPE results to RG-1.108-based reliability parameters in the most efficient manner, only the PRA/IPE failure mode data for the EDG were used.

The averages of the PRA/IPE results for the EDG train failure modes are shown in Table 5. The information contained in Table 5 was derived solely from the plants reporting in accordance with the requirements identified in RG-1.108. Figure 5 is a plot of the plant-specific estimates derived from PRA/IPE information and the RG-1.108 estimates and associated uncertainty bands. Several IPEs did not report uncertainties, therefore, only a point estimate is provided for these plants. The information presented in Table 5 and Figure 5 are grouped according to the assumed mission times stated in the respective PRA/IPE. Further, Susquehanna reported a 72-hour mission time as part of the EDG

Table 5. Average failure probabilities derived from PRA/IPE information for the Regulatory

Guide 1.108 reporting plants and grouped by assumed mission time.

Failure mode	Plant mission time 24 Hour	8 Hour	6 Hour
FTS	1.1E-2	1.7E-2	7.0E-3
FTR probability	9.9E-2	2.0E-2	2.0E-2
FTR (per hour)	4.1E-3	2.5E-3	3.3E-3
MOOS	3.6E-2	5.3E-3	1.6E-2
Unreliability	1.5E-1	4.4E-2	4.4E-2

success criteria. The RG-1.108 values plotted in Figure 5 for Susquehanna are calculated for a 24 hour mission time. Even though the IPE stated a 72-hour mission time, the FTR estimate derived from RG-1.108 data is restricted to less than a 24-hour run time. Extrapolating the FTR probability to 72 hours was not done since the failure data was based solely on the cyclic surveillance test's 24-hour endurance run. The Palo Verde IPE utilized a 7-hour mission time as their success criteria. The RG-1.108 values for Palo Verde are based on an 8-hour mission time. The difference between the 7-hour and 8-hour estimates is negligible. The EDGs for these plants are grouped in the 24-hour and 8-hour time frames, respectively.

The PRA/IPE estimates for EDG train unreliability range from 2.3E-2 to 2.4E-1. As shown in Figure 5, the spread in the train estimates are largest for the plants with a mission time of 24 hours reported in the PRA/IPE. The plants with a stated mission time of 24 hours also exhibit the greatest variability when compared to the RG-1.108-based estimates. The average PRA/IPE estimate of EDG train unreliability for the plants that assumed a 24-hour mission time is 1.5E-1. This is approximately a factor of three higher than the estimates based on RG-1.108 data. The RG-1.108 plant-specific estimates range from 4.1E-2 to 7.0E-2 for the same population of plants. For the plants with a 6- and 8-hour mission time postulated in their PRA/IPE, generally good agreement exists between the RG-1.108 and PRA/IPE derived estimates. The average PRA/IPE estimate for 6- and 8-hour run times is 4.4E-2. This estimate compares well to the RG-1.108 estimate of 4.4E-2.

Figure 5 reveals plant-to-plant variability based on the RG-1.108 data for four of the 11 multi-plant sites. The corresponding PRA/IPE-derived estimates suggest no variability. Generally, the PRA/IPE for multi-plant sites pooled the failure data for all diesel generators at the site. A failure probability estimate was calculated from the pooled data. This estimate was then used for all the plants at the particular site, regardless of whether or not the plants had their own dedicated EDGs or if one of the plants had a higher failure rate of the EDGs compared to the other plants. Based on the intra-site variability seen in the RG-1.108 data, pooling the EDG train failure data at sites with multiple plants can mask the true performance of an individual EDG train. The Catawba, McGuire, and South Texas sites demonstrate the inter-plant variability at multi-plant sites. The plants located at these sites have their own dedicated EDG trains with no sharing of EDG trains (i.e., swing diesels). Further insights and engineering analysis of plant-specific records for the causes of this variability is provided in Section 4 of this report.

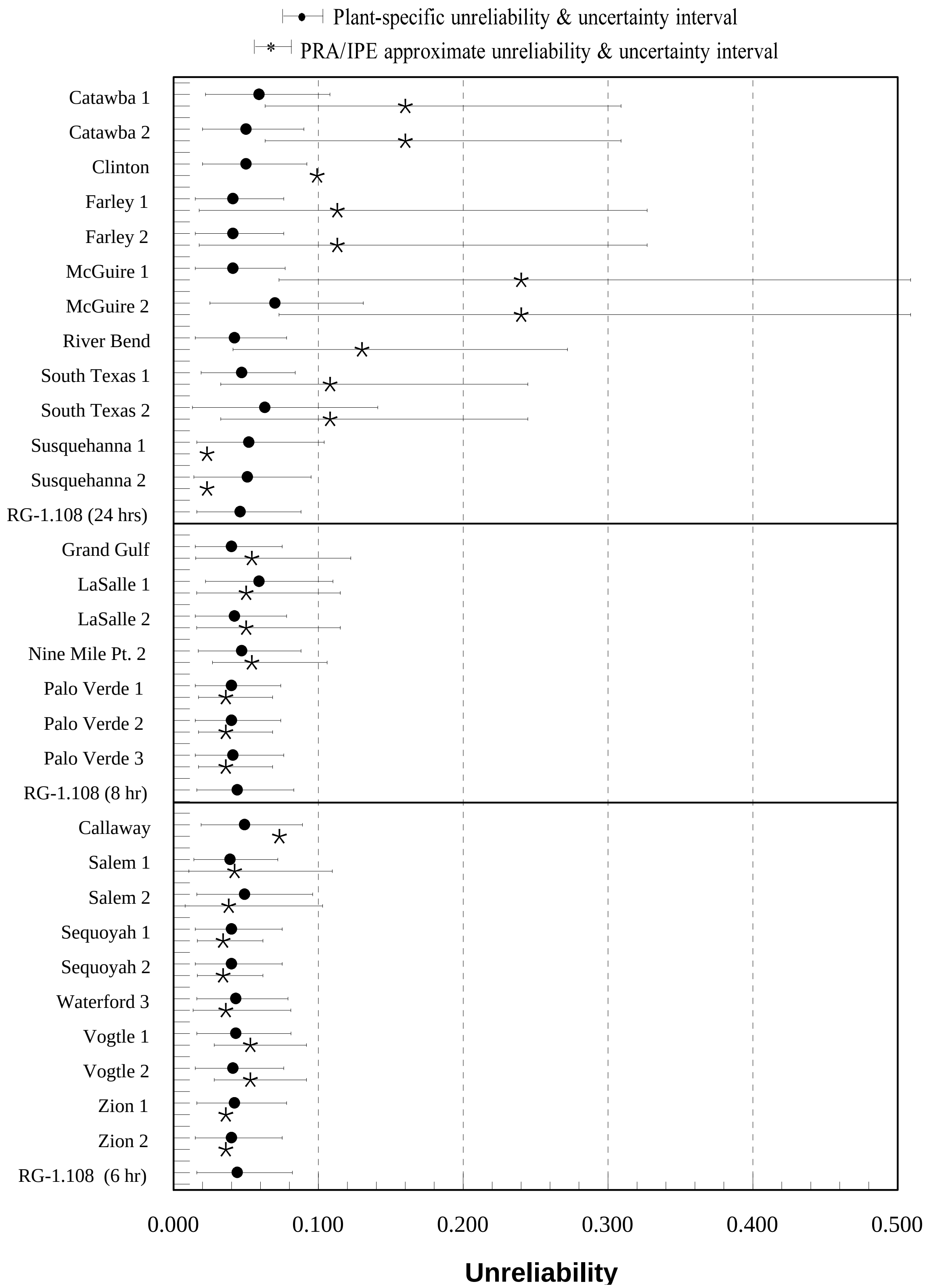


Figure 5. Plot of PRA/IPE and RG-1.108 estimates of EDG train unreliabilities and uncertainties with recovery for Regulatory Guide 1.108 reporting plants. The FTR contribution is based on the mission time stated in the PRA/IPE (with the exception of Susquehanna and Palo Verde).

3.3 Additional PRA Insights

The relative contributions to EDG unreliability by individual failure modes defined in the PRA/IPEs were compared to the estimates (without recovery) based on the RG-1.108 data. In order to make the failure mode comparisons, the following basic events identified in the PRA/IPEs for the EDG train were used:

FTS	Failure to start
FTR	Failure to run
MOOS	Maintenance out of service.

The failure probabilities for FTS and MOOS were averaged across all the plants since these failure modes and probabilities are independent of mission time. For the FTR averages, the hourly failure rates reported in the PRA/IPEs were integrated over the 6-, 8-, and 24-hour time frame, respectively, for each plant. The results for each time period were then averaged across all the plants to get a 6-, 8-, and 24-hour FTR probability for the PRA/IPE population. For example, the hourly FTR rates reported in each of the 29 RG-1.108 plants were used to calculate a 6-hour FTR probability. The results from the 6-hour calculation were then averaged across the 29 plants. Similar calculations were performed for the 8-hour average and the 24-hour average. Because of the varying degrees of information available in the PRA/IPEs and the difficulty in assigning all basic event parameters to the appropriate failure mode, providing uncertainty intervals for the EDG train failure modes was not practical. Further, the Susquehanna IPE did not differentiate between FTS, FTR, and MOOS. A single composite estimate was presented in the Susquehanna IPE for the failure of the EDG on demand. The estimate of EDG train failure probability for Susquehanna is 9.3E-2 for the "C" diesel and 2.3E-2 for the remaining diesels, and represents the probability that the EDG completes its assigned mission (i.e., start, loads, and runs for 72 hours). Because no separate failure probabilities are presented for FTS, FTR, or MOOS in the Susquehanna IPE, only the RG-1.108 plant-specific estimate is shown for these failure modes.

The failure mode averages derived from the PRA/IPEs and the corresponding estimates based on RG-1.108 data are presented in Table 6. The estimates provided in Table 6 do not include the effects of recovery. The percentage contribution (in parenthesis) for the FTS, FTR, and MOOS failure probability to the total train unreliability are based on an 8-hour mission. Based on the PRA/IPE

Table 6. Failure probabilities calculated for 6-, 8-, and 24-hour mission times, based on failure rates reported in PRA/IPEs and on the estimates calculated from the RG-1.108 data without recovery.

Failure mode		PRA/IPE average	RG-1.108 estimate
FTS		1.2E-2 (**20**%)	1.2E-2 (**17**%)
FTR			
	6-hour	2.2E-2	2.3E-2
	8-hour	2.8E-2 (**46%**)	2.6E-2 (**38**%)
	24-hour	1.3E-1	4.0E-2
MOOS		2.1E-2 (**34**%)	3.1E-2 (**45**%)
	Total	6.1E-2	6.9E-2

averages, the FTS, FTR, and MOOS failure modes contribution to EDG train failure probability are 20, 46, and 34%, respectively. For the RG-1.108 estimates, the FTS, FTR, and MOOS contributes 17,38, and 45%, respectively, to the overall EDG train unreliability. The contributions based on PRA/IPE data are generally in good agreement with those based on the RG-1.108 data. The MOOS contribution derived from the

PRA/IPE information is lower than the contribution based on RG-1.108 data. Further failure mode details are provided in the following sections.

3.3.1 Failure to Start

The FTS failure probability (without recovery) based on the RG-1.108 data is 1.2E-2 per demand. The lower 5% and upper 95% uncertainty bounds for this estimate are 5.0E-4 and 3.8E-2, respectively. Plant-to-plant variability was statistically identified; hence, an individual failure probability estimate for FTS is calculated for each of the plants reporting under Regulatory Guide 1.108 requirements. The PRA/IPE probability estimates of FTS range from 2.9E-3 to 3.0E-2, with an average of 1.2E-2. A comparison of the PRA/IPE mission time specific averages for the 6-, 8-, and 24-hour PRA/IPE plants resulted in 7.0E-3, 1.7E-2, and 1.1E-2 per demand, respectively (see Table 5). A plot of the PRA/IPE and RG-1.108 estimates of FTS probability is provided in Figure 6.

3.3.2 Failure to Run

Analysis of the RG-1.108 data identified three distinct failure rates for the EDG run time failures. The failure function correlated to a early time frame (i.e., less than one-half hour), a middle time frame (half hour to 14 hours), and a late time frame (14 to 24 hours). Failure probability estimates of FTR were calculated for each of these time frames. The failure probabilities were then transformed into a hourly failure (See Appendix A, Section A-2.1.5 for further details). The hourly failure rates, based on the RG-1.108 data (without recovery) for these time frames are 2.5E-2, 1.8E-3, and 2.5E-4 per hour, respectively. In comparison to the PRA/IPE information, approximately 80% of the PRA/IPEs reviewed for this report used a single hourly failure rate for the entire mission time. The average failure rate for these PRA/IPEs is 5.9E-3 per hour. The remaining PRA/IPEs differentiated between less than one hour and greater than one hour failure rates. The average failure rate based on the less than hour PRA/IPE data is 1.1E-2 per hour. The greater-than-one-hour average failure rate based on the PRA/IPE data is 2.3E-3 per hour.

The plant-specific estimates of FTR probability were calculated for the respective mission times postulated in the PRA/IPE. The mission times postulated in PRA/IPE accidents were 6, 8, and 24 hours. Susquehanna assumed a 72-hour mission time, but details on how this was factored into the EDG unreliability estimate are not available. The RG-1.108 values for Susquehanna are calculated for a 24 hour mission time. Even though the IPE stated a 72-hour mission time, RG-1.108 data is restricted to less than a 24-hour run time. Extrapolating the FTR probability to 72 hours was not done since the failure data was based solely on the cyclic surveillance test's 24-hour endurance run. The Palo Verde IPE utilized a 7-hour mission time as their success criteria. The RG-1.108 values for Palo Verde are based on an 8-hour mission time. The difference between the 7-hour and 8-hour estimates is negligible. The EDGs for these plants are grouped in the 24-hour and 8-hour time frames, respectively. Figure 7 presents a plot of the plant-specific FTR probabilities for 6, 8, and 24 hour mission times using the PRA/IPE and RG-1.108 data. For all three mission times, the PRA/IPEs typically result in higher FTR probabilities. The average PRA/IPE contribution of FTR to EDG train unreliability based on plants with a mission time of 6 hours is approximately 45%. For PRA/IPEs with

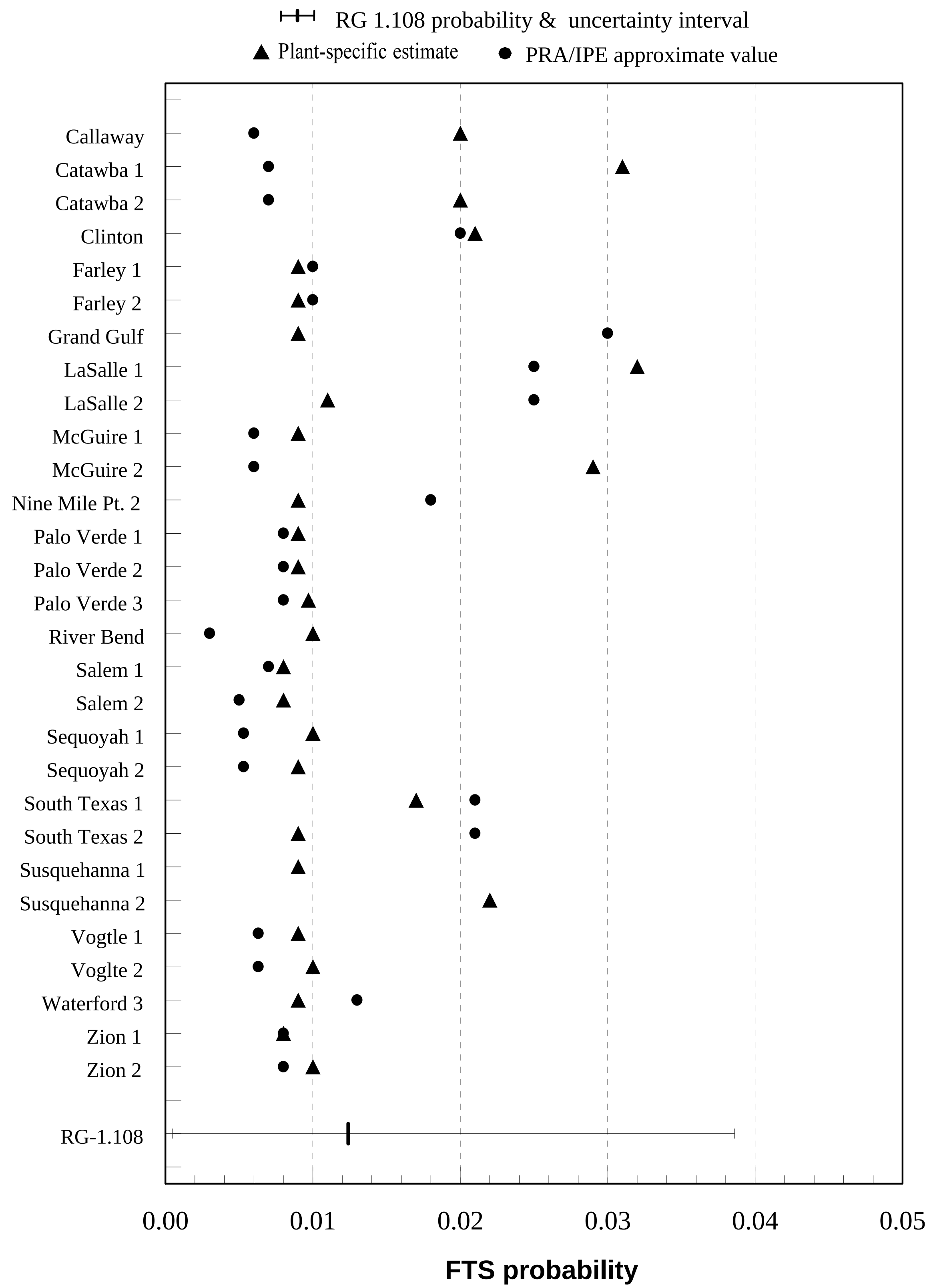


Figure 6. Plot of PRA/IPE and RG-1.108 estimates of failure to start probabilities without recovery for the Regulatory Guide 1.108 reporting plants.

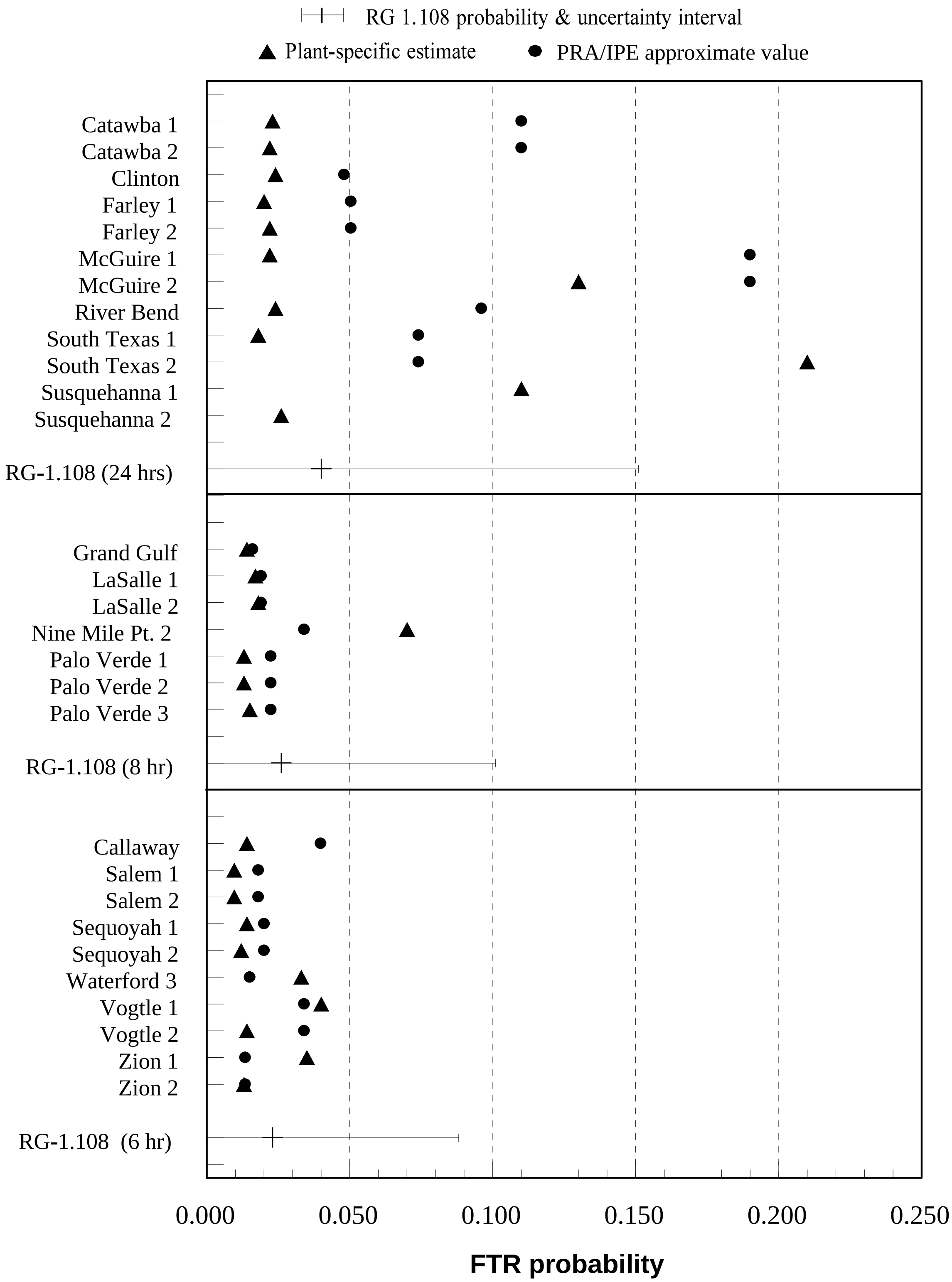


Figure 7. Plot of PRA/IPE and RG-1.108 estimates of failure to run probabilities without recovery for the Regulatory Guide 1.108 reporting plants. The FTR probability is based on the mission time stated in the PRA/IPE (with the exception of Susquehanna and Palo Verde).

a mission time of 8 hours, the average contribution to EDG train unreliability due to FTR failure mode is approximately 45%. Similarly, the average contribution from FTR for plants with mission times of 24 hours is 66% of the total EDG train unreliability reported in the PRA/IPEs (The percentages were calculated from the information provided previously in Table 5). The 6-, 8-, and 24-hour FTR contributions to EDG train unreliability based on RG-1.108 estimates are 35%, 38%, and 48%, respectively.

3.3.3 Maintenance Out of Service

The MOOS failure probability was estimated from the RG-1.108 data for two cases: (1) unplanned demands while the plant was in a shutdown condition, and (2) unplanned demands while the plant was not in a shutdown condition. For the “shutdown” case, the plant was either in a hot shutdown, refueling, or cold shutdown status. For the “not shutdown” case, the plant was either in a startup, power operation, or hot standby status. The EDG train estimates of unreliability contained in this report are based on the MOOS data corresponding to a “not shutdown” condition at the plant. Even though the train estimates were calculated assuming that the greatest risk for the plant is while the plant is not shutdown, plant conditions (i.e., decay heat) immediately following shutdown may be similar to the plant operating status. For these instances, the shutdown risk can be high. The estimate based on the RG-1.108 data for MOOS while the plant is shutdown is 1.0E-1. This estimate is a factor of three higher than the estimate for the “not shutdown” case.

The MOOS contribution is a dominant contributor to EDG train unavailability based on both the PRA/IPE information (34%) and RG-1.108 estimates (45%). The PRA/IPE average failure probability for MOOS is 2.1E-2 per demand compared to the RG-1.108 estimate of 3.1E-2. The MOOS failure probabilities found in the PRA/IPEs generally range from 1.2E-3 to 5.2E-2 per demand. The uncertainty range of the RG-1.108 estimate is 9.7E-3 to 6.2E-2. The RG-1.108 data used for the MOOS estimate show no statistical evidence of plant-to-plant variability.

Figure 8 presents a plot of the MOOS estimates based on the PRA/IPE and RG-1.108 data. A point of interest in Figure 8 is that approximately 25% of the PRA/IPE data lie below the lower 5% uncertainty limit for the RG-1.108 data. The PRA/IPE data for these EDGs come from the plants with a 7- to 8-hour mission time. The average value for these plants is about 5.3E-3, which is about a factor of 5.8 lower than the RG-1.108 average. One must be cautious when comparing MOOS estimates of the RG-1.108 to the PRA/IPE estimates. Risk analysis generally accounts for MOOS probability as an unavailability estimate. The RG-1.108 estimate of MOOS is based on the contribution to EDG train unreliability. While these two methods of estimating system performance should produce equivalent results (based on large samples), they are not precisely the same.

3.3.4 Common Cause Failure

Common cause failures (CCF) of the EDGs can be an important contributor to core damage frequency (CDF), particularly for boiling water reactors where station blackout accident sequences often dominate the CDF. However, the analysis presented in this report is not performed in the context of a full PRA. Instead, it concentrates on the performance of a single EDG train. Because emergency ac power is a support system that provides power to other systems, typically on a train basis (i.e., train-A ac power supports the A-train of other systems, and train-B ac power supports the B-train of other systems), the multiple trains of ac power are typically modeled separately. CCFs across multiple trains of ac power are important in the context of the overall plant risk, but not so important in the context of mission requirements for an individual train. It is the train level that is the focus of the present study.

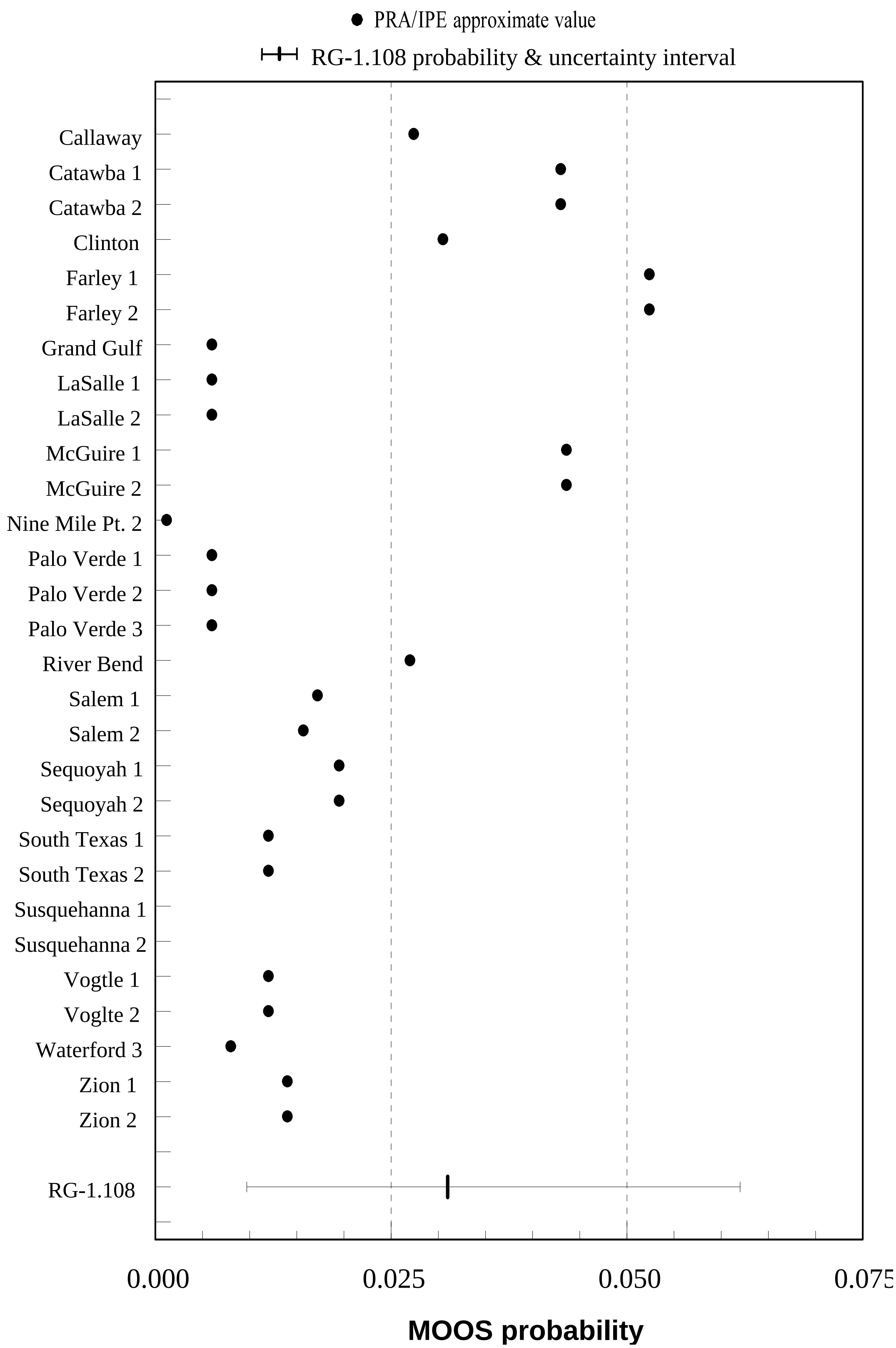


Figure 8. Plot of PRA/IPE and RG-1.108 estimates of maintenance out of service probabilities for Regulatory Guide 1.108 reporting plants.

The estimates of EDG train unreliability based on the RG-1.108 data implicitly include the contribution from CCF. That is, all CCF failures are attributed to a specific failure mode (i.e., FTS, FTR, and MOOS) identified in Figure 3. The failure mode probabilities were estimated regardless of whether they resulted in a single EDG failing or multiple EDGs failing. However, it is possible to separate out the CCFs to estimate the probability of multiple EDG train failures. Because of the various EDG configurations, different techniques for modeling CCF, and the general lack of detailed information in the PRA/IPEs, an in-depth analysis of the RG-1.108 data and comparison to PRA/IPEs is not performed here. Only cursory level CCF statistics are presented. The primary focus of this section will be on the CCF information contained in the RG-1.108 data. Estimates are presented of the CCF probability based on the RG-1.108 data to provide the information for conducting additional CCF analysis. The estimates provided herein represent the failure probability per demand of multiple trains attributable to CCF. Do not confuse the estimates provided herein with any of the parametric methods of modeling CCFs based on fractions of all failures attributed to CCF (e.g., Beta factor, Multiple Greek Letter, etc.). That is, in the nomenclature of CCF methodologies, the basic CCF parameter is estimated directly, not through the use of an intermediate estimator such as a Beta factor or Alpha factor.

The four CCF events included in the RG-1.108 data occurred during 297 cyclic testing demands (These are equated to multiple train demands and differ from the single-train demands listed in Tables 2 and 3). No CCF events occurred in the 39 unplanned demands identified for the RG-1.108 plants. Simultaneous testing of the EDGs is not feasible during a plant's routine cyclic test. As a result, if multiple EDG trains failed because of a CCF, they would not necessarily be detected at the same time. However, since the cyclic test will in fact demonstrate the performance of all EDGs (just not simultaneously), events involving multiple EDGs failures during this time period (i.e., refueling outage) are potential CCF candidates. Additionally, only those failure events involving a similar failure mechanism of the EDG train are considered CCF. Four CCF events were identified (one FTS, two FTR, and one restoration failure of offsite power [RFP]) in the cyclic test data. These events are identified in Table B-5 of Appendix B. A probability estimate and associated 90% uncertainty interval were derived by empirical Bayes techniques based on the four CCF events and 336 demands. The estimation resulted in a lower bound, mean, and upper bound of 4.1E-3, 1.2E-2, and 2.4E-2 (per demand), respectively.

Various EDG configurations exist across the industry. Approximately 63% of the plants have a two-EDG train configuration. The one CCF event identified as FTS occurred at a plant with a two-EDG train configuration. The two CCF events identified as FTR occurred in plants with EDG configurations involving more than two EDGs. One of the FTR events occurred at a plant with three dedicated EDGs. The other FTR event occurred at a plant with five swing EDGs available. The FTS and FTR failures caused by CCF are included in the appropriate failure mode estimates defined in Table 3. The remaining CCF event identified as RFP occurred at a plant with a two-EDG configuration. Since this failure mode is not part of the EDG train model depicted in Figure 3, the failure data associated with this event are not included in the estimate of EDG train unreliability.

3.4 Summary of Unplanned Demand Data for Non-RG-1.108 Plants

As explained in Section 2, the plants not reporting under Regulatory Guide 1.108 requirements do not report independent test failures in the LERs. Because of this, the data for this population of plants were not pooled with the RG-1.108 plant data (cyclic test and unplanned demand). However, EDG failures during unplanned demands are reported. To provide insights into the performance of EDG trains at the non-RG-1.108 plants, reliability estimates were calculated from the unplanned demand data identified for this population of plants. The estimates are calculated for the population of non-RG-1.108 plants as a whole. No plant-specific estimates were calculated owing to the sparseness of the information for the individual failure modes. Table 7 presents the estimates calculated from the unplanned demand data for the non-RG-1.108 plants.

The non-RG-1.108 estimates for FTS and MOOS (while not shutdown) generally agree with the RG-1.108 estimates presented in Table 3. The most noticeable difference in the estimates is the "Maintenance out of service (MOOS) while shutdown" failure mode. This failure mode was statistically identified as being different between the RG-1.108 and non-RG-1.108 plants. There were only eight failures in 83 demands for the RG-1.108 plants compared to the 21 failures in 82 demands for the non-RG-1.108 plants.

The estimates of EDG train unreliability and associated 90% uncertainty interval based on the unplanned demand data for the non-RG-1.108 population are shown in Table 8. The estimate includes the recovery failure modes and the contribution of "MOOS while not shutdown." The unreliability estimates for the RG-1.108 plants (see Table 4) based on cyclic test and unplanned demand data are included in Table 8 for comparison.

Plant-specific estimates of EDG train unreliability derived from the PRA/IPE information for the non-RG-1.108 plants are plotted along with the population estimates calculated from non-RG-1.108 unplanned demand data in Figure 9. The PRA/IPE information for the 15 non-RG-1.108 plants were grouped by 6-, 8-, and 24-hour mission times and averages calculated for each group. The PRA/IPE averages for the various mission time groupings and failure modes are presented in Table 9. PRA/IPE differences between the RG-1.108 and non-RG-1.108 EDGs are apparent when comparing Table 9 and Table 5 information.

Table 7. Failure mode data and non-informative Bayesian probability estimates based on unplanned demands at plants not reporting under Regulatory Guide 1.108 requirements.

Failure mode	Failures	Demands	Distribution	Bayes mean and 90% interval[a]
Failure to start (FTS)	2	152	Beta 2.5, 150.5	3.8E-3, 1.6E-2, 3.6E-2
Failure to recover from FTS	1	2	Beta 1.5, 1.5	9.7E-2, 5.0E-1, 9.0E-1
Failure to run (FTR)	1	151	Beta 1.5, 150.5	1.2E-3, 9.9E-3, 2.6E-2
Failure to recover from FTR	1	1	Beta 1.5, 0.5	2.3E-1, 7.5E-1, 1.0E-0
Maintenance out of service (MOOS) while not shutdown	2	93	Beta 2.5, 91.5	6.2E-3, 2.7E-2, 5.8E-2
Maintenance out of service (MOOS) while shutdown	21	82	Beta 21.5, 61.5	1.8E-1, 2.6E-1, 3.4E-1

a. All estimates are in units of failures per demand.

Table 8. EDG train unreliability estimates (includes recovery and an 8-hour mission time) and associated 90% uncertainty interval for the RG-1.108 and non-RG-1.108 plants.

Plant group	Unreliability mean and 90% interval
Non-RG-1.108	1.6E-2, 4.2E-2, 7.7E-2
RG-1.108	1.6E-2, 4.4E-2, 8.3E-2

Table 9. Failure mode average estimates derived from PRA/IPE information for the non-RG-1.108 plants and grouped by assumed mission time as stated in the PRA/IPE.

	Plant mission time		
Failure mode	24-Hour	8-Hour	6-Hour
FTS	5.6E-3	7.0E-3	1.3E-2
FTR (probability)	5.5E-2	1.8E-2	1.4E-2
FTR (per hour)	2.3E-3	2.3E-3	2.3E-3
MOOS	3.6E-2	2.2E-2	2.4E-2
Unreliability	6.4E-2	4.7E-2	4.7E-2

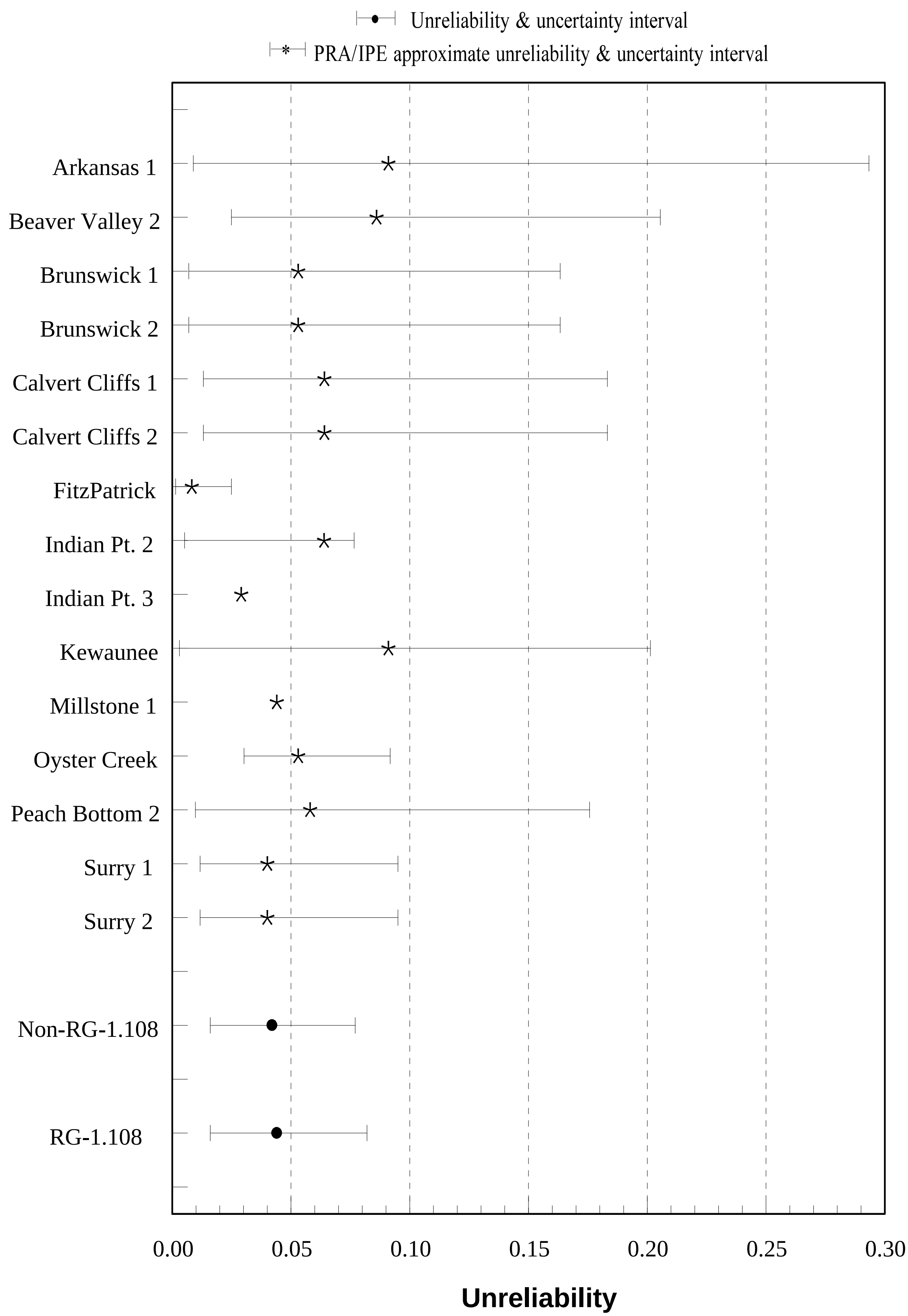


Figure 9. Non-RG-1.108 and RG-1.108 estimates of EDG train unreliability (includes recovery and an 8-hour mission time) as compared with the PRA/IPE derived estimates.

3.5 Station Blackout Insights

Station blackout accidents at commercial nuclear power plants are significant contributors to the likelihood of core damage. The impacts of station blackout at nuclear power plants have been identified in PRAs and further analyzed as an Unresolved Safety Issue. Technical findings related to the Station Blackout Unresolved Safety Issue are documented in NUREG-1032, Reference 5 of this report. The U.S. NRC Station Blackout Rule[36] addressed the need to maintain highly reliable emergency ac power systems to control the risk from station blackout accidents. To ensure the availability of emergency ac power for the loss-of-offsite-power events, NRC established reliability goals (Regulatory Guide 1.155[37]) for the EDG trains that supply emergency ac power to safety-related buses. In this section, the performance of the EDG trains, as calculated from the RG-1.108 plant data, are compared to the EDG target reliability goals set by Regulatory Guide 1.155.

Plant-specific reliabilities and associated uncertainties were estimated using plant-specific FTS and FTR probability estimates and uncertainties based on the RG-1.108 data. The RG-1.108 MOOS estimate and associated uncertainties were used for all evaluations, since statistical analysis identified no plant-to-plant variability in the MOOS data. A mission time of eight hours was used in the EDG reliability calculations.

NUREG-1032 identified the ability to restore a failed EDG to an operable condition as being important when analyzing station blackout risk. To provide a *best* estimate of EDG reliability, the recovery probabilities for failure to start and failure to run (see Table 3 for failure probability estimates of recovery) are integrated into the RG-1.108-based estimates of EDG train reliability.

The impact of MOOS during an unplanned event provides insight into the significance of this failure mode on the ability of the EDG train to perform its mission during a station blackout event. NUREG-1032 estimated the impact from maintenance and testing unavailability to be small (0.006). MOOS failures are a contributor to the unreliability of the EDG during an unplanned demand. The reliabilities with MOOS included are displayed separately in the following sections of this report to illustrate the effects of MOOS on EDG train reliability. The MOOS contribution to EDG train of reliability is based solely on the MOOS failures observed while the plant was not in a shutdown condition (i.e., MOOS failures observed while the plant was shutdown were excluded).

3.5.1 EDG Target Reliability 0.95

The RG-1.108 plants having an EDG target reliability of 0.95 are displayed in Table 10 along with the estimates of reliability and associated 90% uncertainty intervals based on the RG-1.108 data. Estimates are provided with and without the effects of MOOS. Table 10 also presents the probability of each plant’s EDG train meeting or exceeding the target reliability goal (i.e., that percentage of the reliability distribution lying to the right of 0.95). The probability specified is the degree of belief of at least attaining the target reliability goal. For example, Arkansas 2 has a mean reliability (with MOOS) of 0.959. The probability of a EDG train reliability meeting or exceeding the target goal of 0.95 is 0.72; in other words, there is about a 72% probability that the plant's EDG trains actually exceed the target reliability goal.

Based on the mean estimate, all of the RG-1.108 plants with a EDG target reliability goal of 0.95 attain the EDG target goal when MOOS is ignored. The overall estimate for the population of EDGs at RG-1.108 plants with a 0.95 target goal is 0.987, with a corresponding uncertainty interval of 0.958, 0.999. The EDGs associated with these RG-1.108 reporting plants have a 97% chance of meeting or exceeding the 0.95 target goal when MOOS is ignored.

The effect of MOOS on the EDG's ability to meet the target goal when the plant is not shutdown is significant. The overall estimate for the population of EDGs at RG-1.108 reporting plants with a 0.95 target goal is 0.956, with a corresponding uncertainty interval of 0.92, 0.98. The probability of meeting or exceeding the target reliability goal of 0.95 for this population of RG-1.108 EDGs is about 67%.

3.5.2 EDG Target Reliability 0.975

The RG-1.108 reporting plants having a EDG target reliability of 0.975 are displayed in Table 11 along with the mean reliability and associated 90% uncertainty intervals. Estimates of EDG reliability are presented with and without the effects of MOOS. Table 11 also presents the probability of each plant's EDG meeting or exceeding the target reliability goal (i.e., that percentage of the reliability distribution lying to the right of 0.975).

Based on the mean estimate, 18 of the 19 RG-1.108 plants having a EDG target reliability goal of 0.975 attain the target goal when the contribution of MOOS is ignored. The EDGs associated with the plant not achieving the 0.975 reliability goal had a mean reliability of 0.971. However, when uncertainty is accounted for, the EDGs at the plant not meeting the SBO target reliability have approximately a 0.54 probability of meeting or exceeding the 0.975 reliability goal. The estimate for the overall population of EDGs at RG-1.108 reporting plants with a 0.975 target goal is 0.985, with a corresponding uncertainty interval of 0.953, 0.999. The EDGs targeted with a 0.975 reliability for the RG-1.108 plants have a 80% chance of meeting or exceeding the 0.975 target goal when MOOS is ignored.

As shown for the 0.95 target reliability EDGs, the effects of MOOS on a plant's ability to meet its EDG target goal is significant. For the RG-1.108 reporting plants with a 0.975 EDG target goal, none achieve the goal based on the mean with MOOS contribution included in the reliability estimates. The estimate for the overall population of EDGs at RG-1.108 plants with a 0.975 target goal is 0.954, with a corresponding uncertainty interval of 0.913, 0.984. The probability of meeting or exceeding the target reliability goal of 0.975 for this population of RG-1.108 EDGs is about 17%.

Table 10. Reliability estimates (includes recovery and an 8-hour mission time), including 90% uncertainty bounds, for RG-1.108 plants with an EDG reliability goal of 0.95.

	Reliability (R_{EDG})without MOOS				Reliability (R_{EDG}) with MOOS			
Plant name	Lower 5% bound	Mean	Upper 95% bound	Probability of R_{EDG} meeting or exceeding 0.95	Lower 5% bound	Mean	Upper 95% bound	Probability of R_{EDG} meeting or exceeding 0.95
Arkansas 2	0.968	0.990	1.000	0.991	0.923	0.959	0.985	0.722
Braidwood 1	0.969	0.990	1.000	0.992	0.924	0.959	0.985	0.729
Braidwood 2	0.947	0.980	0.998	0.939	0.907	0.950	0.981	0.549
Browns Ferry 2	0.952	0.985	0.999	0.956	0.912	0.954	0.984	0.631
Byron 1	0.932	0.973	0.996	0.868	0.895	0.943	0.978	0.443
Byron 2	0.970	0.990	1.000	0.993	0.925	0.960	0.985	0.733
Catawba 1	0.930	0.972	0.997	0.859	0.893	0.942	0.978	0.437
Catawba 2	0.953	0.982	0.998	0.960	0.912	0.951	0.981	0.580
Clinton	0.950	0.981	0.998	0.950	0.910	0.950	0.981	0.565
Comanche Peak 1	0.969	0.990	1.000	0.992	0.924	0.959	0.985	0.729
Comanche Peak 2	0.959	0.986	0.999	0.973	0.917	0.956	0.984	0.662
Diablo Canyon 1	0.962	0.987	0.999	0.980	0.919	0.957	0.984	0.678
Diablo Canyon 2	0.955	0.982	0.998	0.966	0.913	0.952	0.981	0.590
Farley 1	0.972	0.991	1.000	0.995	0.926	0.960	0.985	0.745
Farley 2	0.970	0.990	1.000	0.993	0.925	0.960	0.985	0.735
Fermi 2	0.948	0.978	0.996	0.941	0.908	0.948	0.978	0.512
Grand Gulf	0.971	0.991	1.000	0.994	0.925	0.960	0.985	0.738
Haddam Neck	0.970	0.990	1.000	0.992	0.924	0.960	0.985	0.731
Harris	0.971	0.991	1.000	0.994	0.925	0.960	0.985	0.741
Hatch 1	0.973	0.991	1.000	0.995	0.926	0.960	0.985	0.749
Hatch 2	0.968	0.990	1.000	0.990	0.923	0.959	0.985	0.719
Hope Creek	0.977	0.993	1.000	0.998	0.929	0.962	0.986	0.777
Limerick 1	0.961	0.985	0.998	0.983	0.918	0.954	0.981	0.631
Limerick 2	0.952	0.984	0.999	0.956	0.912	0.954	0.984	0.627
McGuire 1	0.970	0.990	1.000	0.993	0.925	0.960	0.985	0.735
McGuire 2	0.913	0.964	0.994	0.758	0.879	0.934	0.975	0.331
North Anna 1	0.972	0.991	1.000	0.995	0.926	0.960	0.985	0.749
North Anna 2	0.970	0.990	1.000	0.993	0.925	0.960	0.985	0.735
Palo Verde 1	0.972	0.991	1.000	0.995	0.926	0.960	0.985	0.743
Palo Verde 2	0.972	0.991	1.000	0.995	0.926	0.960	0.985	0.749
Palo Verde 3	0.969	0.990	1.000	0.992	0.924	0.959	0.985	0.726
Perry	0.969	0.990	1.000	0.992	0.924	0.959	0.985	0.729
River Bend	0.969	0.990	1.000	0.991	0.924	0.959	0.985	0.724
San Onofre 2	0.972	0.991	1.000	0.995	0.926	0.960	0.985	0.747
San Onofre 3	0.973	0.991	1.000	0.996	0.927	0.961	0.985	0.753
Summer	0.972	0.991	1.000	0.995	0.926	0.960	0.985	0.743
Turkey Point 3	0.971	0.991	1.000	0.994	0.925	0.960	0.985	0.737
Turkey Point 4	0.970	0.990	1.000	0.992	0.924	0.960	0.985	0.731
Vogtle 1	0.961	0.987	0.999	0.978	0.918	0.956	0.984	0.671
Vogtle 2	0.969	0.990	1.000	0.991	0.924	0.959	0.985	0.724

Table 10. Cont.

Plant name	Reliability (R_{EDG}) without MOOS: Lower 5% bound	Mean	Upper 95% bound	Probability of R_{EDG} meeting or exceeding 0.95	Reliability (R_{EDG}) with MOOS: Lower 5% bound	Mean	Upper 95% bound	Probability of R_{EDG} meeting or exceeding 0.95
Wash. Nuclear 2	0.965	0.988	0.999	0.987	0.921	0.958	0.984	0.696
Wolf Creek	0.951	0.984	0.999	0.953	0.911	0.953	0.983	0.612
Zion 1	0.966	0.989	0.999	0.989	0.922	0.958	0.984	0.706
Zion 2	0.969	0.990	1.000	0.992	0.924	0.959	0.985	0.729

3.5.3 EDG Train Reliability Comparisons to NUREG-1032

The EDG train reliability parameters used in NUREG-1032 (Reference 5) and the corresponding RG-1.108 estimates of these parameters are presented in Table 12. The estimates calculated in NUREG-1032 are based on the information contained in NUREG/CR-2989 (Reference 1) and NSAC/108 (Reference 4). The RG-1.108-based estimate assumes an 8-hour run time, includes recovery, and includes the contribution from MOOS while the plant is not in a shutdown condition. The parameters are averaged over an 8-hour mission time. The *High* and *Low* parameters for the RG-1.108 plants correspond to the upper 95% and lower 5% Bayes interval calculated from the RG-1.108 data. The significance of the parameter differences are discussed below.

The NUREG-1032 and RG-1.108 failure to start parameters differ by a factor of 2. The disparity in the parameters is due to the effects of maintenance unavailability. Appendix B of NUREG-1032 specifies that the failure to start mode includes the likelihood of the EDG to start and load, the unavailability resulting from scheduled and unscheduled maintenance, and the unavailability of support systems. The failure probability resulting from MOOS (while the plant is not shutdown) is included in the RG-1.108-based parameters for the failure to start probability. MOOS is included to be consistent with NUREG-1032 assumptions for the EDG train reliability analysis.

The findings reported in NUREG-1032 identified that unavailabilities resulting from test and maintenance are not large contributors to system unavailability. Regulatory Guide 1.155 specifies that the effect of maintenance and testing on emergency ac power system unavailability can be significant. However, it further states that the typical unavailability resulting from maintenance and testing (0.007) is small compared to the minimum EDG target reliabilities. Regulatory Guide 1.155 concludes that as long as the maintenance and testing unavailabilities do not differ significantly from 0.007 the EDG target reliabilities would result in acceptable overall reliability of the emergency ac power system. Based on the RG-1.108 data, the effect of maintenance on EDG train reliability is significant. Only 64% of the RG-1.108 reporting plants meet the minimum EDG target reliability goals when MOOS failures while not shutdown are included in the EDG unreliability estimates.

Table 11. Reliability estimates (includes recovery and an 8-hour mission time), including 90% uncertainty bounds, for plants with an EDG target reliability goal of 0.975.

	Reliability (R_{EDG}) without MOOS				Reliability (R_{EDG}) with MOOS			
Plant name	Lower 5% bound	Mean	Upper 95% bound	Probability of R_{EDG} meeting or exceeding 0.975	Lower 5% bound	Mean	Upper 95% bound	Probability of R_{EDG} meeting or exceeding 0.975
Callaway	0.951	0.981	0.998	0.733	0.910	0.951	0.981	0.113
Cook 1	0.969	0.990	1.000	0.909	0.924	0.959	0.985	0.211
Cook 2	0.970	0.990	1.000	0.919	0.925	0.960	0.985	0.217
LaSalle 1	0.926	0.971	0.997	0.540	0.890	0.941	0.978	0.078
LaSalle 2	0.966	0.989	1.000	0.891	0.922	0.958	0.985	0.201
Millstone 3	0.971	0.991	1.000	0.928	0.925	0.960	0.985	0.223
Nine Mile Pt. 2	0.952	0.984	0.999	0.785	0.912	0.953	0.983	0.157
Salem 1	0.975	0.992	1.000	0.948	0.928	0.961	0.986	0.239
Salem 2	0.938	0.981	0.999	0.725	0.901	0.950	0.984	0.161
Seabrook	0.955	0.985	0.999	0.809	0.914	0.954	0.984	0.164
Sequoyah 1	0.969	0.990	1.000	0.912	0.924	0.959	0.985	0.213
Sequoyah 2	0.970	0.990	1.000	0.921	0.925	0.960	0.985	0.218
South Texas 1	0.961	0.985	0.998	0.825	0.918	0.954	0.981	0.131
South Texas 2	0.924	0.976	0.999	0.648	0.890	0.946	0.984	0.142
St. Lucie 1	0.961	0.987	0.999	0.848	0.918	0.956	0.984	0.174
St. Lucie 2	0.952	0.981	0.998	0.738	0.911	0.951	0.981	0.114
Susquehanna 1	0.954	0.984	0.999	0.794	0.913	0.954	0.983	0.156
Susquehanna 2	0.947	0.980	0.998	0.706	0.907	0.950	0.981	0.110
Waterford 3	0.961	0.987	0.999	0.851	0.919	0.956	0.984	0.175

Table 12. EDG train reliability parameters identified in NUREG-1032 and the corresponding estimates based on RG-1.108 data.

Parameter		NUREG-1032	RG-1.108-based
Failure to start (per demand)	Average	0.02	0.041
	High	0.08	0.095
	Low	0.005	0.010
Failure to run (per hour)	Average	0.0032	0.0033
	High	0.01	0.013
	Low	0.001	less than 1E-6
Reliability (per demand)	Average	0.98	0.956
		Range 0.9, 1.0	Uncertainty 0.92, 0.98

The average EDG train reliability reported in NUREG-1032 is better than the RG-1.108-based estimate (0.98 compared to 0.96). This better performance primarily results from the small contribution of maintenance and testing unavailability estimated for the NUREG-1032 study. Owing to the small contribution, the importance of MOOS is overshadowed by the failure to start and/or run contributions. The impacts on core damage frequency from station blackout as a function of EDG reliability is documented in NUREG/CR-5994, Emergency Diesel Generator: Maintenance and Failure Unavailability, and Their Risk Impacts.[38] NUREG/CR-5994 concludes that for a factor of 3 increase in the average maintenance unavailability, the resultant impact on core damage frequency is not significant. However, NUREG/CR-5994 states that for plants with a maintenance unavailability of 0.04 the increased change in CDF can be about 1.0E-5 (assuming no reduction or improvement is received on the failure to start and/or run unavailability resulting from the increased maintenance). The MOOS estimate derived from the RG-1.108 data is 3.1E-2. This is greater than a factor of 4 more than the 0.007 estimate used in the Regulatory Guide 1.155 analysis. Further, the RG-1.108 estimate for MOOS failure probability is approaching 0.04.

3.5.4 SBO Reliability for the Non-RG-1.108 Plants

The reliability estimates for the non-RG-1.108 plants are based solely on the unplanned demand data, including recovery and the effects of MOOS while the plant is not shutdown. The non-RG-1.108 failure mode estimates presented in Table 7 were used in the reliability calculations. Owing to the sparseness of the data for most of the failure modes, only sampling variation was modeled in the statistical analyses. Therefore, no plant-specific estimates for EDG train reliability were calculated for the non-RG-1.108 plants. Table 13 presents the estimates for the non-RG-1.108 EDGs with respect to the station blackout target goals. The reliability estimates of the EDG train for the non-RG-1.108 is the same for both the 0.95 and 0.975 EDGs owing to the non-informative Bayesian estimates calculated.

The effects of MOOS on the EDG train reliability for the non-RG-1.108 plants is significant. There is a 99% chance of the non-RG-1.108 EDGs meeting the 0.95 station blackout target reliability without MOOS. When MOOS is included, there is only a 71% chance. For the 0.975 non-RG-1.108 EDGs, there is about a 85% chance without MOOS as compared to only a 19% chance with MOOS.

Table 13. Station blackout target reliability estimates (includes recovery and an 8-hour mission time), including 90% uncertainty bounds, based on the non-RG-1.108 unplanned demand data.

Maintenance unavailability included	EDG train reliability (R_{EDG})	90% uncertainty	Probability that R_{EDG} reliability is at least 0.95	Probability that R_{EDG} reliability is at least 0.975
No	0.984	0.966, 0.996	0.99	0.85
Yes	0.958	0.923, 0.984	0.71	0.19

TABLE 1 TABLE 2TABLE 3TABLE 4TABLE 5TABLE 6TABLE 7TABLE 8TABLE 9TABLE 10TABLE 11TABLE 12TABLE 13

FIGURE 1FIGURE 2FIGURE 3FIGURE 4FIGURE 5FIGURE 6FIGURE 7FIGURE 8FIGURE 9

4. ENGINEERING ANALYSIS OF THE OPERATIONAL DATA

This section documents the results of an engineering evaluation of the EDG train operational data derived from LERs and Special Reports. The data include 353 EDG train failures and 195 unplanned demands. The quantitative analysis presented in this section of the report is limited to the data provided by the plants reporting in accordance with Regulatory Guide 1.108. Data from the plants not reporting in accordance with the regulatory guide were used only to obtain additional insights or to perform qualitative analysis of the types of failures and failure mechanisms observed at these plants.

The engineering data analysis opens qualitative insights into the performance of the EDGs throughout the industry and on a plant-specific basis. These qualitative insights characterize the factors contributing to the quantitative estimates of EDG reliability presented previously in Section 3. The reader is cautioned when comparing the individual plant data to the reliability estimates provided in Section 3. A plant-specific estimate derived solely from the failure data at a particular plant may result in a different estimated unreliability than an estimate derived from the population as a whole, especially when the data are sparse. In addition, the effects of recovery and mission time will influence any comparisons to the results shown in Section 3. See Appendix A for additional information into the effects of performing group-specific investigations.

The results of the engineering evaluation are as follows:

- Trending analysis of the failure and unplanned demand rate data indicate no statistically significant trend in either rate over the 7 years of the study period. However, the smallest numbers of both failures and unplanned demands for any given year occurred in 1993.

- The EDG train failures that occurred during unplanned demands and directly contributed to unreliability were typically electrical related. These failure events were primarily the result of hardware malfunctions and appear to have been difficult for operators to diagnose and recover. The typical recovery time for these events using offsite power was 2 hours. In addition, because of the design of the EDG sequencer circuitry, a single fault in the circuitry causes a demand for and subsequent failure of the EDG train. These sequencer-induced demands and subsequent failures result in a loss of power to the associated safety-related bus, and present difficulties for the plant operators in recovering power to the safety-related bus. The sequencer faults are most likely to occur during shutdown maintenance activities.

- The EDG train failures that occurred during cyclic surveillance tests that directly contributed to unreliability were either the result of electrical-related failures, or leaking or loose components.

    1. The electrical-related failures primarily contributed to the FTS probability, and comprised hardware-related malfunctions of the EDG governor, voltage regulator, and sequencer.

    2. The failures that resulted from either leaking or loose components dominated the FTR probability. No one component within any subsystem clearly dominated the failures; however, the leaking or loose components were primarily the result of errors associated with maintenance (improper assembly of the components) and either vibration or wear induced fatigue failure. In addition, over two-thirds of these failures occurred after one-hour of EDG operation, and therefore would not have appeared on the monthly tests owing to the short run time of the monthly test as compared to the cyclic test's endurance run.

3. Three distinct EDG fail to run rates were found based on the cyclic surveillance test data. The failure rate during the first half-hour was 2.5E-2 per hour. The failure rate decreased sharply to 1.8E-3 per hour for the period between 0.5 hours and 14 hours. For periods greater than 14 hours, the failure rate again decreased to 2.5E-4 per hour.

4. The number of failures found during monthly testing of the EDG trains was 78, and the number of failures found during cyclic testing was 44. Given that there are approximately 18 times the number of monthly tests performed than cyclic tests, the expected number of failures are not consistent assuming monthly and cyclic tests are comparable. In addition, fewer failures classified as failures to run were found during the monthly tests (22) than the cyclic tests (27). The reason the number of monthly surveillance test failures is low in comparison to the number of cyclic surveillance test failures is apparently owing to the completeness (i.e., 24-hour endurance run) of the cyclic test as compared to the monthly test.

5. Approximately one-third of the failures detected during the performance of surveillance tests affect restoration of the EDG to standby operating conditions. In many cases, these restoration failures will cause a trip of the EDG during the restoration of normal power.

- Transamerica Delaval and Cooper Bessemer represent 38% of the EDGs in use at the commercial nuclear plants reporting EDG failures in accordance with the requirements identified in Regulatory Guide 1.108; however, these manufacturers account for 58% of the total number of failures. The reason these two manufacturers contributed to a majority of the EDG failures is apparently owing to the large number of instrumentation and controls subsystem failures associated with these manufacturers as compared to the other manufacturers. In addition, the Cooper Bessemer EDGs experienced a significant number of failures in the fuel, electrical and engine mechanical subsystems as compared to the other manufacturers.

- Analysis of plant-specific unreliability by low-power license date indicate no statistically significant trend. Analysis of plant-specific EDG failure rate by low-power license date does indicate a statistically significant trend. The trend indicates that the plants with low-power license dates from 1980 to 1990 typically had an EDG failure rate greater than those plants with a low-power license date prior to 1980. The trend observed by low-power license date for the EDG failure rates requires further analysis to determine the cause of the trend. Information provided in the LERs was not sufficient to determine the reason for the trend.

The following discussion documents the review of the operational data. Specifically, this review includes (a) an analysis of the operational data for trends and patterns in system performance across the industry and at specific plants; (b) identification of the subsystems, components, and causes that resulted in EDG train failure; (c) a comparison of the failure mechanisms found during surveillance tests and unplanned demands; (d) analysis of the failures for the effects of aging; and (e) a review of Accident Sequence Precursor (ASP) events related to the EDG system.

4.1 Industry-wide Evaluation

4.1.1 Trends by Year

Table 14 lists the number of EDG train failures and unplanned demands that occurred in the industry for each year of the study period. Figures 10 and 11 plot the failures and unplanned demands for each year of the study with 90% uncertainty intervals. Included with each figure is a fitted trend line and a 90% confidence band for the fitted trend.

As shown in Figures 10 and 11, trending analysis of the failure and unplanned demand rate indicate no statistically significant trend in either rate over the 7 years of the study period. However, the smallest number of events for any given year occurred in the 1993.

Table 14. EDG failures and unplanned demands by year.

Category	1987	1988	1989	1990	1991	1992	1993	Total
Failures	34	77	57	51	61	53	20	353
Unplanned demands	28	30	30	25	32	29	21	195

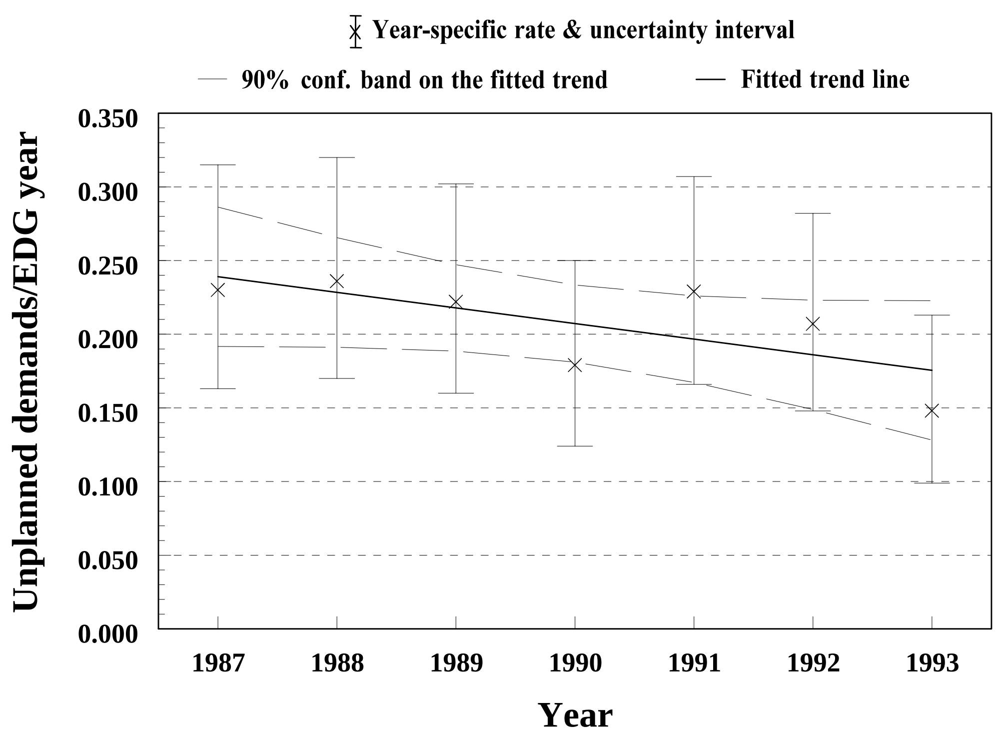


Figure 10. EDG unplanned demands per EDG-year with 90% confidence intervals and fitted trend. The trend is not statistically significant (P-value=0.08).

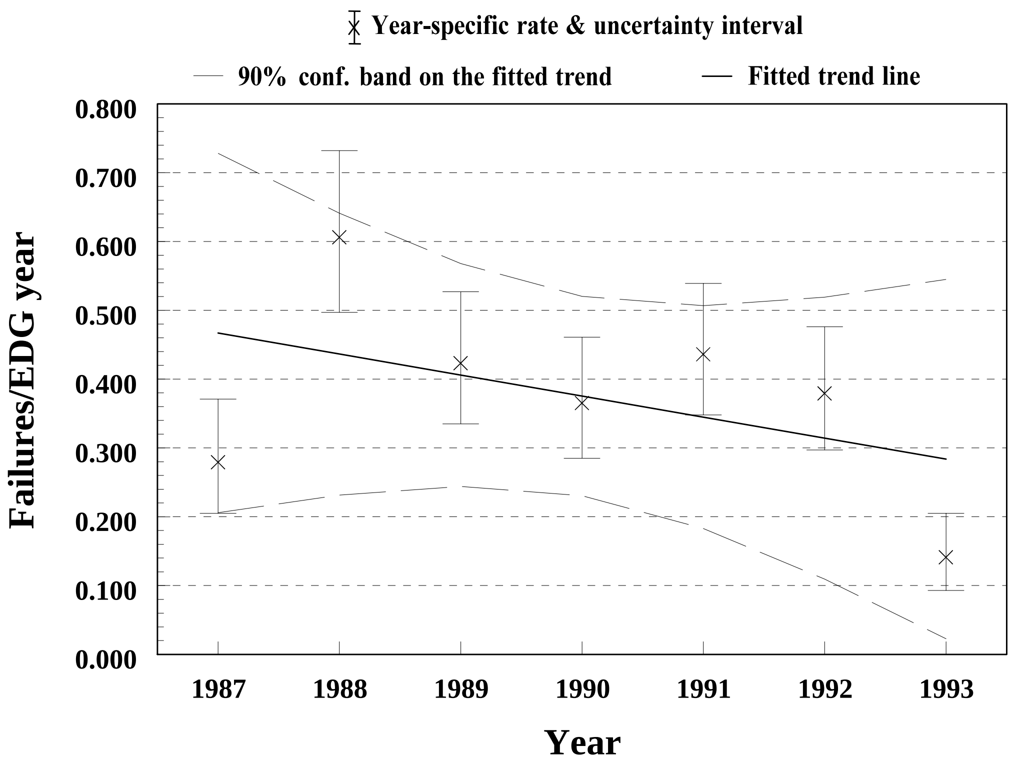


Figure 11. EDG failures per EDG-year with 90% confidence intervals and fitted trend. The trend is not statistically significant (P-value=0.30).

4.1.2 Factors Affecting System Reliability

The EDG train failures were reviewed to determine the factors affecting overall train reliability. To focus the review, the failures were partitioned by method of discovery for each subsystem. The methods of discovery are unplanned demands, surveillance tests, and "other." The "other" category consists of failures found from plant tours, control room annunciators or indications, design reviews, etc. The three subsystems with the highest contribution to the overall EDG train failures were further partitioned by the component within the subsystem that actually failed. Table 15 summarizes the failures by method of discovery. Figure 12 is a histogram of the data provided in Table 15 normalized by percent contribution.

In addition to the data analysis discussed above, the EDG train failures were partitioned by the three dominant failure modes, FTS, FTR, and restoration failure (RF), to determine if a difference exists and to evaluate the differences. The results of this data partition are presented in Table 16, and Figure 13 is a histogram of the data presented in Table 16 normalized by percent contribution. The self-initiated failure (SIF) failure mode was evaluated with the FTS failure mode because of the small number of failures contributing to this mode; the CCF events are reviewed in Section 4.5 of this report (Definitions of the RF and SIF failure modes are provided in Section 2.2.1).

Table 15. Number of EDG train failures by method of discovery.

	Method of discovery							
Subsystem	Overall		Unplanned demands		Surveillance tests		Other	
Fuel	93	—	0	—	68	—	25	—
Governor	—	51	—	0	—	39	—	12
Leaks	—	12	—	0	—	9	—	3
Other fuel-related failures	—	30	—	0	—	20	—	10
Electrical	85		6		65		14	—
Voltage regulator	—	55	—	0	—	44	—	11
Output breaker	—	18	—	0	—	16	—	2
Sequencer	—	6	—	4	—	2	—	0
Generator	—	4	—	0	—	3	—	1
Other electrical related	—	2	—	2	—	0	—	0
failures	—	—	—	—	—	—	—	—
Start and shutdown instrument and	93		2		62	—	29	—
controls (I&C)					—		—	—
Automatic trip circuit	—	73	—	2	—	53	—	18
Normal control circuit	—	13	—	0	—	5	—	8
Other controls related	—	7	—	0	—	4	—	3
failures	—	—	—	—	—	—	—	—
Lubrication oil	18	—	0	—	13	—	5	—
Cooling	26	—	0	—	16	—	10	—
Engine	20	—	0	—	13	—	7	—
Air start	17	—	0	—	9	—	8	—
EDG room heating and ventilation (HVAC)	1	—	0	—	1	—	0	—
Total	353	—	8	—	247	—	68	—

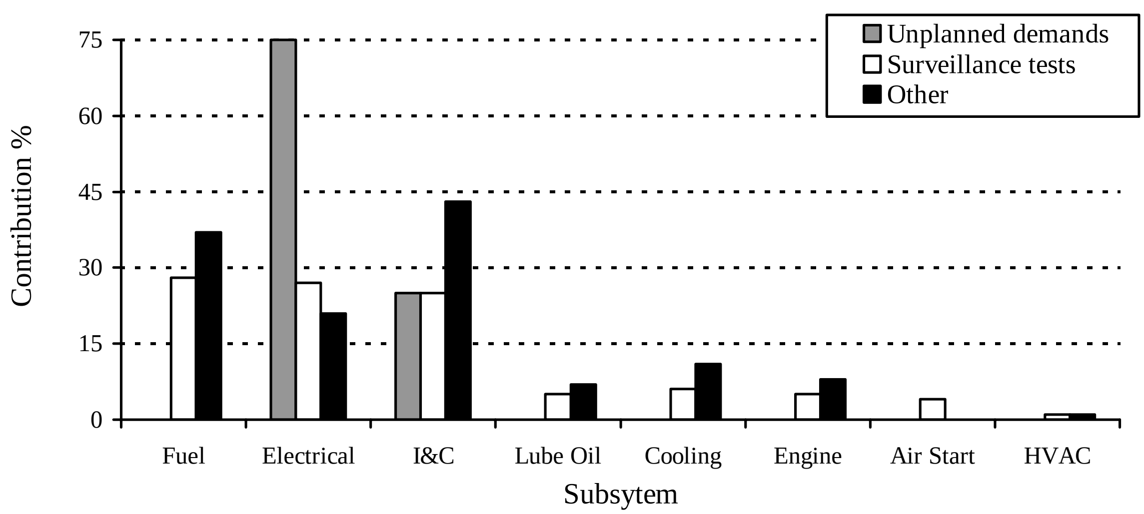


Figure 12. Histogram of EDG subsystem failures by method of discovery, normalized by percent contribution.

Table 16. Number of EDG subsystem failures by failure mode.

Subsystem	Failure mode FTS		FTR		RF	
Fuel	45	—	29	—	19	—
Governor	—	30	—	5	—	16
Leaks	—	0	—	12	—	0
Other fuel-related failures	—	15	—	12	—	3
Electrical	45		17		23	
Voltage regulator	—	26	—	12	—	17
Output breaker	—	11	—	1	—	6
Sequencer	—	6	—	0	—	0
Generator	—	2	—	2	—	0
Other electrical-related failures	—	0	—	2	—	0
Start and shutdown instrument and controls	29	—	4	—	60	—
Automatic trip circuit	—	16	—	2	—	55
Normal control circuit	—	11	—	1	—	1
Other controls-related failures	—	2	—	1	—	4
Lubricating oil	4	—	7	—	7	—
Cooling	2	—	18	—	6	—
Engine mechanical	1	—	14	—	5	—
Air start	15	—	2	—	0	—
EDG room heating and ventilation (EDG HVAC)	0	—	0	—	1	—
Total	141	—	91	—	121	—

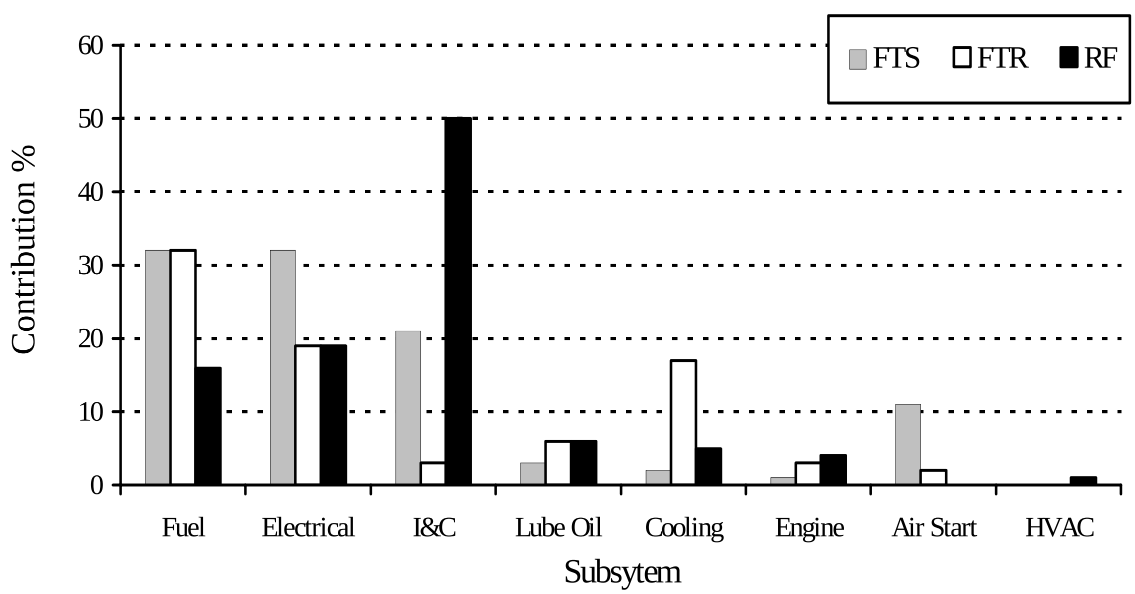


Figure 13. Histogram of EDG subsystem failures by failure mode, normalized by percent contribution.

Overall Findings. Three subsystems dominated the EDG train failures: fuel, electrical, and start/shutdown instrumentation and controls. These subsystems accounted for 77% of the failures, with each subsystem contributing approximately equally. The governor, voltage regulator, and automatic trip circuit were the significant component contributors to the three dominant subsystem groups respectively.

The cause of most of the failures is attributed to hardware malfunctions, a majority of which were electrical-related failures of fuses, relays, and contacts. The second leading cause is personnel error. This latter group comprises mostly problems associated with procedures or administrative errors during maintenance activities.

Unplanned Demands. A total of eleven failures occurred during an unplanned demand, eight of which were used to determine the contribution of unplanned demand failures to overall unreliability presented in Section 3. The remaining three failures contributed to the SIF failure mode; these three were not used in the unreliability calculations presented in Section 3.

Of the eight failures contributing to unreliability, three were classified as MOOS events, three as FTR events, and two as FTS events. The FTR events occurred during a loss of offsite power, and the FTS events occurred during a plant-centered loss of a single 4160-vac vital bus. For most of these events, power was restored to the vital bus within a short period of time, typically less than 30 minutes. However, for only the FTR events was power restored by the EDG; for the FTS events, power was restored to the vital bus by restoration of normal power. This is mostly likely the result of the cause of the initial demand for the EDG to supply emergency power, and not the result of the type or mechanism of the EDG failure. That is, the FTR events occurred in conjunction with a loss of offsite power, where restoration of the EDG was the most expeditious recovery action for plant operators. For the events in which a loss of a single bus in conjunction with a failure of the EDG to start occurred, the most expeditious recovery action was by restoring power from the normal source.

The three FTR events were caused by problems associated with the instrumentation and controls (2), and electrical (1) subsystems. Two were the result of hardware failures and one was the result of personnel error. In the two hardware-related failures, a root cause was not identified in the LER; only speculation of the apparent cause was given. In both of these cases, the EDG tripped during a loss-of-offsite-power event, and after troubleshooting (in one case for 2.5 hours) the EDG was restarted without any corrective maintenance actions taken. The most likely cause was intermittent actuation of temperature and pressure switches in the automatic shutdown circuits. The personnel error was the result of performing a ground isolation evolution on a running EDG during a loss-of-offsite-power event. The procedure was intended for use when offsite power was available.

The two FTS events observed in the unplanned demand data were the result of a failure in the electrical and shutdown instrument and controls subsystems. Both of the failures were hardware-related. One was the result of timer "drift" in the sequencer, which prevented the EDG train from loading the vital bus. The second failure was the result of a false low lubrication oil pressure signal caused by air and sediment in the sensing lines.

There were three instances that an EDG was out of service for maintenance during an unplanned demand used to determine the MOOS contribution to EDG unreliability presented previously in Section 3. In each case one EDG was not available to power its safety-related bus owing to maintenance. It is uncertain from the LERs the reason for the maintenance (i.e., corrective or preventative). However, in each case it is reasonably certain given the nature of the cause of the loss of power to the safety-related bus that there was no test of the EDG in progress. The initiating event for all three was a plant-centered loss of power. In one case a failed relay in the generator circuitry caused a loss of power during a plant shutdown when in-house loads were being transferred to offsite power. In another case a personnel error during the surveillance test of the firewater system resulted in the deluge valves opening and wetting both the main and auxiliary transformers. In the final case, an improperly installed relay tripped the supply breaker to a safety-related bus during a reactor coolant pump start.

There were three failures of the EDG train during unplanned demands that were not used to develop the unreliability estimates presented in Section 3 (SIF events) because of the mechanism of the failure. These three failures occurred in the electrical subsystem and were specifically related to the sequencer. Two were caused by personnel error, and one was a result of a hardware failure. In each case, the sequencer actually caused a load shed sequence to be activated that de-energized the safety bus and subsequently prevented the EDG train from loading the bus. In each event, the EDG started and its output breaker closed to power the safety bus, but the load shed signal was maintained, thus preventing the safety-related loads from receiving power. These events are unusual in that a single fault is both demanding and failing the safety function of the EDG train. As an example, for some safety-related systems, they initiate using an "one-out-of-two-taken-twice logic" which prevents this type of situation. That is, a single fault does not cause a demand for or prevent the system from functioning.

The cause of two of the SIF events was the result of equipment operators inadvertently removing fuses for the circuit that senses power on a safety bus during surveillance testing that is normally performed with the plant in cold shutdown. This action caused the normal power supply breaker for the safety bus to open, the EDG to start, and its output breaker to close, but since the power-sensing circuit fuses were removed, the sequencer did not sense voltage on the bus. Therefore, no loads were sequenced onto the bus nor could they be manually connected. These SIF events required over 2 hours to restore power to the safety-related bus, and in each case the EDG train was not used for power restoration. Given that there were 47 instances during the study period where an EDG train was inadvertently demanded during a surveillance test or maintenance activity that is normally only performed when the plant is in cold shutdown, these SIF failures occurred at a frequency of 4.5E-2. In other words, approximately 1 out of every 25 times an EDG was inadvertently demanded during a surveillance test or maintenance activity in cold shutdown the safety-related bus was not powered by the EDG and subsequently not powered by any source for over 2 hours.

The third SIF EDG sequencer failure resulted from the failure of an integrated circuit chip. The failed chip initiated a loss of power load shed sequence that de-energized the safety-related bus and also prevented the sequencer from reloading the bus after electrical power was applied to the bus by the EDG. The vital bus loads were without power for 7 hours, at which time normal power was restored. This event could have occurred under any plant operating condition.

In addition to the above failures of the EDG train that occurred during unplanned demands at the plants reporting in accordance with Regulatory Guide 1.108, four failures of the EDG output breaker were observed during unplanned demands of the plants not reporting in accordance with the regulatory guide.

The four EDG output breaker failures were observed in the 175 unplanned demands of the EDG trains for the plants not reporting in accordance with the regulatory guide (includes both shutdown and operational periods). This indicates an estimated unreliability of the output breaker of 2.3E-2 per demand. Three of the four failures were hardware-related malfunctions, and the fourth failure was the result of personnel error. The hardware-related failures were caused by problems with the breaker's amptector, a defective switch in the closing logic, and with the contacts in the breaker's control switch. In the three hardware-related failures, the EDG train failed to start and was not able to be recovered. In each case, restoration of power to the emergency bus was accomplished by restoring normal power.

Overall, it appears based on the data provided in the LERs that the failures of the EDG train during unplanned demands were mostly electrical. These failure events may be difficult for operators to diagnose and recover from using the EDG train based on a mean time to recovery using offsite power of 2 hours. In addition, because of the design of the EDG sequencer circuitry, a single fault in the circuitry causes a demand for and subsequent failure of the EDG train. These sequencer induced demands and subsequent failures result in a loss of power to the associated safety-related bus, and present difficulties for the plant operators in recovering power to the safety-related bus.

Surveillance Tests. Overall, surveillance testing detected subsystem failures different from those found during unplanned demands. Surveillance test failures were approximately evenly distributed between the fuel, electrical, and start/shutdown instrument and controls subsystems, with each accounting for approximately 25% of the total number of failures (remaining 25% were spread among the other subsystems). Within these subsystems, the governor, voltage regulator, and automatic trip circuit accounted for the majority of the failures in each respective subsystem. The failure mechanisms of these components and their contribution to the total number of EDG failures are as follows:

- Failures of the governor accounted for 16% of the surveillance test failures. The types of failures attributed to the governor include malfunctions of the governor itself, the governor control and sensing circuitry, and the power supply to the governor and sensing circuits.

- Failures of the voltage regulator accounted for 18% of the surveillance test failures. The types of failures attributed to the voltage regulator include malfunctions of the exciter, failures of the field flash circuitry, the voltage regulator sensing circuitry, and the power supplies to the voltage regulator and sensing circuits.

- The automatic trip circuitry accounted for 21% of the surveillance test failures. The types of failures observed in the automatic trip circuitry include sensors that supply trip signals, the controls systems that process trip signals (pneumatics), and the circuitry that processes the trip signals.

Cyclic Surveillance Tests. Because cyclic surveillance test data were used in the unreliability estimates presented in Section 3, the EDG train failures that occurred during surveillance tests were partitioned by failures that occurred either during cyclic and other periodic surveillance tests, of which most were monthly tests. The results of this data partition indicates a different distribution of the failures among the various EDG subsystems than that observed in the aggregate surveillance test data set.

During the cyclic surveillance tests, the fuel, electrical, engine mechanical, and cooling subsystems contributed to over 75% of the failures. The other 25% of the failures were distributed among the other subsystems, with the instrumentation and control subsystem contributing approximately 10% of the failures compared to 21% in the aggregate data set.

For the FTS failure mode, the fuel and electrical subsystems contributed to a majority of the FTS events, 12 of 17. Within these two subsystems, three components comprised all the subsystem failures: the governor (6), voltage regulator (5), and sequencer (1). These failures were primarily the result of electrical-related hardware malfunctions associated with all three components. The failures of these three components were the result of blown fuses and the malfunction of relays, potentiometers, contacts, solenoids, and resistors. Other EDG train failures were associated with maintenance-related errors, such as mis-adjustment of settings and switches left in the wrong position. The subsystem failures that contributed to the FTS probability were different than the subsystem contribution to the FTS probability found in the PRA/IPEs. A review of the PRA/IPE data indicate that the EDG output breaker and actuation logic are the significant contributors to the FTS probability. However, as discussed, the governor and voltage regulator were observed to contribute approximately 66% of the FTS probability based on the operational data.

In addition, only 17 FTS events were observed during the performance of cyclic surveillance tests, compared to 56 FTS events during the performance of monthly surveillance tests (a factor of ~3 difference). Given that there are approximately 18 times the number of monthly tests performed than cyclic tests, the expected number of failures are not consistent assuming monthly and cyclic tests are comparable. Analysis of the failure data between the two testing frequencies does not indicate a difference in either the mechanism or cause of the failures, or significant difference in the distribution of the failures between the subsystems.

For the FTR failure mode, no one component within any subsystem clearly dominated the total number of failures found during cyclic surveillance testing. However, as shown later in Section 4.1.3 differences were apparent for the subsystem contribution to the early and middle time periods based on the cyclic surveillance test data.

Most of the FTR events were the result of either leaking or loose components. The leaking or loose components were primarily the result of errors associated with maintenance (improper assembly of the components) and either vibration- or wear-induced fatigue failure. In addition, over two-thirds of the failures that contributed to the FTR probability during cyclic surveillance tests occurred after one-hour of EDG operation, and therefore would not have appeared on the monthly tests owing to the short run time of the monthly test compared to the cyclic test's endurance run. Moreover, fewer EDG train failures (FTR events) were found during the monthly tests (22) than the cyclic tests (27). As stated previously for the FTS events, the number of FTR events found during the monthly tests appears to be inconsistent assuming monthly and cyclic tests are comparable. This may be owing to the long endurance run (24 hours) of the cyclic test compared to the monthly test's one-hour run.

Restoration Failures. Two insights were revealed during the analysis of the aggregate surveillance test data. First, approximately one-third of the EDG failures found during surveillance testing would have affected the restoration of normal power. These "restoration failures" occurred because either the malfunction condition was bypassed for an emergency start of the EDG or the malfunction was related to the EDG unit when operated in parallel with the grid. These restoration failures have the potential to initiate a second loss of power that is difficult to diagnose and recover. The second insight was that the proper restoration of the EDG following surveillance testing was not always performed in accordance with established plant procedures.

The first type of restoration failure applies to most of the EDGs. This restoration failure results when the trips that are bypassed during an emergency start become active during the recovery of normal power. As soon as a previously bypassed trip is re-instituted, the EDG trips. For some EDGs, the trip circuitry is automatically restored when certain interlock conditions are met. For others, it is re-instituted by operator action, generally when the safety injection (SI) signal is "reset." This reset is typically performed at the ECCS equipment control board, not at the EDG control board, where the bypassed EDG trip alarms alert the operator of the failed condition. If the reset is performed without prior transfer to offsite power, a second loss of electrical power to the affected safety-related bus could occur.

The second type of restoration failure occurs during transfer to offsite power, when the EDG must be placed in parallel with the grid. The failure mechanism does not appear until the EDG is shifted from independent to parallel operation. When the EDG is placed in parallel with the grid, unstable governor or generator voltage operation may result. The unstable operation will likely result in a trip of the diesel and/or the generator. A trip of the EDG under these conditions may cause power distribution breaker trips and lockouts of supply sources, in addition to the EDG output breaker lockout. The effect of EDG loss during restoration of offsite power may cause further disruption of power continuity.

A small percentage of the EDG failures were a result of failing to correctly align the EDG to a proper pre-start configuration. Examples of these failures include voltage regulators left in manual or set too low, wrong governor settings, improper droop controls, and load limits set low. These failures are attributed to failure to follow operations or maintenance procedures.

Other Failures. The start/shutdown instrument and controls subsystem was the dominant contributor to the "other" failure category. A significant portion of the failures found in the start/shutdown instrument and controls subsystem were a result of blown fuses, of which the LERs did not provide sufficient data to determine the cause of the blown fuse, simply that the fuse interrupted power. Analysis of the failure data for the remaining subsystems did not reveal any significant cause or correlation among the failures.

4.1.3 Time-Trends Observed in FTR Events

The EDG failures that occurred after a successful start sequence were evaluated to determine if time-related trends existed, and if there was an associated failure mechanism for any trend. There were 27 FTR events observed in the cyclic surveillance test data. The duration of the EDG run times prior to the failure of the EDG were reported in 19 of the LERs.

Each of the cyclic surveillance test demands is for at least 24 hours. Based on this assumption, the number of failures as a function of time can be used to detect trends. To detect trends over a 24-hour period, the cumulative number of failures based on cyclic testing were plotted as a function of time. The result is illustrated in Figure 14. Since the number of cyclic surveillance tests can be estimated reasonably accurately, the failure rate can be determined. Analysis of these data indicates that three distinct failure rates existed. The failure rate during the first half-hour was 2.5E-2. The failure rate decreased significantly to 1.8E-3 for the period between 0.5 hours and 14 hours. For periods greater than 14 hours, the failure rate again decreased to 2.5E-4.

The change in the failure rate per hour was linked to a change in the mechanism of the EDG train failures. That is, the cooling subsystem dominated the early failures, accounting for about one-third of all the failures that occurred during the first half-hour; the electrical and fuel subsystems combined account for half of the failures in the period between 0.5 hours and 14 hours; and beyond 14 hours the only failures observed occurred in the electrical subsystem.

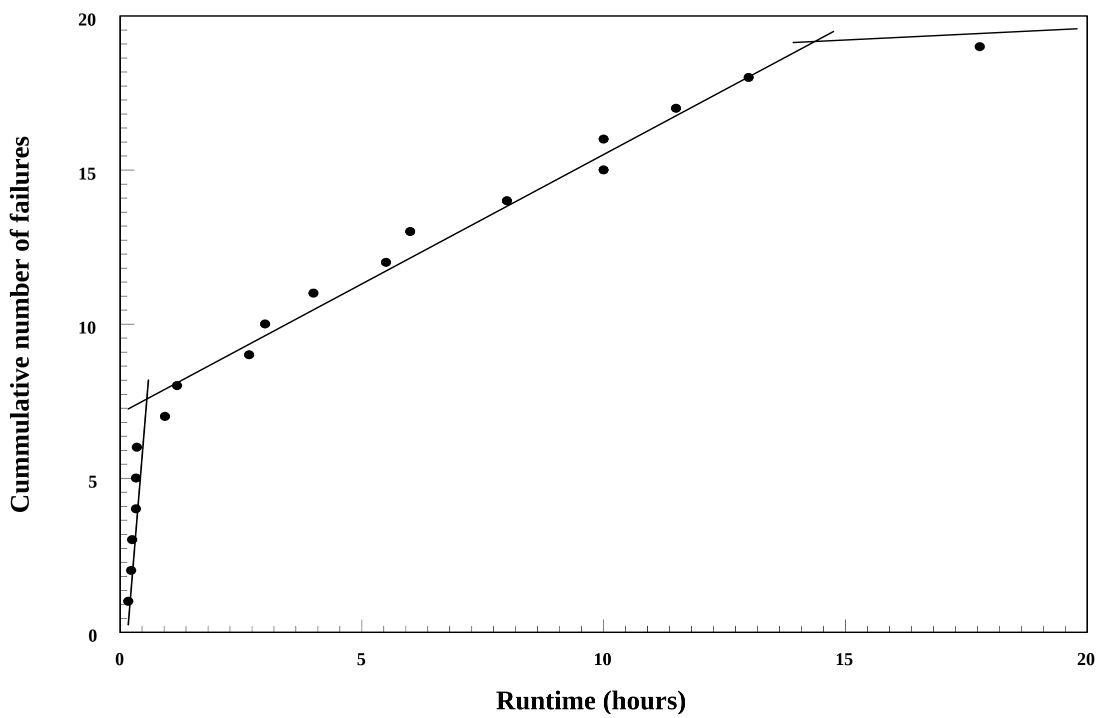


Figure 14. EDG cumulative number of FTR events observed during the cyclic surveillance test's 24-hour loaded run segment versus known run time of the failure.

4.1.4 Comparison with Previous Studies

Subsystem failures contained in this study were compared with the subsystem failures identified in NUREG-1032. Figure 15 is a histogram showing the results of this comparison. The purpose of the comparison is to determine whether or not differences exist in the subsystem contribution to EDG failures for this study compared to earlier studies. The subsystem failures identified in NUREG-1032 were partitioned into two time periods, 1976–1980 and 1981–1982, and are shown as two separate bars for each subsystem. The third bar represents the subsystems used in this study for the 1987-1993 time period. Most of the subsystems identified in NUREG-1032 are similar to the subsystems used in this study. Some differences, however, did exist between the two studies; the fuel subsystem defined in this study is two subsystems in NUREG-1032. The fuel subsystem was divided into the governor and fuel. The lubricating oil and engine subsystem used in this study were not specifically identified in NUREG-1032. Only subsystems that were clearly identified in both studies were compared. Therefore, the percentages shown in Figure 15 do not add up to 100%.

As shown in Figure 15, the only significant difference exists with the instrumentation and control subsystem, which has a higher percent contribution to EDG failures from 1987 to 1993 than in the earlier time periods. Because it is not clear from NUREG-1032 what types of failures were included in the logic and control subsystem, the exact reason for this difference is uncertain. However, about half of the failures for the instrumentation and control subsystem in the 1987 through 1993 study were restoration failures where instrumentation caused the EDG to trip during an non-emergency start. It is not clear if these types of failures were addressed in the earlier studies.

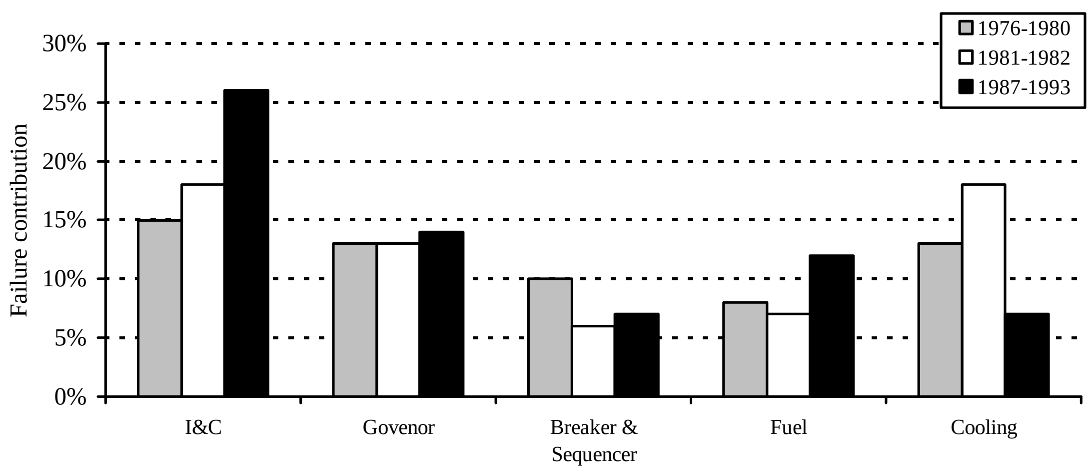


Figure 15. Plot of EDG subsystem failures observed from 1987-1993 compared with previous study periods.

4.2 Individual Plant Evaluation

Table 17 shows the following information for each plant reporting in accordance with the requirements of Regulatory Guide 1.108: number of EDGs, operating years during the study period, number of failures, number of unplanned demands, and the rate of failures and unplanned demands. As used here, a rate is simply the number of failures or unplanned demands per EDG-year. The number of EDG-years is the product of the number of EDGs at the plant and operating years. Operating years do not include time prior to receipt of the low-power license or regulatory outages.

Plant-specific unplanned demand rates and failure rates are plotted in Figures 16 and 17. For each plant, the estimate is shown with the 90% Bayesian interval. Because the plants with high failure rates do not necessarily have high demand rates, Figure 18 shows the two rates plotted on one graph. Plants are identified by name if either a high unplanned demand rate, failure rate, or both are observed.

In contrast to those plants with a high number of EDG failures, a review of the data identified 18 plants with one or fewer reported EDG train failures for the 7-year period. These plants are identified in Table B-1 of Appendix B. Of particular interest is that some of these plants (Braidwood 1, Harris, Palo Verde 2, and Zion 2) have EDGs supplied by a manufacturer that exhibits a high number of failures at other plants.

An analysis of the operational data for each of the plants identified in Figure 18 that have either a high failure rate, high unplanned demand rate, or both, was performed in an effort to determine if recurring problems or trends existed. The failure and unplanned demand rates shown in the following tables and graphs provide qualitative insights that can be used to characterize the factors contributing to the quantitative estimates of EDG reliability presented previously in Section 3. The reader is cautioned when comparing the individual plant data to the reliability estimates provided in Section 3. Plant-specific estimates derived solely from the failure data at a particular plant may produce results that differ from those presented in Section 3. There are several reasons for this, two of which are the sparse data associated with looking at EDG performance at individual plants and the ability to recover from EDG failures. However, sparse data alone does not create differences between the best estimates of unreliability presented in Section 3 (which are calculated using Bayesian statistics) and what can be calculated if only the individual plant data were used (that is, using classical statistics). Sparse data provide the opportunity for rare or atypical performance to overly influence any unreliability estimate that is based soley on the plant-specific data. (Note that in the long run, the atypical “good” performance will be balanced out by atypical “bad” performance. “Sparse data” is defined such that the EDG experience is not long enough to allow the data to converge on the true unreliability.) This atypical data can result in the unreliability estimate either over predicting or under predicting the true unreliability of the plant EDGs. Of course it is impossible to determine absolutely whether or not the sparse data are atypical of the true EDG performance; maybe the EDGs really are as good or as bad as the data suggests. Nevertheless, to minimize the chance of producing non-representative estimates based on atypical (sparse) data, the best estimates presented in Section 3 are calculated using Bayesian statistics that utilize the industry-wide data along with the plant-specific EDG data. Hence, the estimated unreliability of any plants that displayed atypical performance (either better or worse) during the relatively short time frame of this study period, is moderated by the industry-wide data. For example, Catawba 1 has a best (Bayesian) estimate of unreliability of 0.058. However, the operating experience at Catawba 1 resulted in 2 failures in 3 unplanned demands and 1 failure in 10 cyclic surveillance tests. A simple (classical statistics) estimate of unreliability based on this data is 0.23 (3/13). At the same time, the Bayesian estimate of unreliability for the overall population of nuclear power plant EDGs is 0.044. Comparing these three estimates, it can be seen that the Bayesian estimate for the Catawba 1 plant is pulled from the simple (classical) estimate towards the overall industry average estimate. This behavior is a fundamental premise of Bayesian statistics that says we actually know more about the reliability of the Catawba 1 EDGs than can be discerned from the Catawba 1 data alone. Specially, in the case being examined here, we have the operating experience of the entire industry we can utilize and factor into our “best” estimate of the unreliability of the EDGs at Catawba 1.

The second issue to consider when reviewing the individual plant experience is the possibility of recovering from an EDG failure. Industry-wide, there were three opportunities in which plant personnel were motivated to recover the EDG from a FTR event. In all three instances, the recovery was successful. Consequently, the unreliability estimates presented in Section 3 include a very high likelihood that FTR events will be successfully recovered. Whereas the individual plant-specific experience presented in Section 4 does not necessarily include consideration of recovery. Hence any unreliability estimate generated using classical statistics and based on plant-specific data for an individual plant will likely be inaccurate with respect to consideration of the possibility of recovering from a failure.

Table 17. EDG train failures and unplanned demands differentiated by plant.

Plant name	Number of EDGs	Operating years	Failures	Failure rate	Unplanned demands	Demand rate
Arkansas 2	2	7.00	2	0.14	1	0.07
Braidwood 1	2	6.62	0	0.00	4	0.30
Braidwood 2	2	6.04	5	0.41	1	0.08
Browns Ferry 2	4	2.61	2	0.19	0	0.00
Byron 1	2	7.00	6	0.43	0	0.00
Byron 2	2	7.00	6	0.43	2	0.14
Callaway	2	7.00	8	0.57	2	0.14
Catawba 1	2	7.00	20	1.43	3	0.21
Catawba 2	2	7.00	14	1.00	0	0.00
Clinton	2	7.00	8	0.57	0	0.00
Comanche Peak 1	2	3.90	2	0.26	4	0.51
Comanche Peak 2	2	0.91	0	0.00	0	0.00
Cook 1	2	7.00	1	0.07	2	0.14
Cook 2	2	7.00	1	0.07	2	0.14
Diablo Canyon 1	3	7.00	4	0.19	4	0.19
Diablo Canyon 2	2	7.00	2	0.14	8	0.57
Farley 1	3	7.00	1	0.05	4	0.19
Farley 2	2	7.00	0	0.00	3	0.21
Fermi 2	4	7.00	11	0.39	6	0.21

Table 17. cont.

Plant name	Number of EDGs	Operating years	Failures	Failure rate	Unplanned demands	Demand rate
Grand Gulf	2	7.00	16	1.14	0	0.00
Haddam Neck	2	7.00	2	0.14	5	0.36
Harris	2	7.00	0	0.00	6	0.43
Hatch 1	3	7.00	1	0.05	0	0.00
Hatch 2	2	7.00	1	0.07	0	0.00
Hope Creek	4	7.00	1	0.04	2	0.07
LaSalle 1	2	7.00	4	0.29	3	0.21
LaSalle 2	1	7.00	1	0.14	0	0.00
Limerick 1	4	7.00	5	0.18	0	0.00
Limerick 2	4	4.48	10	0.56	0	0.00
McGuire 1	2	7.00	13	0.93	4	0.29
McGuire 2	2	7.00	16	1.14	5	0.36
Millstone 3	2	7.00	2	0.14	2	0.14
Nine Mile Pt. 2	2	7.00	14	1.00	9	0.64
North Anna 1	2	7.00	0	0.00	6	0.43
North Anna 2	2	7.00	3	0.21	3	0.21
Palo Verde 1	2	7.00	2	0.14	8	0.57
Palo Verde 2	2	7.00	1	0.07	6	0.43
Palo Verde 3	2	6.77	3	0.22	3	0.22
Perry	2	7.00	5	0.36	0	0.00
River Bend	2	7.00	10	0.71	2	0.14
Salem 1	3	7.00	0	0.00	9	0.43
Salem 2	3	7.00	11	0.52	4	0.19
San Onofre 2	2	7.00	0	0.00	1	0.07
San Onofre 3	2	7.00	0	0.00	0	0.00
Seabrook	2	4.60	4	0.43	3	0.33
Sequoyah 1	2	5.14	2	0.19	9	0.88
Sequoyah 2	2	5.64	2	0.18	3	0.27
South Texas 1	3	6.36	25	1.31	11	0.58
South Texas 2	3	5.04	14	0.93	8	0.53
St. Lucie 1	2	7.00	5	0.36	1	0.07
St. Lucie 2	2	7.00	10	0.71	2	0.14
Summer	2	7.00	1	0.07	7	0.50
Susquehanna 1	3	7.00	6	0.29	0	0.00
Susquehanna 2	2	7.00	2	0.14	0	0.00
Turkey Point 3	2	7.00	4	0.29	4	0.29
Turkey Point 4	2	7.00	3	0.21	5	0.36
Vogtle 1	2	6.96	14	1.01	5	0.36
Vogtle 2	2	4.89	10	1.02	2	0.20
Wash. Nuclear 2	2	7.00	2	0.14	1	0.07
Waterford 3	2	7.00	22	1.57	3	0.21
Wolf Creek	2	7.00	6	0.43	4	0.29
Zion 1	3	7.00	6	0.29	2	0.10
Zion 2	2	7.00	1	0.07	1	0.07
RG-1.108 total or mean	144	6.50	353	0.38	195	0.21

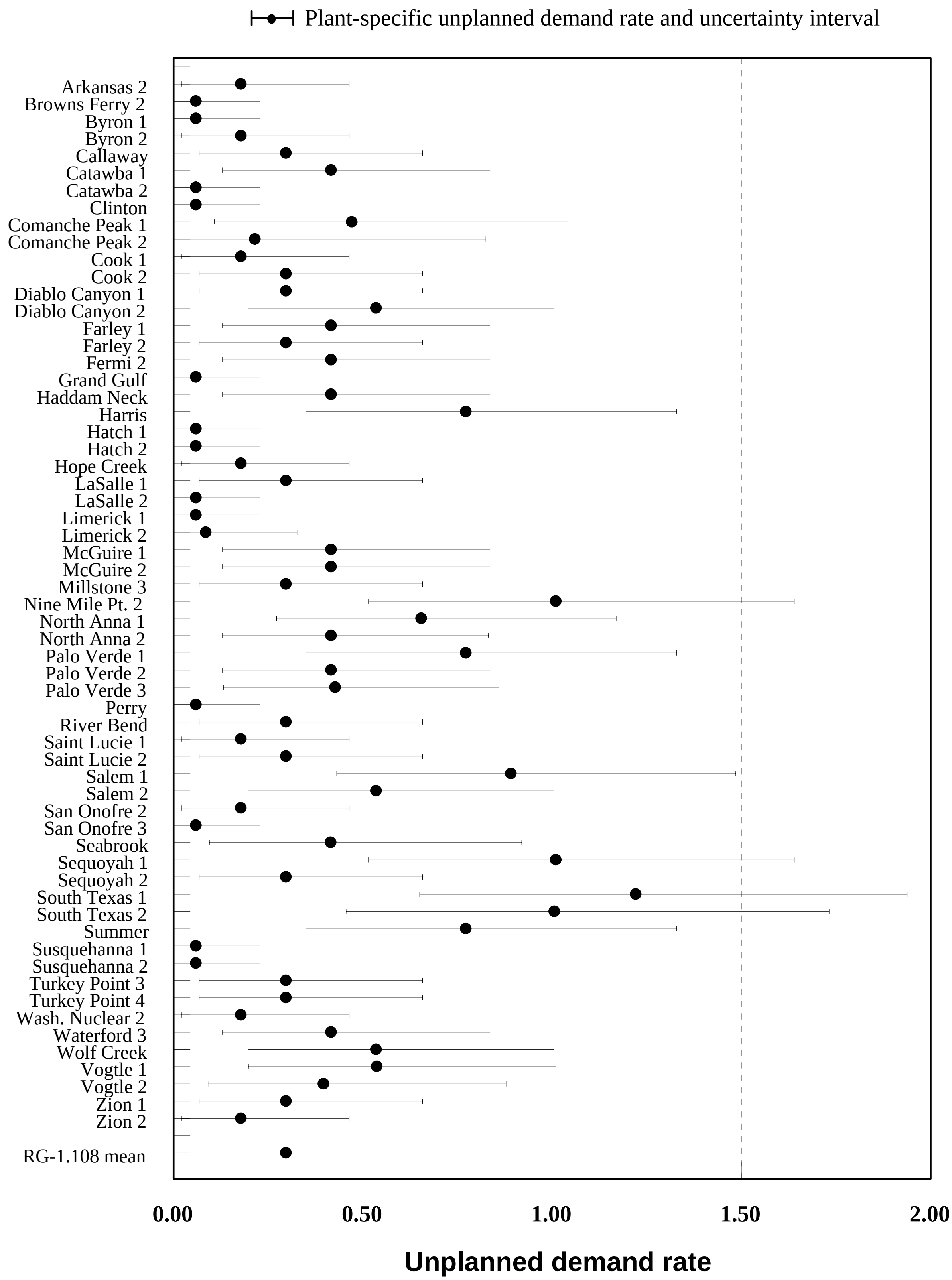


Figure 16. Plant-specific unplanned demand rate per EDG-year with 90% Bayesian intervals.

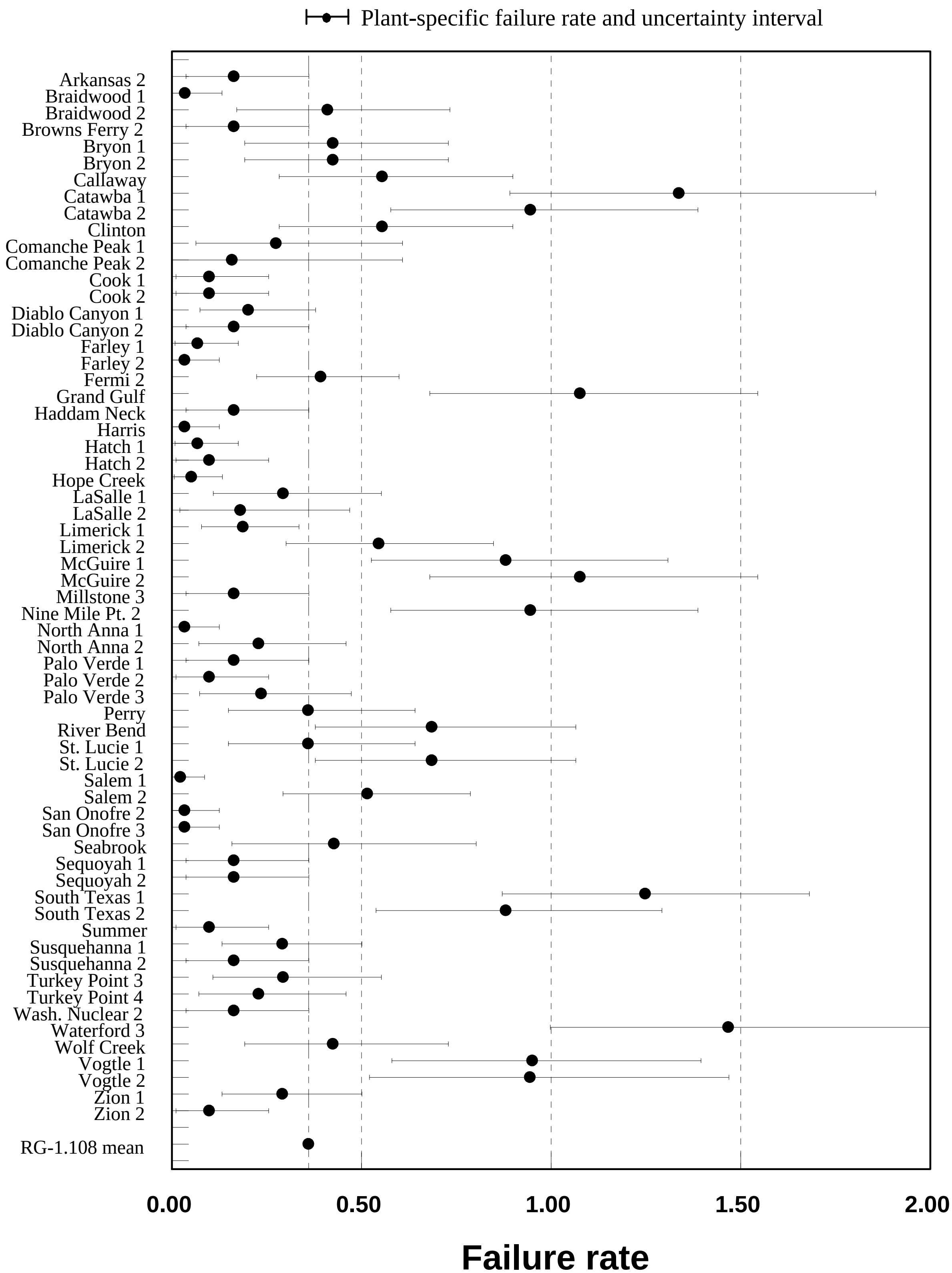


Figure 17. Plant-specific failure rate per EDG-year with 90% Bayesian intervals.

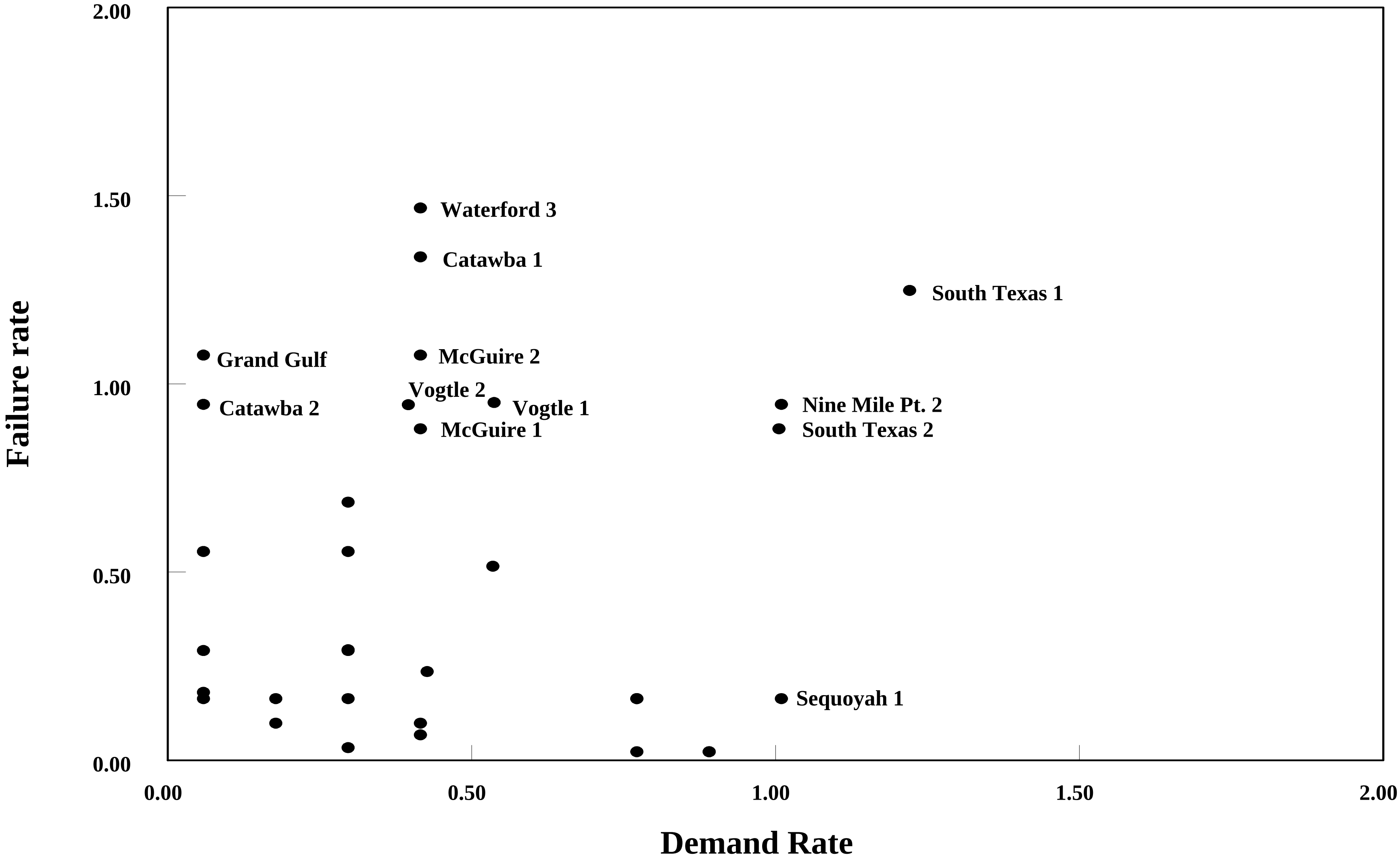


Figure 18. EDG plant-specific failure rate versus unplanned demand rate.

Catawba 1 had a failure rate of 1.43 failures per EDG-year, which is the second highest in the industry. Over half of the failures occurred in 1987 and 1988. Most of the failures were classified as failures of the EDG to start and were associated with the instrumentation and control subsystem, specifically, malfunctions of the automatic trip circuitry. Recurring problems in 1987 and 1988 associated with the design of the lubrication oil low pressure trip instrumentation caused most of these failures for both EDGs at the plant. The remaining failures occurred in the electrical subsystem, primarily in the voltage regulator.

The failures and associated demands that contributed to the reliability estimate provided previously in Section 3 for Catawba 1 were two failures to start and one maintenance out of service event. The failures and the maintenance out of service event were observed in 3 unplanned demands and 20 cyclic surveillance test start attempts. The two failures to start occurred during an unplanned demand and a cyclic surveillance test. The unplanned demand failure to start was the result of a failed sequencer owing to “timer drift”, this failure was not recovered using the EDG. The cyclic surveillance test failure to start was the result of a failure that occurred in the instrumentation and controls subsystem, specifically in the low lubrication oil pressure shutdown circuit. The two failures to start in 22 attempts (the MOOS event reduces the count to 22) contributed to a relatively high failure to start probability as compared to the other RG-1.108 plants.

Catawba 2 had a failure rate of 1.00 failures per EDG-year. Most of the failures occurred from 1991 through 1993 and were primarily associated with the instrumentation and controls subsystem. Approximately 70% (10) of the failures involved various sensors of the automatic trip circuitry and affected both EDGs. Both Catawba units have experienced a significant number of problems with various sensors in the instrumentation and controls subsystem. These failures were dominated by failures to start and restoration failures. All but two of the failures were discovered during surveillance tests, four of which were cyclic surveillance tests (1 FTS and 3 RFR). No unplanned demands occurred at Catawba 2 during the study period.

The reliability estimate provided previously in Section 3 for Catawba 2 is based on one failure to start in 24 demand attempts. The failure to start event was the result of personnel error in adjustment of the governor settings. No others failures or MOOS events were observed that contributed to unreliability at Catawba 2.

Grand Gulf had a failure rate of 1.14 failures per EDG-year, most of which occurred in 1988 and 1992. Of the failures that occurred in these two years, only 3 of the 11 were due to the same cause; the remainder were diverse. About half of the failures are related to the electrical subsystem, specifically the voltage regulator of EDG 11. Most of the remaining failures involved the automatic trip circuitry, primarily on EDG 12. A majority of the failures were discovered during surveillance tests, though none were cyclic surveillance tests. No unplanned demands occurred at Grand Gulf during the study period. The reliability estimate presented previously in Section 3 is based on no failures during 12 cyclic surveillance tests.

McGuire 1 experienced an EDG failure rate of 0.93 per EDG-year during the study period. Most of these failures occurred between 1988 and 1990. These failures were diverse, with no clear majority being associated with a specific subsystem or failure mode, but half were either related to maintenance or operator error and included painted fuel racks, oil and water leaks, a torn gasket, loose valve covers, loose wires, and breaker or valve mis-positioning problems. The failures were distributed between both EDGs at the plant. The method of discovery for the failures at McGuire 1 was evenly divided between surveillance tests and other.

The reliability estimate presented previously in Section 3 for McGuire 1 is based on no failures to start or run observed in four unplanned demands and 10 cyclic surveillance tests. There was only one maintenance out of service event observed at McGuire 1 during the four unplanned demands.

McGuire 2 experienced an EDG failure rate of 1.14 per EDG-year during the study period. The failures at McGuire 2 were similar to the failures experienced at McGuire 1. Most were related to maintenance or operator error, with no clear majority being associated with a specific subsystem.

The failures and associated demands that contributed to the reliability estimate for McGuire 2 were two failures to start and four failures to run, during five unplanned demands and 24 cyclic surveillance test start attempts and associated endurance runs. The two failures to start were observed during an unplanned demand and a cyclic surveillance test. The unplanned demand failure to start was the result of a failed lubrication oil pressure switch that was subsequently not recovered. The cyclic surveillance test failure to start was the result of a failure that occurred in the instrumentation and controls subsystem, specifically, intermittent failure of contracts in the EDG start timing relay. The two failures to start in 29 demand attempts contributed to a relatively high failure to start probability as compared to the other RG-1.108 plants. The four failures to run were observed only during the cyclic surveillance test's endurance run. One of the failures was observed during the early period of the run (less than half-hour), two failures were observed during the middle period of the run (greater than half- hour and less than 14 hours), and the fourth failure to run had an unknown run time prior to failure. These failures contributed to relatively high failure to run rates for each period as compared to the other RG-1.108 plants. These failures were associated with four different subsystems; however, three can be attributed to maintenance practices, specifically, leaking fittings and gaskets.

Nine Mile Point 2 had a failure rate of 1.00 per EDG-year. The failures were diverse and had no common link to any specific cause or subsystem. Most of the failures occurred during surveillance tests, two of which were cyclic surveillance tests. This plant had the second highest unplanned demand rate in the industry, with 0.64 demands per EDG-year. The failures were evenly distributed over the review period; however, all but one of the unplanned demands occurred in the last two years of the review period.

The failures and associated demands that contributed to the reliability estimate for Nine Mile Pt. 2 were two failures to run that occurred in the middle period of the endurance runs during cyclic surveillance testing. Both of these failures were associated with the fuel subsystem owing to a fuel oil leak caused by cracks in the fuel injector pump delivery valve. These failures contributed to a relatively high failure to run rate for the middle period as compared to the other RG-1.108 plants. Nine Mile Pt. 2 also experienced two maintenance out of service events during nine unplanned demands, however, these events occurred during cold shutdown conditions and were related to shutdown maintenance activities. Therefore, they were not used in the reliability estimate.

Salem 2 experienced a relatively low overall failure rate and unplanned demand rate compared to the other RG-1.108 reporting plants. However, Salem 2 had several failures that contributed to a relatively low reliability. The failures and associated demands that contributed to the reliability estimate were four failures to run observed during the cyclic surveillance test's endurance run. Two of the failures to run were observed in the early period, one during the middle period, and one had an unknown run time prior to failure. These failures contributed to relatively high failure to run rates for each period as compared to the other RG-1.108 plants. The failures were attributed to maintenance practices, primarily associated with the cooling subsystem that eventually resulted in subsystem leaks.

South Texas 1 had a failure rate of 1.31, the third highest in the of the RG-1.108 plants. The failures were diverse, affecting all three EDGs, though EDG 12 and EDG 13 had the majority of the failures. The main contributors to the failures were the automatic trip circuitry and the voltage regulator. The data also indicated that several of the failures were for the same reason. Some failures occurred several weeks apart from each other. Approximately half of the failures occurred within the first two years after low-power license date. The failures that occurred in the two years after low-power license date were shared between EDG 12 and EDG 13 and were due to various causes and subsystems. Most of the failures were restoration failures. Two-thirds of the failures occurred during surveillance tests, two of which were cyclic surveillance tests (1 FTR and 1 RFR). There were no unplanned demand failures. The plant has also exhibited the industry's third highest unplanned demand rate of 0.58 unplanned demands per EDG-year.

The reliability estimate for South Texas 1 is based on one failure to start observed during 41 demand attempts. This failure was the result of a faulty voltage regulator that tripped the EDG output breaker during the performance of a cyclic surveillance test. No other failures or MOOS events were observed at South Texas 1 that contributed to the reliability estimate.

South Texas 2 had a failure rate of 0.93 per EDG-year during the study period. Over half of the failures occurred in 1991 and were distributed between all three EDGs, with most associated with EDG 22. About a third of the failures were related to the automatic trip circuitry. Most of the failures occurred during surveillance tests, with four of the failures occurring during cyclic tests. The plant has also had a high unplanned demand rate of 0.53 unplanned demands per EDG-year. All of the unplanned demands occurred in 1989. For both units the failures appear to be design-related recurring problems that occurred within the first two years of operations.

The reliability estimate for South Texas 2 is based on four failures to run observed during the cyclic surveillance test’s endurance run. One of the failures to run was observed in the early period, two during the middle period, and one had an unknown run time prior to failure. These failures contributed to relatively high failure to run rates for each period as compared to the other RG-1.108 plants. The four FTR cyclic surveillance test failures were associated with three subsystems (two fuel, one electrical, and one engine mechanical) and appear to be unrelated.

Vogtle 1 had a failure rate of 1.01. Half of the failures occurred in 1990. These failures were evenly distributed between the air start system, the voltage regulator, and automatic trip circuitry. The failures were primarily discovered during surveillance testing and appear to be unrelated. Vogtle 1 had an unplanned demand rate of 0.36. All but one of the demands occurred in 1990.

The reliability estimate for Vogtle 1 is based on one failure to run observed during an unplanned demand. This failure occurred during the early period and contributed to a relatively high failure to run rate as compared to the other RG-1.108 plants. The failure was the result of intermittent actuation of the high jacket water temperature switch, and the EDG was recovered by operator action.

Vogtle 2 had a failure rate of 1.02. Most of failures occurred in 1990, and all but two of the failures occurred during the first two years of low-power operations. Most were recurring problems caused by an air pilot valve sticking. Most of the failures were discovered during surveillance testing. However, there were no failures observed during any of the demands used to estimate EDG unreliability in this report during the study period.

Waterford 3 had a failure rate of 1.57, the highest for the plants reporting in accordance with RG-1.108. All but two of the failures occurred on EDG A, and were distributed between 1987 and 1991. Most of the failures were related to the automatic trip circuitry for EDG A, the majority being a recurring problem associated with a pressure switch in the turbocharger lubrication oil system. All but four of the failures were classified as restoration failures that did not contribute to the EDG reliability estimate.

The reliability estimate for Waterford 3 is based one failure to run observed during a cyclic surveillance test. This failure occurred during the middle period and contributed to a relatively high failure to run rate as compared to the other RG- 1.108 plants. This failure was the result of crankcase over-pressurization that was caused by stuck piston rings. Waterford 3 also experienced one maintenance out of service event during three unplanned demands, however, this event occurred during refueling conditions and was related to shutdown maintenance activities. Therefore, the event was not used in the reliability estimate.

In an attempt to determine if any common problems exist within a utility, the plants listed in Table 17 were reviewed based on their respective utilities. Of the plants listed in Table 17, utilities that operate one plant were removed from this analysis. Of those utilities that remained, comparisons were made to determine if any commonalities exist between plants. It was difficult to make definitive conclusions in most cases because of no obvious patterns in the data. In addition, the affect that different EDG manufacturers may have when a utility has different manufactured EDGs at various plants is unclear. The following summarizes the information based on utility.

Duke Power Company operates four plants that use EDGs as an emergency power source at two different sites (McGuire and Catawba), all of which have relatively high failure rates. The only other plants operated by Duke Power Co. are at Oconee, which do not have EDGs. It is also of interest that these two sites have EDGs made by different manufacturers, Nordberg and Transamerica Delaval. As discussed, most of McGuire's failures were related to poor maintenance or operator errors. Although the causes of most of the Catawba failures are not clear, many appear to be design-related recurring failures. Both sites have high failure rates and involve two different EDG manufacturers.

Houston Lighting and Power Company operates two plants at one site (South Texas), both of which have relatively high failure rates. This is the only site operated by Houston Lighting and Power Co. The EDGs at South Texas are manufactured by Cooper Bessemer, which are shown in Section 4.3 as one of the manufacturers with a high number of failures. Over half of the failures that occurred at this site occurred within the first two years of low-power operations. Many of the failures appear to be design-related repetitive failures. Without another site for comparison it is difficult to draw any utility conclusions from these data.

Georgia Power Company operates four plants at two different sites (Vogtle and Hatch). Only one site, Vogtle with its two plants, has a high failure rate. The sites have EDGs with different manufacturers. Vogtle EDGs are manufactured by Transamerica Delaval, which are shown in Section 4.3 as one of the manufacturers with a high number of failures, while Hatch's EDGs are manufactured by Fairbanks Morse/Colt. Of the failures that occurred at the Vogtle site, about half occurred within the first two years of low-power operations.

Florida Power and Light Company operates two different sites (St. Lucie and Turkey Point), with four plants total. Both sites have EDGs from the same manufacturer. Only one of these plants (St. Lucie 2) has a high failure rate. The failures at St. Lucie 2 involved both EDGs, and although many involved the governor, they were not recurring type failures. Since the high failure rate at St. Lucie 2 cannot be attributed to a specific EDG or failure mechanism, and no other conclusions can be drawn from the failure data, it appears this is a plant-specific concern.

4.3 Trends by Manufacturer

Table 18 displays the average number of failures (total failures/number of EDGs) over the entire study period of 1987–1993 by manufacturer. Included with the table are the number of failures that contributed to the FTS, FTR, and RF failure modes. In addition, the EDG failures were partitioned by subsystem for each manufacturer, which is shown in Table 19.

As the data in Table 18 show, there is a large difference in the average number of failures between the EDG manufacturers. Two of the manufacturers; Nordberg Mfg. and Worthington Corp., have too few EDGs in service throughout the industry to allow for meaningful comparison. Three manufacturers have a relatively low number of failures per EDG: ALCO Power, Electro Motive, and Fairbanks Morse/Colt. Two of the manufacturers, Transamerica Delaval and Cooper Bessemer, have a relatively high number of failures.

Table 18. Distribution of EDG failures by manufacturer for the entire study period (1987–1993).

Manufacturer	Number of EDGs	Total failures	FTS	FTR	RF	Failure average
ALCO Power (AP)	11	17	10	7	0	1.5
Cooper Bessemer (CB)	34	113	32	29	52	3.3
Electro Motive (EM)	29	45	24	14	7	1.6
Fairbanks Morse/Colt (FC)	42	56	27	16	13	1.3
Nordberg (NM)	4	29	10	11	8	7.3
Transamerica Delaval (TD)	20	91	36	14	41	4.6
Worthington Corp (WC)	4	2	2	0	0	0.5
Industry	144	353	141	91	121	2.5

Table 19. Number of EDG subsystem failures by manufacturer over the study period (1987–1993).

Subsystem	AP	CB	EM	FC	NM	TD	WC	TOT
Fuel	5	34	16	24	5	8	1	93
Electrical	3	22	18	18	3	21	0	85
Start and shutdown instrument and controls	1	32	4	5	10	41	0	93
Lubrication oil system	0	4	1	2	6	4	1	18
Cooling system	5	5	3	4	3	6	0	26
Mechanical	2	13	2	0	1	2	0	20
Air start system	1	2	1	3	1	9	0	17
EDG room heating and ventilation (EDG HVAC)	0	1	0	0	0	0	0	1
Number of EDGs	11	34	29	42	4	20	4	144

Transamerica Delaval and Cooper Bessemer account for 38% (54 of 144) of the EDGs in use at commercial nuclear plants; however, these manufacturers account for 58% (204 of 353) of the total failures. The EDGs manufactured by Transamerica Delaval and Cooper Bessemer had a relatively high failure rate at several plant sites and different utilities. Although the failure averages per EDG were relatively high for these two manufacturers, only about half of these failures contributed to the FTS and FTR failure modes, the remainder of the failures were attributed to restoration failures. The data in Table

20 indicate that restoration failures were observed to have occurred more often among these two manufacturers than the other manufacturers. For Copper Bessemer EDGs, 79% of the restoration failures occurred at only three plants, South Texas 1 and 2, and Waterford 3. The restoration failures of Transamerica Delaval EDGs were more evenly spread among the plants. Although a high average number of failures occurred with Transamerica Delaval and Cooper Bessemer EDGs, one plant having Transamerica Delaval EDGs (Harris), and one plant having Cooper Bessemer EDGs (Braidwood 1), had no reported EDG failures during the study period. Looking at the failure rates on a plant by plant basis for these two manufacturers shows only a small percentage (4 of 15) of the plants with Cooper Bessemer EDGs have failure rates twice the industry average, while most of the plants with Transamerica Delaval EDGs have failure rates twice the industry average (6 of 9; Comanche Peak 2 was excluded due to less than 1 year of operation).

Although Cooper Bessemer only supplies 24% (34 of 144) of the EDGs, it has experienced 65% (13 of 20) of the mechanical subsystem failures. Cooper Bessemer also accounts for 37% and 34%, respectively, of the fuel subsystem and the start and shutdown instrument and control subsystem failures. Similarly, Transamerica Delaval only supplies 14% (20 of 144) of the EDGs, but it has experienced 44% of the start and shutdown instrument and control subsystem failures. For the air start subsystem, Transamerica Delaval accounts for 53% (9 of 17) of these failures. Investigation as to the causes and mechanisms of the failures indicated no specific reason as to why these two manufacturers have higher failure rates associated with these subsystems as compared to the other EDG manufacturers. The causes of the failures and failure mechanisms were relatively the same among all manufacturers, however, Copper Bessemer and Transamercia Delaval experienced them more often. Cooper Bessemer EDGs have also experienced a significant number of design-related repetitive problems at some plants, but not at all plants. The LER and Special Report data reviewed for this study do not contain enough information to make more meaningful comparisons or provide more insights other than that provided.

Analysis of the EDG trends by year for each manufacturer was performed, the results of the analysis indicated three manufacturers had an observed reduction in the number of failures; the EDGs manufactured by Transamerica Delaval and Nordberg had a reduction in the number of failures from 1990-1993, and Cooper Bessemer had a reduction in failures from 1992 to 1993 (19 to 2). The reason for the reduction in the number of failures could not be readily determined from the LER and Special Report data. The plants contributing to the failures and failure mechanisms were relatively the same for 1987-1992, and the sparse data for 1993 does not allow for a definitive conclusion to be drawn for the decline in the number of failures. No other trends in the reduction or increase in EDG failures were apparent from 1987-1993.

4.4 Evaluation of EDG Failures Based on Low-Power License Date

To indicate how the passage of time affects EDG performance, plant-specific total failures per EDG operating year and plant-specific unreliability were plotted against the plant low-power license date. The failure rate for an EDG was estimated as the number of EDG failures/number of EDG-years, with EDG-years estimated as described in Section A-1.3 of Appendix A. Plant-specific unreliability was calculated as described in Section 3 and Appendix A, Section A-1.4. The EDG failure rates and 90% Bayesian intervals are plotted in Figure 19. The plant-specific unreliability as a function of low-power license date are plotted in Figure 20. A fitted trend line and a 90% confidence band on the fitted line are also shown in the figures.

Analysis of the failure data by low-power license date indicates that the EDG failures per operating year as a function of low-power license date had a statistically significant trend (P-value=0.007). The trend indicates that the plants with low-power license dates from 1980 to 1990 typically had an EDG failure rate greater than that of plants with low-power license dates earlier than 1980. Analysis of the plant-specific unreliability as a function of low-power license date indicates no statistically significant trend (P-value=0.62).

Some plants experienced a high number of failures within the first two years after the low-power license date. Some of the failures that occurred with the first two years of the low-power license date can be attributed to design-related repetitive problems, however, this is not the case for all plants. As a result, the trend observed by low-power license date for the EDG failure rate requires further investigation as to the cause of the trend. Information contained in the LERs and Special Reports were not sufficient to determine the reason for the trend.

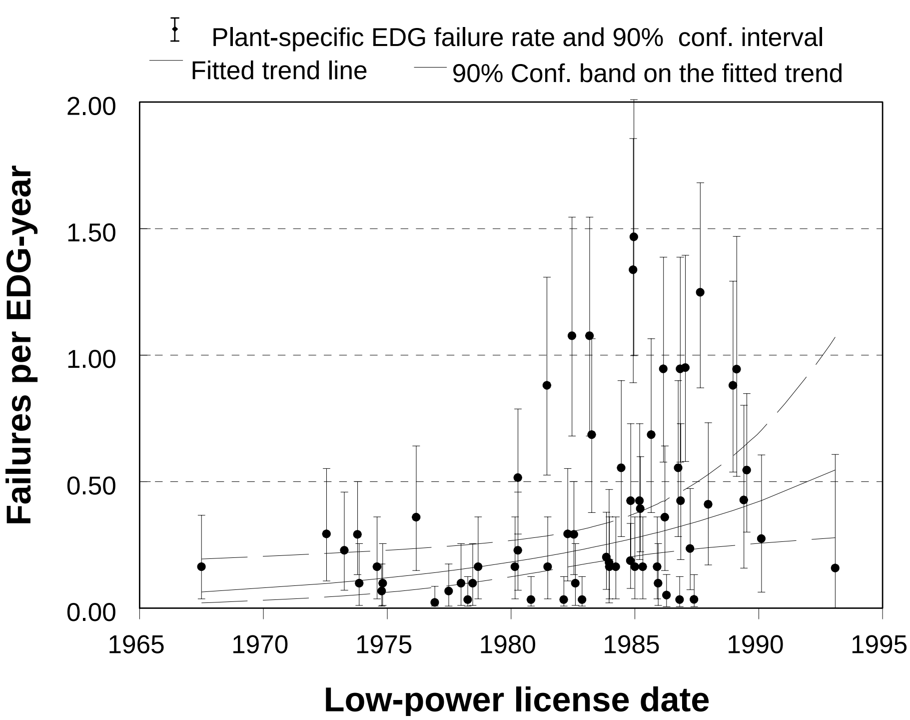


Figure 19. Plant-specific EDG failures per EDG-year, plotted against low-power license date. Ninety percent Bayesian intervals and a fitted trend are included. The trend, based on a fit of the logarithms of the rates as a function of low-power license date, is statistically significant (P-value=0.007).

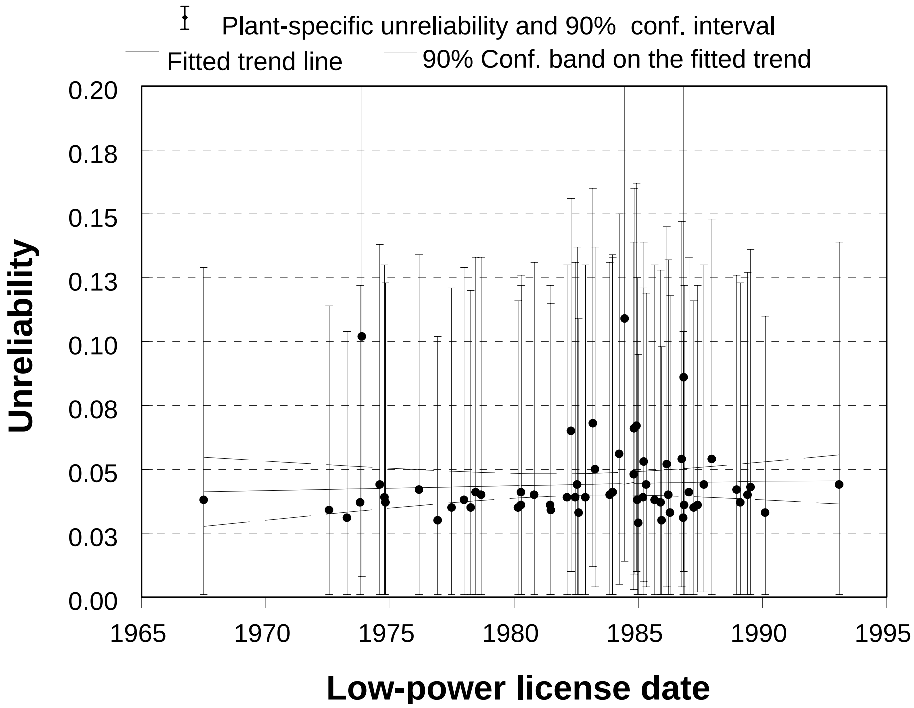


Figure 20. Plant-specific unreliability based on constrained noninformative prior distributions and an 8-hour mission, plotted against low-power license date. Ninety percent Bayesian intervals and a fitted trend are included. The trend is not statistically significant (P-value=0.62).

4.5 Common Cause Failure Events

All plants are required to report both potential and actual EDG common mode failures per 10CFR 50.73(a)(2)(v) and 50.73(a)(2)(vii). Therefore, this section includes common cause failures from all plants and is not limited to only those required to report by Regulatory Guide 1.108. Each of the EDG failures were reviewed to determine if a common cause failure occurred. From these failures, 34 CCF events were identified for further review. Many LERs and Special Reports list only one actual failure, but the reports indicate that failure of a second EDG would have occurred from the same cause if a start and run had been attempted. If the cause of the failure would prevent another EDG from operating for the same reason, then the event was identified as a CCF. If the report did not specify that another EDG would have also failed from the same cause, the event was not considered a CCF. For purposes of CCF investigation, a personnel error resulting in more than one inoperable EDG, even without any component malfunction, is considered a CCF event. All CCF events identified in this study are listed in Table B-5 in Appendix B. This classification criterion is the same classification criterion identified in Reference 39, Mosleh, et al. Common Cause Failure Systems: Volume 2 - Definition and Classification of Common Cause Failure Events Draft, NUREG/CR-6268, October 1994.

The majority of the CCFs were evenly distributed between the cooling, fuel, electrical, and instrumentation and control subsystems. Only one of the electrical subsystem CCFs involved the ability of the sequencer to properly load the EDGs.

Partitioning the CCF events by method of discovery shows no CCF events occurred during unplanned demands. When the CCF events were further partitioned by testing frequency (cyclic and monthly tests), about the same number of CCF events were found during cyclic surveillance tests (6) and monthly surveillance tests (8). Considering that there are 18 times more monthly tests performed than cyclic tests, the proportion of CCFs found on monthly tests should be significantly higher assuming the tests are comparable.

Owing to the sparsity of the data and the diversity of the failures, no explanations can be made as to why the event counts were similar for the two types of tests. The electrical subsystem caused half of the CCF events, during cyclic testing, but the electrical failures were all different. The cooling subsystem led the monthly test CCF failures. Monthly testing would not identify some potential CCF events, since the load sequencer is not tested, and the EDG is not run at full load as long as it is during a cyclic test. Although these are known differences between monthly and cyclic testing, the failure data do not indicate these differences.

4.6 Accident Sequence Precursor Review

A review was conducted of the events identified by the Accident Sequence Precursor (ASP) Program (NUREG/CR-4674). The purpose of this review was to relate the operational data to the types of events that resulted in a conditional core damage probability (CCDP) of greater than 1.0E-6. The search for ASP events was limited to the 1987–1993 study period and included all ASP events in which the EDG system was identified in the ASP database. The search resulted in the identification of 98 EDG-related events.

These 98 ASP events occurred at 58 different plants, with only four plants accounting for more than two events; Fort Calhoun accounted for 4 events, and Crystal River 3, Brunswick 2, and McGuire 1 each accounted for three. The distribution of ASP events by CCDP shows that 28% had a CCDP of less than 1.0 E-5, 30% had a CCDP that ranged from 1.0 E-5 to 1.0 E-4, and 42% had a CCDP equal to or greater than 1.0 E-4. A summary of the events with a CCDP greater than 1.0 E-4 are provide in Table 20.

When these ASP events were compared with the operational data used in this study to assess EDG performance, only 7% of the EDG failure events identified in this study were also found in the ASP data. Of these EDG failures found in the ASP data, only one was an EDG failure during an unplanned demand. The other ASP events that identified EDG failures were conditions in which multiple EDGs at a plant were failed or were failures of EDGs resulting from a common cause mechanism.

There were 20 ASP events in which either no EDG was available to provide emergency power at an individual plant or a common cause failure of multiple EDGs occurred. These events had a CCDP that ranged from 2E-6 to 9E-4. The events were difficult to correlate with the CCDP, and were related to either simultaneous EDG failures or one EDG failure while the other EDG was out for maintenance. The ASP results for each of these events identified a potential need for the EDGs if a loss of offsite power was to occur. Of these 20 events, four were classified as common cause failures for this study, and three of these four events had the highest CCDPs.

Table 20. Summary of the EDG-related ASP events with CCDP greater than 1.0 E-4.

Plant name	LER number	Event date	CCDP	Description
Diablo Canyon	27588014*	05/05/88	4.1E-4	EDG 1-1 could not maintain load during surveillance test. A fungus in the day tanks and main fuel storage tanks resulted in a clogged primary fuel filter. The fungus would have affected all EDGs.
Duane Arnold	33187009*	05/27/87	3.3E-4	The B EDG automatically shutdown during performance of a LOCA actuation surveillance test. The trip was caused by an incorrect setpoint on a phase differential overcurrent relay. The relays on both EDGs were incorrectly set following their recent installation.
Fort Calhoun 1	28587025	07/08/87	6.2E-4	EDG 2 tripped on high coolant temperature when the exhaust air damper failed to open during a surveillance test. The air-operated damper failed to open as a result of water intrusion into the instrument air system. The water intrusion event also potentially affected EDG 1.
Fort Calhoun 1	28590020*	09/13/90	6.5E-4	During a performance test, the voltage regulator of EDG 1 failed. The failure was caused by overheating of the exciter cabinet from improper design. Both EDGs used the same exciter cabinet design.
McGuire 1	36990017*	06/26/90	2.7E-4	During surveillance testing, the 1A EDG failed to run and load properly. The cause was determined to be paint on the commutator rings and fuel racks. The same problems were found on the 1B EDG. Both EDGs had been painted four days prior to the surveillance test.

Table 20. Cont.

Plant name	LER number	Event date	CCDP	Description
Millstone 2	33691009*	08/21/91	2.1E-4	Both EDGs experienced erratic governor operation during surveillance testing. The cause was determined to be either an erratic electronic governor unit or contaminated hydraulic oil, or a combination of both.
Perry	44087009*	02/27/87	2.3E-4	During surveillance testing, both EDGs failed to start due to leaking control air solenoid valves.
Perry	44091009	03/14/91	5.3E-4	During surveillance testing, the Division 2 EDG failed to generate output voltage due to a contact failure in the control circuit. The Division 2 EDG failure required the Division 1 EDG be tested. However, during testing the Division 1 EDG's speed could not be controlled due to a failure of the governor control circuit, causing both EDGs to be inoperable.
Three Mile Island	28989002*	11/14/89	2.4E-4	During testing, the radiator fan drive train clutch overheated due to a seized bearing that resulted from lack of lubrication. Sludge was found in the gear drive units for both EDGs.
Turkey Point 3	25092009	08/27/92		EDG A for unit 3 tripped after 3.5 days of operation during Hurricane Andrew. No cause for the trip was identified and the EDG was restored in 2.5 hours with no further trips experienced.
Vogtle 1	42490006	03/20/90	9.7E-4	During a refueling outage with the B EDG tagged out

Table 20. Cont.

Plant name	LER number	Event date	CCDP	Description
				for maintenance, a truck hit a switchyard tower causing a loss of offsite power. The A EDG started but tripped, leaving the unit without power for 36 minutes until the A EDG could be restarted. The cause of the EDG A tripping was determined to be failure of the jacket water high temperature switches.

*. Indicates CCF event.

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Appendix A

EDG Train Data Collection and Analysis Methods

Appendix A

EDG Train Data Collection and Analysis Methods

To characterize emergency diesel generator (EDG) train performance, operational data pertaining to EDGs train from U. S. commercial nuclear power plants from 1987 through 1993 were collected and reviewed. For new plants, data started at the low-power license date. First, all reported EDG train events were screened; only those events that resulted in the loss of a safety function (failures) were further characterized. The failures and unplanned demands were studied from the perspective of overall trends and the existence of patterns in the performance of particular plants. Second, the failures were analyzed from an engineering perspective to identify the major performance issues. A quantitative analysis then focused on the failures for which EDG train demands could also be estimated. From a knowledge of these failures and the associated demands, occurrence probabilities for each failure mode and the associated unreliability were estimated.

Descriptions of the methods for the basic data characterization and the estimation of unreliability are presented below. The descriptions detail the methods, summarize the quality assurance measures used, and discuss some of the reasoning behind the choice of methods.

A-1. DATA COLLECTION AND CHARACTERIZATION

The sources of EDG train operational data used in this report were based on the LERs found using the Sequence Coding and Search System (SCSS) database, and the Special Reports pertaining to EDG performance found in the NRC's Nuclear Documents System (NUDOCS) database.

The SCSS database was searched for all EDG-related records for the years 1987–1993. The search criteria included all SCSS timing codes, actual pre-existing failures, previously detected failures, not previously detected failures, and potential failures. Actual pre-existing failures in the SCSS database include cases where the EDG train was out of service for maintenance. Along with the inclusion of all the timing codes, the search for EDG events included the engine and generator, and all attendant subsystems, which included the load shedding and sequencing controls. Each of the events identified from the SCSS database search were then independently reviewed by two engineers with commercial power plant experience from a risk and reliability perspective to determine the information necessary for subsequent analyses. Each event considered for the EDG train reliability estimate was also quality checked by the NRC technical monitor and a team of independent contractor consultants with extensive experience in risk assessments to ensure the event accurately represented EDG train performance relative to a risk-based mission.

A second SCSS database search was conducted to identify all unplanned engineered safety feature (ESF) actuations associated with an EDG train during the study period. Each of the events identified from the SCSS database search of EDG ESF actuations were then independently reviewed by two engineers with commercial power plant experience to determine whether the ESF actuation was in response to an actual low-voltage condition on the safety-related bus. The EDG ESF actuation in response to an actual low-voltage condition best represents the type of demand the EDG train would experience in a risk-based mission.

Differences that may exist among the plants in reporting EDG ESF actuations and failures were not considered in this report. It was assumed in this report that every plant was reporting EDG ESF actuations and failures as required by the LER rule, 10.CFR 50.73, and by the guidance in NUREG-1022, *Event Reporting Systems 10 CFR 50.72 and 50.73.*[A-1] EDG train events that were reported in accordance with the requirements of 10 CFR 50.72 were not used in this report because of the sparseness of the data provided in the 10 CFR 50.72 report as compared to the information provided in the LER. The LER data provide a more detailed account of the event, which is needed to determine successful operation or failure of the EDG train, the associated failure mode, and the failure mechanism and cause. The 10 CFR 50.72 report generally only provides a brief description of the event, which does not always contain enough data to determine failure modes or other important reliability- and risk-related information.

In addition to the LER-based SCSS data, EDG train failures resulting from a test are required by Regulatory Guide 1.108 *Periodic Testing of Diesel Generator Units Used as Onsite Electrical Power Systems*[A-2] to be documented in a Special Report for those plants reporting EDG train failures, both valid and invalid, in accordance with the reporting requirements of the regulatory guide. Approximately 60% of the plants are required to report EDG train failures during a test in accordance with requirements in Regulatory Guide 1.108. The specific plants reporting in accordance with the regulatory guide are identified in Table B-1. The Special Reports provide additional data that were not available through the LER reporting requirements. Therefore, the NUDOCS database was searched for all records that identified an EDG train Special Report for the 1987–1993 study period. Each of the events identified from the NUDOCS database search were then independently reviewed by two engineers with commercial power plant experience from a risk and reliability perspective to determine the information necessary for subsequent analyses. Each event that was considered for the reliability estimate for the EDG train was also quality checked in the same manner as the LERs discussed above.

Because a significant number of plants identified in Table B-1 are not required to report EDG train failures in accordance with the reporting requirements identified in Regulatory Guide 1.108, not all EDG train data are available for this report. The data available from these plants result from unplanned ESF actuations, any associated failures observed during the ESF actuations [10.CFR 50.73(a)(2)(iv)], and failures that occurred as the result of a common cause mechanism [10.CFR 50.73(a)(2)(vii)]. As a result of the reporting differences, the plants reporting in accordance with Regulatory Guide 1.108 and 10 CFR 50.73 provide the most complete data source for this study for performing plant-specific analyses. The information available from the LERs for the plants not reporting in accordance with Regulatory Guide 1.108 were too sparse to provide plant-specific analyses.

A-1.1 Failure Classification

As stated, not all EDG train events reported in the SCSS or NUDOCS databases resulted in an actual failure. The term *inoperability* is used here to describe any occurrence in which a plant reported an EDG train problem either in accordance with the requirements of 10.CFR 50.73 or Regulatory Guide 1.108. The term *failure*, which is also an inoperability, is an event for which the safety function of the EDG train was lost, i.e., the EDG train did not or could not supply electrical power to safety-related loads for the required mission time. The condition reported in the LER or Special Report was such that the EDG train would not have been reasonably capable of responding to a bus low-voltage condition or averting a station blackout event.

As a result of the focus of this study on predicting EDG train response during a loss of bus voltage condition, the classifications of the various EDG train failure modes found in this report are based on the criteria identified in NUREG/CR-2989, *Reliability of Emergency AC Power Systems at Nuclear Power Plants.*[A-3] NUREG/CR-2989 contains the results of a reliability analysis of the onsite ac power system relative to calculating the expected frequency of a station blackout. These criteria are different than those in Regulatory Guide 1.108 and Regulatory Guide 1.9, *Selection, Design, and Testing of Emergency Diesel Generator Units Used as Class 1E Onsite Electrical Power Systems.*[A-4] These two regulatory guides provide criteria for evaluating EDG train performance during testing, which do not always simulate a complete EDG train response as would be observed during a loss-of-offsite-power event.

The EDG train events identified as failures in this study represent actual malfunctions that prevented the successful operation of the EDG train. Slow engine starting times that exceeded technical specification requirements were not considered failures since facility analyses stated that a sufficient safety margin was present to preclude core damage even with a slow engine starting time. No starts greater than 19 seconds were observed in the data. Most late starts were generally 10 or 12 seconds in duration and were within a few seconds of the technical specification-required start time. EDG train events reported as potential failures because of inadequate seismic design, environmental qualification, or other similar concerns were not considered failures. Administrative inoperabilities, such as late performance of a surveillance test, did not constitute a failure for the purposes of this report. An example of an administrative inoperability that was excluded from this study would be that the fuel oil sampling requirements were performed too late for the delivery of fuel oil. The late fuel oil sample would not prevent the EDG from starting or running on a loss of power. In addition, EDG train events related to trouble-shooting activities, such as immediately after major maintenance and prior to the pos-tmaintenance test, were not considered as failures. Also, equipment malfunctions used solely for the purposes of testing the EDG and which did not affect the EDG's ability to operate were not considered as failures.

The events classified as failures in this report differ from the failures as defined by Regulatory Guides 1.108. For example, an EDG failure that occurs during surveillance testing with an EDG load less than 50%, or before one hour of a test run, would not be considered a failure per Regulatory Guide 1.108. However, many failures were observed in the operational data (i.e., during unplanned and test demands) that occurred within one hour after start and with loads less than 50%. These failure data are important in estimating the unreliability of the EDG, since during an actual emergency situation (i.e., station blackout), without a concurrent loss of coolant accident, the EDG load is expected to be less than 50%.

In addition, unsuccessful start and load attempts that can be definitely attributed to operator error were also potentially considered as failures in this report based on the nature of the personnel error. That is, operator error that would have prevented an automatic start and loading were considered failures; for example, an improper prestart line up or significant setting errors in the governor or voltage regulator controls. These types of errors would have prevented fulfillment of the EDG train design function. Personnel error events that were not considered as failures included operator error in paralleling to the grid or improper adjustment of voltage or speed controls. These were not considered as failures because these actions do not normally apply to an actual unplanned demand of the EDG train.

To estimate unreliability of the EDG train, classification of the failure events was necessary by failure mode. The detailed review of the operational data identified by the above mentioned database searches indicated that when the EDG receives an automatic start signal as a result of an under-voltage condition, the EDG is required to start, obtain rated speed and voltage, close the output breaker to the affected safety-related bus, sequence required loads onto the bus, and maintain power to the bus for the duration of the mission. Failure may occur at any point in this process. As a result, the following failure modes were observed in the operational data:

- Maintenance out of service (MOOS) occurred if, because of maintenance or testing, the EDG was prevented from starting.

- Failure to start (FTS) occurred if the EDG failed to automatically start, reach rated speed and voltage, close the output breaker, or sequence the loads onto its respective safety-related electrical bus.

- Self-initiated failure (SIF) is a failure of the EDG to successfully start. These failures were differentiated from the FTS events because the demand for the EDG train also caused the EDG train to fail. The demand and failure of the EDG was typically the result of a sequencer fault that strips the safety-related bus and subsequently prevents the bus from loading.

- Failure to run (FTR) occurred if, at any time after the EDG successfully started delivering electrical power to its safety-related electrical bus, the EDG failed to maintain electrical power while it was needed.

- Restoration failure-reset (RFR) is an incipient failure, that occurs when emergency actuation signals are reset and a protective trip signal (e.g., low cooling water flow/discharge pressure, high vibration, etc.) of the EDG is present. This condition would result in tripping the EDG and a potential interruption of power. This mode does not apply to all EDGs and depends on the design of the trip reset function.

- Restoration failure-power (RFP) is an incipient failure that occurs while attempting to restore the EDG to standby with the EDG operating in parallel with offsite power. During parallel operations, failure mechanisms exist (e.g., relevant to the performance of the voltage and speed regulators) for the EDG that are not present when the EDG is operating independent of offsite power. These failure mechanisms have the potential to trip the EDG and/or cause electrical disturbances on the electrical bus, potentially resulting in an interruption of power to the bus.

- Common cause failure (CCF) is a set of dependent failures resulting from a common mechanism in which more than one EDG train exists in a failed state at the same time, or within a short time interval.

The operational experience used for this report identified events pertaining to the recovery of a failed EDG train. Recovery of an EDG was only considered in the unplanned demand events, because these are the types of events where recovery of power to the safety-related bus is necessary. To recover an EDG train from a FTS event, operators have to recognize that the EDG was in a failed state, restart the EDG, and restore electrical power to the safety-related bus using the EDG. Recovery from a FTR was defined in a similar manner. Each failure reported during an unplanned demand was evaluated to determine whether recovery of the EDG train by operator actions had occurred. Some events identified recovery of power to the safety-related bus using off-site power when the EDG failed to respond to the bus low-voltage condition. These events were not considered a successful recovery of the EDG train because the EDG train was left in the failed state. In these events, the initiator of the bus low-voltage condition was actually corrected.

A-1.2 Run Times and Demands

For the reliability estimation process, demand counts or run times must be associated with failure counts. Three criteria are important in determining what types of demands or run times, and the associated failures, to consider in this process. First, a determination of whether the analysis will be based on demand counts or run times for each failure mode is required. Second, each demand or run time must reasonably approximate the conditions required for accident/transient response. Any test data used to estimate unreliability needed to be at least as stressful on the tested portion of the train as an unplanned demand. For this study, this requirement meant that the whole train must be exercised in the test. Third, counts or estimates of the number of demands or run time and associated failures must be reliable.

A-1.2.1 Choice of Analysis Based on Run Time or on Demands

Modeling the probability of failure on demand is natural for failure modes for which the train either operates or fails on demand, particularly when the stress that leads to failures is related to train usage rather than the passage of time. Time-based modeling of standby train failure requires detailed knowledge of testing intervals and the length of time that a failure could remain undetected, which is generally not available in this study. Therefore, the primary modeling method for the failure modes considered in this study is the modeling of the probability of failure on demand based on estimated or known failures and demand counts.

Failure modes such as failure to run given a successful start, on the other hand, are generally modeled based on failures in time. For these events, not all demands are equal; some require more run time than others. Knowledge of run times is required to estimate failure rates. For this study, for failure to run, three time periods having different failure rates were identified. Owing to lack of knowledge of run times for successful unplanned demands, a combination of time-based and demand-based estimates are used. The modeling process is described in Section A-1.2.3 below.

A-1.2.2 Demands

The identification of unplanned demands and of testing demands applicable for the estimation of EDG train reliability is discussed in subsections below.

Unplanned Demands. As discussed previously, a SCSS database search was conducted to identify all unplanned engineered safety feature (ESF) actuations associated with an EDG train during the study period. Each of the events identified from the SCSS database search of EDG ESF actuations were then independently reviewed to determine whether the ESF actuation was in response to an actual low-voltage condition on the safety-related bus. The EDG ESF actuation in response to an actual low-voltage condition that required the EDG train to provide electrical power to the affected bus with all required loads sequenced onto the bus was classified as an unplanned demand of the EDG train for this study. These full demands best represent the type of demand the EDG train would experience in a risk-based mission. Other ESF actuations of the EDG train that were not the result of a bus low-voltage condition were considered as partial demands and were not used in the unreliability estimates.

A partial demand of the EDG often resulted in the starting and obtaining rated speed and voltage of the engine and generator. However, the EDG train was not required to supply electrical power to the safety-related bus. These ESF actuations may have occurred either as a result of a valid or spurious safety injection signal, or human error. Events of this nature did not constitute a complete demonstration of the EDG train's safety function. Therefore, these events were excluded from the count of EDG unplanned demands.

For the events that were classified as an unplanned demand, the mission time for the unplanned demand was the time from the start of the under-voltage condition to restoration of normal electrical power to the safety-related bus. Even though an EDG may not be at design-rated load for an unplanned demand, the EDG mission was assumed to be successful if it carried the required load for the given plant conditions. For example, if a loss of normal power occurred on a safety-related bus and the EDG train restored ac power at 25% of full load (which was all the load that was required based on plant conditions), then the EDG train was considered as successfully completing its mission. The results of the search and subsequent classification of unplanned EDG train demands are presented in Appendix B.

Surveillance Tests. Data from surveillance tests that are performed on a periodic basis may be used to estimate EDG train unreliability for those plants filing Special Reports according to Regulatory Guide 1.108. Among these plants, only surveillance tests that are conducted on a cyclic interval (approximately every 18 months) were used in the unreliability estimation.

Plant technical specifications and Regulatory Guides 1.108 require a variety of surveillance tests. The frequency of the tests are generally monthly and every operating or refuel cycle (18 months). The later tests are referred to in this report as cyclic tests. Cyclic testing, is intended to most completely demonstrate the safety function capability of the EDG train even though the test may not be performed in a continuous manner. The following are the testing requirements of the cyclic surveillance test as presented in Regulatory Guide 1.108.

- To start the EDG by the safety features actuation system (SFAS) signal and verify the start circuits.

- To test the EDG sequencing circuits for loss of offsite power and SFAS loading schemes and time intervals and loading of actual loads to the maximum extent possible without damaging plant systems.

- To demonstrate the EDG operates for 24 hours, during which the first 2 hours the diesel generator is loaded to the maximum rated load, and the following 22 hours is loaded to rated load.

- To demonstrate the EDG can reject the largest load without tripping.

- To satisfy other technical specifications testing requirements.

- To verify the EDG will start from an auto-start signal within 5 minutes of its shutdown following the 24-hour run while simulating a loss of off-site power in conjunction with a safety features actuation signal.

Based on the completeness of the cyclic testing requirements that simulate automatic actuation of the EDG train up through completion of the sequencer actions to load the safety-related bus, the cyclic test demands and associated failures were also used in the estimation of reliability. The cyclic test's 24-hour loaded run segment does not simulate an actual emergency demand since it is performed with the EDG train paralleled with the grid rather than in an independent mode. However, the data do provide important insights into the ability of the EDG train to run for extended periods of time and therefore were used in the estimation of reliability.

Demand counts for cyclic surveillance tests were estimated as follows. The plants are required to perform the test at least every 18 months. These tests are typically scheduled to coincide with a refueling outage. The refueling outage start dates are found in the NRC's OUTINFO database, which is used to develop the operations cycle information for the Performance Indicator Report. For this study, a plant was assumed to perform the cyclic surveillance test at the start of each refueling outage. If the time period until the start of the next refueling outage was more than 550 days (18 months), the necessary number of intermediate tests were assumed. Cyclic test demands at a train level were estimated by multiplying these counts by the number of diesels assigned to each unit.

A partial demonstration (e.g., monthly surveillance testing) of the EDG train's capability was not considered as being representative of the EDG train's performance under actual accident conditions. Testing that does not demonstrate the EDG train's safety function completely as would be observed during a low-bus voltage condition was not used in the assessment of EDG train reliability. For example, the monthly testing requirements identified in Regulatory Guide 1.108 indicate that the sequencer and automatic start circuitry are not required to be tested. The following are the testing requirements of the monthly surveillance test as provided in Regulatory Guide 1.108.

- To verify that the EDG starts slow from a manual signal and accelerates to rated or idle speed and attain generator voltage and frequency (engine prelubrication is permissible).

- To verify operability of at least one of many diesel fuel oil transfer pumps.

- To verify quantities in the diesel fuel oil day tank and storage tank.

- To verify after the EDG is synchronized that it loads to rated KW and operates with this load for a period of at least 60 minutes.

- To verify that all interlocks of the service cooling water or radiators cooling system will start automatically if it is not already running when the EDG starts.

- To verify the normal "standby status" lineup of the EDG and its supporting auxiliary systems upon completion of this surveillance test.

In addition to monthly testing, semiannual testing is also required. The semiannual surveillance test is the same as the monthly surveillance test with the exception of the fast start acceptance criteria. The semiannual may be substituted for performance of the monthly surveillance. A fast start is performed every six months, to verify that the EDG starts from a manual start signal, accelerates to nominal speed, and attains generator voltage of 4160 VAC and frequency of 60 HZ within 10 seconds.

Because of the guidance in Regulatory Guide 1.108, monthly and semiannual test demands do not represent the type of demand that the EDG train would experience during a loss-of-voltage condition, and as a result, these tests cannot be used to estimate the reliability of the EDG train in avoiding or mitigating a station blackout event. These tests are simply manual starts (sometimes by partial simulation of an automatic start signal) with manual synchronization to the grid and controlled loading to full-rated EDG train power for one hour. This surveillance test does not represent an EDG train unplanned demand for emergency operation except for achieving proper voltage or speed, and the sequencer is not used for loading. However, of equal importance is the fact that the total number of EDG train demands for monthly EDG train testing cannot be reasonably determined. Regulatory Guide 1.108 requires increased monthly EDG train testing depending upon the failure history of each EDG train. The start and duration of this increased frequency of testing is not reportable and is therefore not retrievable from the data available for this study. In addition, for some plants, failures from monthly tests and post-maintenance tests are indistinguishable in the LERs and Special Reports. Since post-maintenance tests are not periodic, realistic demand counts for these tests cannot be estimated. Therefore, neither monthly nor post-maintenance test results were used for estimating unreliability.

A-1.2.3 Running Times

Running times influence the selection and use of data for estimating failure to run probabilities or rates. The feasibility of estimating a single constant failure rate or probability of failure to run was addressed by examination of both the unplanned demand and cyclic test data.

EDG running times for the successful unplanned demands used in this study were not reliably reported in the LERs. Furthermore, many of the running times were short, particularly when an event ended with successful and prompt recovery from the initial conditions that caused the loss of a bus. Therefore, unplanned demands were not suitable for showing whether the failure rate was constant.

A 24-hour run time is associated with each cyclic test. The known run times for the failures to run that occurred on the cyclic tests were sorted from small to large. For each run time, the number of failures with as short or a shorter run time was plotted as a function of the run time. With many such tests during the study period among the plants reporting according to Regulatory Guide 1.108, the expected number of failures in later periods during the 24 hours was not significantly reduced by the loss of demands caused by the earlier failures. If failures to run occurred at a constant rate during the 24-hr period, the resulting plot would be approximately linear. However, the plot was steep during the first half-hour and fairly flat after 14 hours. Therefore, failure to run was modeled separately for three time regimes: early (0 to 0.5 hours), middle (0.5 to 14 hours), and late (14 to 24 hours). A constant failure rate was assumed within each of these periods.

Since, for each period, constant failure rates were assumed, and the successful run times were constant (0.5, 13.5, and 10 hours, respectively), the data for each period were modeled as simple demands for performance during fixed mission times. Each such demand either failed or succeeded. Each period was modeled for the probability of running the duration of the period, given successful running at the start.

One-half hour was assumed for the minimum running time of unplanned demands for which the diesel ran successfully. Owing to running time uncertainty for the successes among the unplanned demands, the unplanned demands were considered for use for the early running period only.

A-1.3 Total Calendar Time

The reported EDG train failures and unplanned demands were characterized and studied from the perspective of overall trends and the existence of patterns in the performance of particular plant units. These assessments were based on rates of occurrence per year. Since the EDG trains are required for the plant at all times, i.e., both when a plant is operational and when it is shutdown, there was no need to derive the operational time for each plant. Instead, trends were studied based on calendar time for the plant from low-power license date (to decommissioning date, if applicable). It was also assumed that the original plant EDG trains were never replaced but were only maintained, and thus the ages of the EDG trains were the same as the total calendar time of the plant from the low power license date.

A-2. ESTIMATION OF UNRELIABILITY

As discussed in Section A-1.1, six standard failure modes were considered in the estimation of EDG train unreliability: common cause failures (CCF) during multiple unplanned demands, maintenance out of service (MOOS), FTS, failure to recover from FTS (FRFTS), FTR for the required duration of EDG train performance given a successful start, and failure to recover from FTR (FRFTR).

Although the CCF failures were analyzed separately as a side study in order to assess the probability and uncertainty of such failures, the particular events were retained in the overall data as, for example, failures to start or failures to run. Each such event was analyzed on a train level for the particular failure mode exhibited in the failure. Therefore, CCF was not a separate event in the quantification of unreliability. The unreliability quantified in this study applies to a single diesel and its associated supporting subsystems. No attempt was made in this study to quantify the reliability of the all the diesels at each plant. The latter reliability is affected not only by CCF but also by plant-specific attributes such as the availability of swing diesels for each unit.

The maintenance out of service events were analyzed separately for operational and shutdown periods. For the unreliability estimates, the operational period probability was used.

In quantifying the failure to start, two failures on unplanned demands that occurred while the plant was shutdown that were a result of the test, and that could only occur while the plant was shutdown in the test configuration, were excluded.

As stated above, the FTR event in the unreliability estimate was actually treated as three separate events: early failure to run (FTR_E), during the first half-hour; middle failure to run (FTR_M), during the 0.5-hour to 14-hour period, and late failure to run (FTR_L) (failure during the 14- to 24-hour period).

For reliability calculations, failure rates were computed from the three probabilities of failure to run. This approach allowed the unreliability calculated from the operational data to be tailored for comparison with mission times (ranging from 5 to 24 hours) assumed in PRA and station blackout studies. The approach specifically accounted for the fact that unreliability tends to increase as the mission time gets longer. Based on the failure rates (per hour), the probability of failure to run in any specified time interval can be found. (Details are described below).

The PRA/IPEs typically model recovery as a single act. For this study, two recovery modes were defined, because this division matches the data naturally.

In addition to the above standard failure types, three other failure modes were investigated for possible use in estimating unreliability. The first of these is self-initiated failures (SIF). These are events caused by abnormal EDG train lineups. As command faults, they are unrelated to the unreliability of the diesel train itself. That is, they are outside the boundary defined for the diesel system. Since they were found in the data, they are analyzed as a side topic. They were quantified using the unplanned demands that either occurred at power or reflected situations that were assessed as having the potential to occur at power.

The other two "new" failure modes were related to restoring offsite power to the bus and returning to normal plant operating conditions. Restoration failure upon reset (RFR) of the EDG train controls to non-emergency operating conditions occurred in the data. In addition, restoration failures during off-site power restoration (RFP) occurred.

The individual probabilities were combined to estimate the total unreliability, or probability of failure to start and run for the required mission time given a demand. Estimating the unreliability and the associated uncertainty involves two major steps: (a) estimating probabilities and uncertainties for the different failure modes, and (b) combining these estimates. These two steps are described below.

A-2.1 Estimates for Each Failure Mode

Estimating the probability for a failure mode required a decision about which data sets (unplanned demands, cyclic surveillance tests, or both) to use, a determination of the failure and demand counts in each data set, and a method for estimating the failure probability and assessing the uncertainty of the estimate. In addition, the failure to run mode required further analysis to account for uncertainty in whether three of the failure events occurred in the early, middle, or late period, and to obtain failure rates.

A-2.1.1 A Priori Choice of Data Sets

Maintenance unavailability can be measured only during unplanned demands. The same statement applies to self-initiated failures. Also, recovery of power is not required for an EDG train failure on a test.

Therefore, the failure modes MOOS, SIF, FRFTS, and FRFTR were found only in the unplanned demands, not in the cyclic surveillance tests. For the remaining failure modes, both unplanned demand and the cyclic test data were considered as possibly relevant. The data were examined as described below to show which sets were used.

A-2.1.2 Demand and Failure Counts

Unplanned Demands. The unplanned demands were counted by failure mode as follows. The total demand data set was obtained as described in Section A-1. The number of demands on the system relevant for common cause failures (CCFs) was the number of unplanned events where more than one EDG train was demanded and they were not in a maintenance condition when demanded. That is, counted unplanned demand records were those for which the number of diesels demanded was at least two greater than the number of associated MOOS failures. The number of MOOS demands was simply the number of EDG trains that were demanded, which can be obtained from the LERs. The number of demands to start was taken directly from the LERs, not counting any EDG trains that were out of service when demanded. The subset of this number describing events that occurred or could occur at power was the number of demands showing success or failure from SIF. The number of demands for recovery from fail to start, FRFTS, was the total number of failures to start. The number of demands to run was the number of demands to start minus the number of unrecovered FTS events. Within each of the three time periods for diesel running, the number of demands was the number of demands in the previous period that either did not fail or were recovered. The number of demands for recovery from FTR was the number of failures to run. The number of demands for estimating the restoration failure probabilities was the number of demands to run, minus the unrecovered failures to run.

The failures and demands were counted for each nuclear power plant unit. Recall that only those plants reporting under the requirements of Regulatory Guide 1.108 were used for the cyclic data analysis. The possibility of differences in event probabilities for unplanned demands between the reporting plants and the nonreporting plants was considered in the statistical analysis. This possibility is particularly of concern for common cause failures. The inclusion of nonreporting plants in the set of unplanned demands adds another possible source of variation between unplanned and cyclic demands. Statistical tests were performed to evaluate the feasibility of retaining simplicity and clarity by basing the study entirely on one set of plants known to have the stringent reporting requirements of Regulatory Guide 1.108.

Cyclic Tests. Cyclic surveillance tests are described in Section A-1.2.2. The number of cyclic surveillance test demands for each failure mode were estimated as follows. For each cyclic test, each of the EDG trains at the plant is tested for its ability to start and run. The EDG train is started three times, two of which represent emergency start sequences. Associated with the test is a 24-hour load test representing the loaded-run segment. The number of start demands (failure mode FTS) at each plant is the product of the number of diesels at the given plant times the number of plant-level cyclic surveillance tests, times two. The number of run demands (failure mode FTR_E) at each plant is the product of the number of EDG trains times the number of plant-level cyclic surveillance tests. For FTR_M, FTR_L, RFR, and RFP, the number of cyclic test demands was calculated the same way as for FTR_E. These estimates were obtained solely for the plants reporting in accordance with Regulatory Guide 1.108. Although the testing may be similar at all plants using diesel generators for emergency power, confidence in the reporting of single diesel train failures and in the recognition of series of such failures that may in fact be common cause applies just at the plants reporting in accordance with Regulatory Guide 1.108.

A-2.1.3 Data-Based Choice of Data Sets

At this point, failures and demands had been counted or estimated for two sets of data—unplanned demands and cyclic surveillance tests, for several failure modes. To determine which data to use for each mode, each failure probability and the associated 90% confidence interval was computed separately for unplanned demands and cyclic surveillance tests. Within the unplanned demands, these computations were also performed separately for the plants reporting in accordance with Regulatory Guide 1.108 and non-reporting plants. The confidence intervals assume binomial distributions for the number of failures observed in a fixed number of demands, with independent trials and a constant probability of failure in each data set. A comparison of the plotted confidence intervals gave a visual indication of whether the data sets could be pooled.

The hypothesis is that the underlying probability for unplanned demands and cyclic surveillance tests is the same as was tested for each failure mode. Fisher's exact test (described in many statistics books) was used, based on a contingency table with two rows corresponding to failures and successes and two columns corresponding to unplanned demands and cyclic surveillance tests. When the statistical test found no significant differences in the pairs of data sets, the data from unplanned demands and cyclic tests were combined.

The same methods were applied within the unplanned demands for plants reporting in accordance with Regulatory Guide 1.108 and the nonreporting plants. The action when no significant differences were observed was different, however. To preserve the simple approach of basing the analysis on one set of plants, the data for the nonreporting plants were set aside when no significant differences were seen.

For maintenance unavailability, an additional analysis was performed to identify in each data set whether significant differences existed in rates during operations and during shutdown periods.

To further characterize the failure probability estimates and their uncertainties, probabilities and confidence bounds were computed in each data set for each year and plant. The hypothesis of no differences across each of these groupings was tested in each data set, using the Pearson chi-square test. Often, the expected cell counts were small enough that the asymptotic chi-square distribution was not a good approximation for the distribution of the test statistic; therefore, the computed P-values were only rough approximations. They are useful for screening, however.

As with Fisher's exact test, a premise for these tests is that variation between subgroups in the data be less than the sampling variation, so that the data can be treated as having constant probabilities of failure across the subgroups. When statistical evidence of differences across a grouping is identified, the hypothesis is not satisfied. For such data sets, confidence intervals based on overall pooled data are too short, not reflecting all the variability in the data. However, the additional between-subgroup variation is likely to inflate the likelihood of rejecting the hypothesis of no significant systematic variation between years, plant units, or data sources, rather than to mask existing differences in these attributes.

A-2.1.4 Estimation of Failure Probability Distributions

This section describes how failure probabilities were estimated. Three methods of modeling the data for the unreliability calculations were employed. They all use Bayesian tools, with the unknown probability of failure for each failure mode represented by a probability distribution. An updated probability distribution, or *posterior* distribution, is formed by using the observed data to update an assumed *prior* distribution. One important reason for using Bayesian tools is that the resulting distributions for individual failure modes can be propagated easily, yielding an uncertainty distribution for the overall unreliability.

In all three methods, Bayes Theorem provides the mechanics for this process. The prior distribution describing failure probabilities is taken to be a *beta* distribution. The beta family of distributions provides a variety of distributions for quantities lying between 0 and 1, ranging from bell-shape distributions to J- and U-shaped distributions. Given a probability (p) sampled from this distribution, the number of failures in a fixed number of demands is taken to be binomially distributed. Use of the beta family of distributions for the prior on p is convenient because, with binomial data, the resulting output distribution is also beta. More specifically, if a and b are the parameters of a prior beta distribution, a plus the number of failures and b plus the number of successes are the parameters of the resulting posterior beta distribution. The posterior distribution thus combines the prior distribution and the observed data, both of which are viewed as relevant for the observed performance.

The three methods differ primarily in the selection of a prior distribution, as described below. After describing the basic methods, a summary section describes additional refinements that are applied in conjunction with these methods.

Simple Bayes Method. Where no significant differences were found between groups (such as plants), the data were pooled, and modeled as arising from a binomial distribution with a failure probability p. The assumed prior distribution was taken to be the Jeffreys noninformative prior distribution.[A-5] More specifically, in accordance with the processing of binomially distributed data, the prior distribution was a beta distribution with parameters a=0.5 and b=0.5. This distribution is diffuse and has a mean of 0.5. Results from the use of noninformative priors are very similar to traditional confidence bounds. See Atwood[A-6] for further discussion.

In the simple Bayes method, the data were pooled, not because there were no differences between groups (such as years), but because the sampling variability within each group was so much larger than the variability between groups that the between-group variability could not be estimated. The dominant variability was the sampling variability, and this was quantified by the posterior distribution from the pooled data. Therefore, the simple Bayes method used a single posterior distribution for the failure probability. It was used both for any single group and as a generic distribution for industry results.

Empirical Bayes Method. When between-group variability could be estimated, the *empirical Bayes* method was employed.[A-7] Here, the prior beta(a, b) distribution is estimated directly from the data for a failure mode, and it models between-group variation. The model assumes that each group has its own probability of failure, p, drawn from this distribution, and that the number of failures from that group has a binomial distribution governed by the group's p. The likelihood function for the data is based on the observed number of failures and successes in each group and the assumed beta-binomial model. This function of a and b was maximized through an iterative search of the parameter space, using a SAS routine.[A-6] In order to avoid fitting a degenerate, spike-like distribution whose variance is less than the variance of the observed failure counts, the parameter space in this search was restricted to cases where the sum, a plus b, was less than the total number of observed demands. The a and b corresponding to the maximum likelihood were taken as estimates of the generic beta distribution parameters representing the observed data for the failure mode.

The empirical Bayes method uses the empirically estimated distribution for generic results, but it also can yield group-specific results. For this, the generic empirical distribution is used as a prior, which is updated by group-specific data to produce a group-specific posterior distribution. In this process, the generic distribution itself applies for modes and groups, if any, for which no demands occurred (such as plants with no unplanned demands).

A chi-square test was one method used to determine if there were significant differences between the groups. But because of concerns about the appropriateness and power of the chi-square test, discomfort at drawing a fixed line between significant and nonsignificant, and an engineering belief that there were real differences between the groups, an attempt was made for each failure mode to estimate an empirical Bayes prior distribution over years, over stations, over plants, and over EDG train manufacturers. The fitting of a nondegenerate empirical Bayes distribution was used as the index of whether between-group variability could be estimated. The simple Bayes method was used only if no empirical Bayes distribution could be fitted, or if the empirical Bayes distribution was nearly degenerate, with smaller dispersion than the simple Bayes posterior distribution. Sometimes, an empirical Bayes distribution could be fitted even though the chi-square test did not find a between-group variation that was even close to statistically significant. In such a case, the empirical Bayes method was used, but the numerical results were almost the same as from the simple Bayes method.

When more than one empirical Bayes prior distribution was fitted for a failure mode, such as a distribution describing variation across plants and another one describing variation across years, the general principle was to select the distribution with the largest variability (highest 95th percentile). Exceptions to this rule were based on engineering judgment regarding the most logical and important sources of variation, or the needs of the application.

Alternate Method for Some Group-Specific Investigations. Occasionally, the unreliability was modeled by group (such as by plant or by year) to see if trends existed, such as trends resulting from time or age. The above methods tend to mask any such trend. The simple Bayes method pools all the data, and thus yields a single generic posterior distribution. The empirical Bayes method typically does not apply to all of the failure modes, and so masks part of the variation. Even when no differences can be seen between groups for any one failure mode, so that the above methods would pool the data for each failure mode, the failures of various modes could all be occurring in a few years or at a few plants. They could thus have a cumulative effect and show a clearly larger unreliability for those few years or plants. Therefore, it is useful to calculate the unreliability for each group (each year or plant) in a way that is very sensitive to the data from that one group.

It is natural, therefore, to update a prior distribution using only the data from the one group. The Jeffreys noninformative prior is suitably diffuse to allow the data to drive the posterior distribution toward any probability range between 0 and 1, if sufficient data exist. However, when the full data set is split into many groups, the groups often have sparse data and few demands. Any Bayesian update method pulls the posterior distribution toward the mean of the prior distribution. More specifically, with beta distributions and binomial data, the estimated posterior mean is $(a+f)/(a+b+d)$. The Jeffreys prior, with $a = b = 0.5$, thus pulls every failure probability toward 0.5. When the data are sparse, the pull toward 0.5 can be quite strong, and can result in every group having a larger estimated unreliability than the population as a whole. In the worst case of a group and failure mode having no demands, the posterior distribution mean is the same as that of the prior, 0.5, even though the overall industry experience may show that the probability for the particular failure mode is, for example, less than 0.1. Since industry experience is relevant for the performance of a particular group, a more practical prior distribution choice is a diffuse prior whose mean equals the estimated industry mean. Keeping the prior diffuse, and therefore somewhat noninformative, allows the data to strongly affect the posterior distribution, and using the industry mean avoids the bias introduced by the Jeffrey's prior distribution when the data are sparse.

To do this, the "constrained noninformative prior" was used, a generalization of the Jeffreys prior defined in Reference A-12 and summarized here. The Jeffreys prior is defined by transforming the binomial data model so that the parameter p is transformed, approximately, to a location parameter f. The uniform distribution for f is noninformative. The corresponding distribution for p is the Jeffreys noninformative prior.

This is generalized using the maximum entropy distribution[A-9] for *f*, constrained so that the corresponding mean of *p* is the industry mean from the pooled data, $(f+0.5)/(d+1)$. The maximum entropy distribution for *f* is, in a precise sense, as flat as possible subject to the constraint. Therefore, it is quite diffuse. The corresponding distribution for *p* is found. It does not have a convenient form, so the beta distribution for *p* having the same mean and variance is found. This beta distribution is referred to here as the constrained noninformative prior. It corresponds to an assumed mean for *p* but to no other prior information. For various assumed means of *p*, the noninformative prior beta distributions are tabulated in Reference A-8.

For each failure mode of interest, every group-specific failure probability was found by a Bayesian update of the constrained noninformative prior with the group-specific data. The resulting posterior distributions were pulled toward the industry mean instead of toward 0.5, but they were sensitive to the group-specific data because the prior distribution was so diffuse.

Additional Refinements in the Application of Group-Specific Bayesian Methods. For both the empirical Bayes distribution and the constrained noninformative prior distribution, beta distribution parameters are estimated from the data. A minor adjustment[A-10] was made in the posterior beta distribution parameters for particular plants and years to account for the fact that the prior parameters *a* and *b* are only estimated, not known. This adjustment increases the group-specific posterior variances somewhat.

Both group-specific failure probability distribution methods use a model, namely, that the failure probability *p* varies between groups according to a beta distribution. In a second refinement, lack of fit to this model was investigated. Data from the most extreme groups (plants, stations, manufacturer, or years) were examined to see if the observed failure counts were consistent with the assumed model, or if they were so far in the tail of the beta-binomial distribution that the assumed model was hard to believe. Two probabilities were computed, the probability that, given the resulting beta posterior distribution and binomial sampling, as many or more than the observed number of failures for the group would be observed, and the probability that as many or fewer failures would be observed. If either of these probabilities was low, the results were flagged for further evaluation of whether the model adequately fit the data. This test was most important with the empirical Bayes method, since the empirical Bayes prior distribution might not be diffuse. No strong evidence against the model was seen in this study. See Atwood[A-6] for more details about this test.

Group-specific updates were not used with the simple Bayes approach because this method is based on the hypothesis that significant differences in the groups do not exist.

A-2.1.5 Estimation of Failure Rate Distributions

Special methods were applied for the failure to run failure modes. As explained in the Running Times section above, the total mission time was divided into early, middle, and late periods, each of which was analyzed as having a separate failure probability using the methods described above. Three additional issues pertain to the results for FTR_E, FTR_M, and FTR_L. The first concerns uncertain failure times among the cyclic test failures, the second is the conversion of probabilities to rates, and the third is the use of probabilities and/or rates to compute failure to run probability estimates and distributions for various mission times.

Uncertainty in the failure times. Failure times from the LERs were uncertain for six events, involving seven failures, among the 27 cyclic test failures to run. Three of the events were known to have occurred in the first half-hour, though the exact run times were unknown. The existence of these failures precluded the estimation of a failure rate for the early run period based on the total number of failures and total run time. This uncertainty is a reason for modeling the first half-hour as a single period with a single failure probability instead of trying to determine the total run time among all the diesels tested for this period.

Two of the other three uncertain events could have occurred early, middle, or late, while the last event was known not to have occurred during the late time period. Among the cyclic run times for which the period was known, nine occurred during the early period, 13 during the middle period, and one in the late period. These counts were used to determine fractions for the probability of each unknown event occurring in each interval. For example, to mimic the rest of the data, the last event was assumed to occur in the early period with probability 9/(9+13) and in the middle period with probability 13/(9+13). To obtain failure probabilities and uncertainty distributions, data sets for each of the 3x3x2=18 possible scenarios for these events were constructed and analyzed separately using the failure probability distribution methods of Section A-2.1.4. A probability was assigned to each data set, namely, the product of the probabilities for the particular assignment of the three events. For example, the data set for which all the uncertain failure events were assigned to the middle period was given a probability of 13/23*13/23*13/22. For each data set, and for each of the three failure to run failure modes, simple Bayes and constrained noninformative Bayesian industry distributions were found, and empirical Bayes distributions were sought based on possible variation in plants and in calendar years. The empirical Bayes distributions that were found, and the constrained noninformative industry distributions, were each updated with plant-specific and with year-specific data. Where empirical Bayes distributions were not found, the simple Bayes distribution was assigned for each plant and year. For each resulting beta distribution, the first two moments were weighted by the data-set probabilities and summed across the eighteen data sets. The computed means and variances of the resulting mixture distributions were used to characterize the probability of failure to run for FTR_E, FTR_M, and FTR_L. For each of these three failure modes, industry, plant-specific, and year-specific distributions were obtained. Both best-estimate distributions and data-dependent distributions from the constrained noninformative prior were obtained by fitting beta distributions to the computed means and variances.

Although the duration of unplanned demands was often not known, they were believed to be nearly always more than 30 minutes and typically less than 14 hours. Therefore, the unplanned demand data were included in estimating the failure probabilities in the early time period, but were not used for the middle or late time periods. The cyclic test data were used for all three failure probabilities.

Conversion of probabilities to rates. The probability of a failure on demand in the time interval is $p=\lambda t$, where λ is the failure rate and t is the exposure time. The approximation is very good because failures to run are very rare. Therefore, the beta distributions for *p* were converted to gamma distributions for λ for each failure mode by equating the mean and variance of λ with that of p/t. The exposure time was 0.5 h for the early period, 13.5 h for the middle period, and 10 h for the late run period.

Computation of failure to run probabilities for different mission times. All the mission times of interest were greater than 0.5 hours, and thus the probability of early failure to run (p_{FTRE}) is considered in all the computations. For mission times T_G from 0.5 to 14 hours, the middle period failure to run probability must also be considered. Let prob[FTR_M] be the middle period probability for the full middle period, T_M=13.5 h. As just stated, this probability is prob[FTR_M] $\cong \lambda_M T_M$, where λ_M is the failure occurrence rate for the middle period. The probability for a shorter mission time, such as 8 total hours, is the probability of failure in the early period or in the first 7.5 hours of the middle period. The probability for the latter event is approximately λ_M*(T_G -0.5), or prob[FTR_M]*[(T_G-0.5)/T_M]. Therefore, the mean and variance for this probability can be obtained from the mean and variance of prob[FTR_M], the quantity directly estimated in the process that combined results over the 18 possible data sets. In this calculation, the rate itself is not needed, though the concept of the failure probability depending on the mission time and failure rate is.

In the unreliability calculations described in Section A-2.2, the FTR_M term is the full FTR_M probability for mission times exceeding 14 hours, and the proportionally scaled FTR_M probability shown above for mission times that are less than 14 hours.

The late run period is treated in the same way. For mission times that are less than 14 hours, the late run failure probability is zero. For mission times between 14 and 24 hours, the prob[FTR_L]term computed in the processing of the eighteen data sets is scaled by the portion of the mission time carrying into the late period, divided by the total hours in the late period (T_L=10 h). That is, the probability is

prob[FTR_L]*[(T_G-14.0)/T_L].

The total failure to run probability is the probability of the union of the FTR_E, FTR_M, and FTR_L events. Computations for this process are the same as for finding the union for any set of independent events, and are discussed in Section A-2.2.

A-2.2 The Combination of Failure Modes

The results for each failure mode must be combined to obtain the unreliability. For the primary results, stated in the body of this report, a fault tree was used to quantify the train failure probability.

For the group-specific investigations reported in Appendix C, performing a Monte Carlo simulation for each group is tedious. Therefore, the following algebraic approximation was used.

The method for calculation of unreliability is presented in more detail by Martz and Waller,[A-11] but is summarized for the present application here. According to the logic model, the unreliability for T_G hours is given by

Unreliability(T_G hrs) = Prob{MOOS or (FTS and FRFTS) or [(FTR_E or FTR_M or FTR_L) and FRFTR]}

where FTR_E is the failure to run probability for the full early period (0 to 0.5 hours), FTR_M is the failure to run probability for the part of the middle period covered by the mission time (the full FTR_M probability if T_G is equal or greater than 14 hours; otherwise, the probability for T_G-0.5 h of the 14 hours as explained in the previous section), and FTR_L is the probability for the portion of the mission time exceeding 14 hours (if any). FTR_L is zero if the mission time is less than or equal to 14 hours; otherwise, it is the portion of the full FTR_L included in the mission [(T_G-14.0)/10 hours, times the full FTR_L probability].

This can be rewritten by repeatedly using the facts that

Prob(*A* and *B*) = Prob(*A*)*Prob(*B*)
Prob(*A* or *B*) = 1 - Prob(not *A*)*Prob(not*B*) = 1 - [1 - Prob(*A*)]*[1 - Prob(*B*)]

where *A* and *B* are any independent events. The resulting algebraic expression is linear in each of the seven failure probabilities.

The estimated mean and variance of the unreliability can therefore be obtained by propagating the means and variances of the seven failure probabilities. These means and variances are readily available from the beta distributions. Propagation of the means uses the fact that the mean of a product is the product of the means, for independent random variables. Propagation of variances of independent factors is also readily accomplished, based on the fact that the variance of a random variable is the expected value of its square minus the square of its mean. In practice, estimates are obtained by the following process:

- Compute the mean and variance of each beta distribution

- Compute the mean and variance of the unreliability for each case using simple equations for expected values of sums for "or" operations and of products for "and" operations

- Compute parameters for the beta distribution with the same mean and variance

- Report the mean of the unreliability and the 5th and 95th percentiles of the fitted beta distribution.

The calculated means and variances are exact. The 5th and 95th percentiles are only approximate, however, because they assume that the final distribution is a beta distribution. Monte Carlo simulation for the percentiles is more accurate than this method if enough Monte Carlo runs are performed, because the output uncertainty distribution is empirical and not required to be a beta distribution. Nevertheless, the approximation seems to be close in cases where comparisons were made.

This process was applied using updated empirical Bayes distributions where they exist, and noninformative prior (Simple Bayes) distributions otherwise, for the PRA and station blackout comparisons in this report. For the station blackout comparisons, the probability of meeting the target was computed as the area under the beta density function estimated for the unreliability, going from 0 to one minus the target reliability. The SAS system provides a function giving this area.

The process was also applied with constrained uninformative priors updated with plant and year-specific data for each failure mode. The resulting unreliabilities were available for the calendar year and plant age trend assessments.

A-3. ESTIMATION OF RATE DISTRIBUTIONS FOR TREND ANALYSIS

In addition to the analyses used to estimate train unreliability, the overall rates of inoperabilities, failures, and unplanned demands were analyzed by plant and by year to identify possible trends and patterns. Two specific analyses were performed for these three occurrence rates. First, the rates were compared to determine whether significant differences exist among the plants or among the calendar years. Rates and confidence bounds were computed for each type of rate for each year and plant unit. The hypotheses of simple Poisson distributions for the occurrences with no differences across the year and plant groupings were tested using the Pearson chi-square test. The computed P-values are approximate since the expected cell counts were often small; however, they are useful for screening.

Regardless of whether particular years or plants were identified as having different occurrence rates, the occurrence rates were also modeled by plant and by year to see if trends exist. For plants, trends with regard to plant age were assessed, as measured from the plant low power license date. For years, calendar trends were assessed. Least-squares regression analyses are used to assess the trends. The paragraphs below describe certain analysis details associated with the rate trend analyses.

With sparse data, estimated event rates (event counts divided by time) are often zero, and regression trend lines through such data often produce negative rate estimates for certain groups (years or ages). Since occurrence rates cannot be negative, logarithmic models are considered. Thus, the analysis determines whether log(rate) is linear with regard to calendar time or age. An adjustment is needed in order to include rates that are zero in this model.

Using $0.5/t$ as a rate estimate in such cases is not ideal. Such a method penalizes groups that have no failures, increasing only their estimated rate. Furthermore, industry performance may show that certain events are very rare, so that $0.5/t$ is an unrealistically high estimate for a rate. A method that adjusts the rates uniformly for all the grouping levels (plants or years) and that uses the overall rate information contained in the industry mean is needed for sparse data and rare events.

Constrained noninformative priors similar to those constructed for probabilities (see Section A-2.1.4) can be formed for rates. This method meets the requirements identified above. Because it also produces occurrence rates for each group (each year or plant) in a way that is very sensitive to the data from that one group, it preserves trends that are present in the unadjusted rate data. The method, described in References A-8 and A-12, involves updating a prior distribution using only the data from a single group. For rates, such distributions are gamma distributions rather than beta distributions. Since industry experience is relevant for the performance of a particular group, a practical prior distribution choice is a diffuse prior whose mean equals the estimated industry mean, $(0.5+N)/T$, where N is the total number of events across the industry, and T is the total exposure time. This specification for the prior distribution mean is the constraint. Keeping the prior diffuse, and therefore somewhat noninformative, allows the data to strongly affect the posterior distribution. This goal is achieved by basing the modeling on a maximum entropy distribution. The details are explained in Reference A-8; the resulting prior distribution is a gamma distribution with shape parameter 0.5 and scale parameter $T/(2N+1)$. The mean of the updated posterior distribution is used in the regression trending. This process thus adds 0.5 uniformly to each event count and $T/(2N+1)$ to each group exposure time.

In practice, an additional refinement in the application of the constrained noninformative prior method adjusts the posterior gamma distribution parameters for particular plants and years to account for the fact that the prior distribution gamma scale parameter is only estimated, not known. This adjustment[A-10] increases the group-specific posterior variances somewhat.

A-4. REFERENCES

A-1. U.S. Nuclear Regulatory Commission, *Event Reporting Systems 10 CFR 50.72 and 50.73,* NUREG-1022.

A-2. U.S. Nuclear Regulatory Commission, *Periodic Testing of Diesel Generator Units Used as Onsite Electrical Power Systems*, Regulatory Guide 1.108.

A-3. R. E. Battle and D. J. Campbell, *Reliability of Emergency AC Power Systems at Nuclear Power Plants*, NUREG/CR-2989, July 1983.

A-4. U.S. Nuclear Regulatory Commission, *Selection, Design, Qualification, and Testing of Emergency Diesel Generator Units Used as Class 1E Onsite Electrical Power Systems at Nuclear Power Plants,* Regulatory Guide 1.9, Rev. 3, July 1993.

A-5. G. E. P. Box and G. C. Tiao, *Bayesian Inference in Statistical Analysis*, Reading, MA: Addison Wesley, 1973, Sections 1.3.4-1.3.5.

A-6. C. L. Atwood, *Hits per Trial*: Basic Analysis of Binomial Data, EGG-RAAM-11041, September 1994.

A-7. H. F. Martz and R. A. Waller, *Bayesian Reliability Analysis*, Malabar, FL: Krieger, 1991, Section 7.6.

A-8. C. L. Atwood, *Constrained Noninformative Priors*, INEL-94/0074, October 1994.

A-9. B. Harris, "Entropy," *Encyclopedia of Statistical Sciences*, Vol. 5, S. Kotz and N. L. Johnson, editors, 1982, pp. 512-516.

A-10. R. E. Kass and D. Steffey, "Approximate Bayesian Inference in Conditionally Independent Hierarchical Models (Parametric Empirical Bayes Models)," *Journal of the American Statistical Association, 84*, 1989, pp. 717-726, Equation (3.8).

A-11. H. F. Martz and R. A. Waller, "Bayesian Reliability Analysis of Complex Series/Parallel Systems of Binomial Subsystems and Components," *Technometrics, 32*, 1990, pp. 407-416.

A-12. M. E. Engelhardt, *Events in Time: Basic Analysis of Poisson Data*, EGG-RAAM-11088, September 1994.

Appendix B

EDG Train Operational Data, 1987–1993

Appendix B

EDG Train Operational Data, 1987–1993

The subsections below present lists of the data used for the EDG train performance study. The plants used are listed first. Then their unplanned demands are described, followed by a table of the identified EDG train failures. In addition, two tables are presented: (1) the events used in the unreliability estimates, and (2) a comprehensive list of the EDG train failures that occurred as a result of a common cause failure.

B-1. PLANTS USED

Table B-1 presents a complete list of the plants included in the study. EDG train failures and unplanned demands were collected from LERs and Special Reports submitted by the U.S. commercial nuclear power plants, listed in Table B-1, for the period from 1987 through 1993. For the new plants, data started from the low-power license date. Several plants were excluded owing to atypical EDG trains or because they were not operational during the study period: Big Rock Point, Browns Ferry Units 1 and 3, Fort St. Vrain, Humboldt Bay 3, Three Mile Island Unit 2, LaCrosse, Oconee Units 1, 2, and 3, and Shoreham. Table B-1 presents for each plant the respective utility, whether the plant is required to report EDG failures per Regulatory Guide 1.108, the EDG train manufacturer, model number, and the number of EDG trains.

Table B-1. Plants, utilities, and EDG train classifications.

Docket	Plant name	Utility name	Report per Regulatory Guide 1.108	Class 1E EDG System Manufacturer	Model	Number dedicated	Number swing
313	Arkansas 1[a]	Arkansas Power and Light Co.	No	EM	20-645-E4	2	0
368	Arkansas 2	Arkansas Power and Light Co.	Yes	FC	38TD8-1/8	2	0
334	Beaver Valley 1[a]	Duquesne Light Co.	No	EM	20-645TE4	2	0
412	Beaver Valley 2	Duquesne Light Co.	No	FC	12PC2V400/EG-BIOC	2	0
456	Braidwood 1[a]	Commonwealth Edison Co.	Yes	CB	KSV-20-T	2	0
457	Braidwood 2	Commonwealth Edison Co.	Yes	CB	KSV-20-T	2	0
260	Browns Ferry 2	Tennessee Valley Authority	Yes	EM	999-20/645E4	—c	4
325	Brunswick 1	Carolina Power & Light Co.	No	NM	NORDBERG-D-4900	2	0
324	Brunswick 2	Carolina Power & Light Co.	No	NM	NORDBERG-D-4900	2	0
454	Byron 1	Commonwealth Edison Co.	Yes	CB	KSV-20-T	2	0
455	Byron 2	Commonwealth Edison Co.	Yes	CB	KSV-20-T	2	0
483	Callaway	Union Electric Co.	Yes	FC	PC-2.5V	2	0
317	Calvert Cliffs 1[a]	Baltimore Gas & Electric Co.	No	FC	3800TD8-1/8	1	1
318	Calvert Cliffs 2	Baltimore Gas & Electric Co.	No	FC	3800TD8-1/8	1	—c
413	Catawba 1	Duke Power Co.	Yes	TD	DSRV-16-4	2	0
414	Catawba 2	Duke Power Co.	Yes	TD	DSRV-16-4	2	0
					R-16-645-E4		
461	Clinton	Illinois Power Company	Yes	EM	12-645-E4	2	0
445	Comanche Peak 1	Texas Utilities Generating Co.	Yes	TD	DSRV-16-4	2	0
446	Comanche Peak 2	Texas Utilities Generating Co.	Yes	TD	DSRV-16-4	2	0
315	Cook 1	Indiana & Michigan Elec. Co.	Yes	WC	SWB12CYL	2	0
316	Cook 2	Indiana & Michigan Elec. Co.	Yes	WC	SWB12CYL	2	0
298	Cooper	Nebraska Public Power District	No	CB	KSV-16T	2	0
302	Crystal River 3	Florida Power Corporation	No	FC	38TD8-1/8	2	0
346	Davis-Besse	Toledo Edison Co.	No	EM	20-645E4	2	0

Table B-1. (continued).

Docket	Plant name	Utility name	Report per Regulatory Guide 1.108	Class 1E EDG System Manufacturer	Model	Number dedicated	Number swing
275	Diablo Canyon 1	Pacific Gas & Electric Co.	Yes	AP	251F18GS	2	1
323	Diablo Canyon 2	Pacific Gas & Electric Co.	Yes	AP	251F18GS	2	—[c]
237	Dresden 2	Commonwealth Edison Co.	No	EM	20-645-E4	1	1
249	Dresden 3[a]	Commonwealth Edison Co.	No	EM	20-645-E4	1	—[c]
331	Duane Arnold	Iowa Electric Light & Power Co.	No	FC	3800TD8-1/8	2	0
348	Farley 1	Alabama Power Co.	Yes	FC	38TD8/PC2V400	2	1
364	Farley 2[a]	Alabama Power Co.	Yes	FC	38TD8/PC2V400	2	—[c]
341	Fermi 2	Detroit Edison Co.	Yes	FC	38TD8-1/8	4	0
333	FitzPatrick[a]	Power Auth. of the State of N.Y.	No	EM	20-645-E4	4	0
285	Fort Calhoun	Omaha Public Power District	No	EM	20-645-E4	2	0
244	Ginna[a]	Rochester Gas & Electric Corp.	No	AP	16-251-F	2	0
416	Grand Gulf	System Energy Resources Inc.	Yes	TD	DSRV-16-4	2	0
213	Haddam Neck	Conn. Yankee Atomic Power Co.	Yes	EM	20-645-E4	2	0
400	Harris[a]	Carolina Power & Light Co.	Yes	TD	DSRV-16-4	2	0
321	Hatch 1	Georgia Power Co.	Yes	FC	38TD8-1/8	2	1
366	Hatch 2	Georgia Power Co.	Yes	FC	38TD8-1/8	2	—[c]
354	Hope Creek	Public Service Electric & Gas Co.	Yes	FC	PC-2.3V	4	0
247	Indian Point 2	Consolidated Edison Co.	No	AP	251	3	0
286	Indian Point 3	Power Auth. of the State of N.Y.	No	AP	251E16	3	0
305	Kewaunee[a]	Wisconsin Public Service Corp.	No	EM	20-645-E4	2	0
373	LaSalle 1	Commonwealth Edison Co.	Yes	EM	20-645-E4	1	1
374	LaSalle 2	Commonwealth Edison Co.	Yes	EM	20-645-E4	1	—[c]
352	Limerick 1	Philadelphia Electric Co.	Yes	FC	38TD8 1/8-12	4	0
353	Limerick 2	Philadelphia Electric Co.	Yes	FC	38TD8 1/8-12	4	0
309	Maine Yankee[a]	Maine Yankee Atomic Power Co.	No	EM	20-645-E4	2	0
369	McGuire 1	Duke Power Co.	Yes	NM	FS-1316-HSC	2	0
370	McGuire 2	Duke Power Co.	Yes	NM	FS-1316-HSC	2	0
245	Millstone 1	Northeast Nuclear Energy Co.	No	FC	38TD8 1/8	1	0

Table B-1. (continued).

Docket	Plant name	Utility name	Report per Regulatory Guide 1.108	Class 1E EDG System: Manufacturer	Model	Number dedicated	Number swing
336	Millstone 2	Northeast Nuclear Energy Co.	No	FC	38TD8 1/8	2	0
423	Millstone 3	Northeast Nuclear Energy Co.	Yes	FC	14PC2V400	2	0
263	Monticello[a]	Northern States Power Co.	No	EM	20-645E4	2	0
220	Nine Mile Pt. 1	Niagara Mohawk Power Corporation	No	EM	20-645-E4	2	0
410	Nine Mile Pt. 2	Niagara Mohawk Power Corporation	Yes	CB	KSV16T	2	0
338	North Anna 1[a]	Virginia Electric & Power Co.	Yes	FC	38TD 1/8	2	0
339	North Anna 2	Virginia Electric & Power Co.	Yes	FC	38TD 1/8	2	0
219	Oyster Creek	GPU Nuclear	No	EM	20-645-E4	2	0
255	Palisades	Consumers Power Co.	No	AP	251F	2	0
528	Palo Verde 1	Arizona Public Service Co.	Yes	CB	KSV-20-T	2	0
529	Palo Verde 2	Arizona Public Service Co.	Yes	CB	KSV-20-T	2	0
530	Palo Verde 3	Arizona Public Service Co.	Yes	CB	KSV-20-T	2	0
277	Peach Bottom 2	Philadelphia Electric Co.	No	FC	38TD8-1/8	—[c]	4
278	Peach Bottom 3[a]	Philadelphia Electric Co.	No	FC	38TD8-1/8	—[c]	—[c]
440	Perry	Cleveland Elec. Illum. Co.	Yes	TD	DSRV-16-4	2	0
293	Pilgrim	Boston Edison Co.	No	AP	251F18GS	2	0
266	Point Beach 1	Wisconsin-Michigan Power Co.	No	EM	—[b]	—[c]	2
301	Point Beach 2[a]	Wisconsin-Michigan Power Co.	No	EM	—[b]	—[c]	—[c]
282	Prairie Island 1	Northern States Power Co.	No	FC	38TD8-1/8	2	0
306	Prairie Island 2	Northern States Power Co.	No	CL	UD 45 V16VS 5D	2	0
254	Quad Cities 1	Commonwealth Edison Co.	No	EM	20-645-E4	1	1
265	Quad Cities 2	Commonwealth Edison Co.	No	EM	20-645-E4	1	—[c]
312	Rancho Seco	Sacramento Municipal Util. District	No	EM	20-645-E4	4	0
458	River Bend	Gulf States Utilities	Yes	TD	DSR-48	2	0
261	Robinson 2	Carolina Power & Light Co.	No	FC	38TD8-1/8	2	0
272	Salem 1[a]	Public Service Electric & Gas Co.	Yes	AP	9X10-1/2 18-251	3	0
311	Salem 2	Public Service Electric & Gas Co.	Yes	AP	9X10-1/2 18-251	3	0
206	San Onofre 1[a]	Southern California Edison Co.	No	TD	DSRV-20-4	2	0

Table B-1. (continued).

				Class 1E EDG System			
Docket	Plant name	Utility name	Report per Regulatory Guide 1.108	Manufacturer	Model	Number dedicated	Number swing
361	San Onofre 2[a]	Southern California Edison Co.	Yes	EM	20-645E4	2	0
362	San Onofre 3[a]	Southern California Edison Co.	Yes	EM	20-645E4	2	0
443	Seabrook	Public Service Co. of New Hampshire	Yes	FC	16-PC-2.3V	2	0
327	Sequoyah 1	Tennessee Valley Authority	Yes	EM	R16-645-E4	2	0
328	Sequoyah 2	Tennessee Valley Authority	Yes	EM	R16-645-E4	2	0
498	South Texas 1	Houston Lighting and Power Co.	Yes	CB	KSV-20-T	3	0
499	South Texas 2	Houston Lighting and Power Co.	Yes	CB	KSV-20-T	3	0
335	St. Lucie 1	Florida Power & Light Co.	Yes	EM	R16-645-E4	2	0
389	St. Lucie 2	Florida Power & Light Co.	Yes	EM	R16-645-E4	2	0
395	Summer	South Carolina Electric & Gas Co.	Yes	FC	12PC2V400	2	0
280	Surry 1	Virginia Electric & Power Co.	No	EM	20-645E4	1	1
281	Surry 2	Virginia Electric & Power Co.	No	EM	20-645E4	1	—[c]
387	Susquehanna 1	Pennsylvania Power & Light Co.	Yes	CB	KSV-16-T	—[c]	5
388	Susquehanna 2	Pennsylvania Power & Light Co.	Yes	CB	KSV-20-T	—[c]	—[c]
289	Three Mile Isl 1	GPU Nuclear	No	FC	3800TD8-1/8	2	0
344	Trojan[a]	Portland General Electric Co.	No	EM	R16-645-E4	2	0
250	Turkey Point 3	Florida Power & Light Co.	Yes	EM	20-645-E4	2	0
251	Turkey Point 4	Florida Power & Light Co.	Yes	EM	S20-645-F4B	2	0
271	Vermont Yankee	Vermont Yankee Nuclear Power Corp.	No	FC	38TD8 1/8	2	0
424	Vogtle 1	Georgia Power Co.	Yes	TD	DSRV-16-4	2	0
425	Vogtle 2	Georgia Power Co.	Yes	TD	DSRV-16-4	2	0
397	Wash. Nuclear 2	Wash. Public Power Supply System	Yes	EM	20-645-E4	2	0
382	Waterford 3	Louisiana Power & Light Co.	Yes	CB	KSV16T	2	0
482	Wolf Creek	Kansas Gas & Electric Co.	Yes	FC	P.C. 2.5V	2	0
029	Yankee-Rowe	Yankee Atomic Electric Co.	No	EM	—[b]	3	0
295	Zion 1	Commonwealth Edison Co.	Yes	CB	KSV-16	2	1
304	Zion 2	Commonwealth Edison Co.	Yes	CB	KSV-16	2	—[c]

Table B-1. (continued).

Docket	Plant name	Utility name	Report per Regulatory Guide 1.108	Class 1E EDG System Manufacturer	Model	Number dedicated	Number swing

a. No EDG train failures were found in the operational data at this plant.

b. Information was not available.

c. Indicates shared EDG trains between units.

B-2. EDG TRAIN UNPLANNED DEMANDS

The EDG train unplanned demands were derived from LERs reporting EDG train ESF actuations from 1987 through 1993. Events that occurred prior to the plant's low-power license date and after the decommissioning date were excluded from the study. An EDG train unplanned demand for the purposes of this study occurred if the EDG train was either manually started or started automatically in response to a low-voltage condition on the respective safety-related bus and the EDG output breaker closed and loads sequenced on the safety-related bus. An EDG train demand was also counted (1) if a failure of the EDG train occurred during the manual or automatic start sequence, (2) or the EDG train was out of service for maintenance or testing at the time of an actual low-voltage condition on the respective safety-related bus. Table B-2 presents the list of EDG train unplanned demands for each plant reporting EDG train failures in accordance with Regulatory Guide 1.108 by plant name. Table B-2A presents the list of EDG train unplanned demands for each plant *not* reporting EDG train failures in accordance with Regulatory Guide 1.108 by plant name.

Table B-2. Emergency diesel generator unplanned demands for the plants reporting per Regulatory Guide 1.108.

Plant name	LER number	Event date	Unit mode	Number of demands
Arkansas 2	36890016	07/16/90	Cold shutdown	1
Braidwood 1	45687048	09/11/87	Cold shutdown	2
Braidwood 1	45688022	10/16/88	Operate	2
Braidwood 2	45788004	01/29/88	Cold shutdown	1
Byron 2	45587019	10/02/87	Operate	2
Callaway	48389008	06/23/89	Operate	1
Callaway	48390015	11/19/90	Operate	1
Catawba 1	41387042	11/17/87	Cold shutdown	1
Catawba 1	41389001	01/07/89	Cold shutdown	1
Catawba 1	41391018	09/06/91	Operate	1
Comanche Peak 1	44591019	06/09/91	Operate	2
Comanche Peak 1	44591021	07/28/91	Operate	2
Cook 1	31591004	05/12/91	Operate	2

Table B-2. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Cook 2	31687007	07/14/87	Operate	1
Cook 2	31690001	01/12/90	Cold shutdown	1
Diablo Canyon 1	27587014	08/25/87	Operate	1
Diablo Canyon 1	27591004	03/07/91	Refuel	3
Diablo Canyon 2	32387019	08/14/87	Operate	1
Diablo Canyon 2	32388007	06/30/88	Operate	1
Diablo Canyon 2	32388008	07/17/88	Operate	3
Diablo Canyon 2	32388012	10/10/88	Refuel	3
Farley 1	34891009	08/19/91	Operate	2
Farley 1	34892006	10/28/92	Cold shutdown	1
Farley 1	34892007	11/28/92	Hot standby	1
Farley 2	36487005	11/11/87	Refuel	2
Farley 2	36487006	11/15/87	Refuel	1
Fermi 2	34188019	05/07/88	Start up	2
Fermi 2	34189003	01/10/89	Cold shutdown	2
Fermi 2	34189023	09/24/89	Refuel	2
Haddam Neck	21389009	05/23/89	Operate	1
Haddam Neck	21393009	06/22/93	Cold shutdown	2
Haddam Neck	21393010	06/26/93	Cold shutdown	2
Harris	40087011	03/07/87	Hot standby	1
Harris	40087059	10/11/87	Cold shutdown	1
Harris	40088013	06/03/88	Operate	1
Harris	40088035	12/21/88	Operate	1
Harris	40090012	04/15/90	Operate	1
Harris	40093007	05/23/93	Operate	1

Table B-2. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Hope Creek	35493003	05/13/93	Operate	2
LaSalle 1	37392015	12/01/92	Refuel	1
LaSalle 1	37393015	09/14/93	Operate	2
McGuire 1	36987021	09/16/87	Cold shutdown	1
McGuire 1	36988038	11/29/88	Cold shutdown	1
McGuire 1	36991001	02/11/91	Operate	2
McGuire 2	36988014	06/24/88	Refuel	2
McGuire 2	37092002	03/05/92	Cold shutdown	1
McGuire 2	37093008	12/27/93	Operate	2
Millstone 3	42387027	06/05/87	Operate	1
Millstone 3	42387038	11/10/87	Refuel	1
Nine Mile Pt. 2	41089010	03/21/89	Cold shutdown	1
Nine Mile Pt. 2	41092006	03/23/92	Refuel	2
Nine Mile Pt. 2	41092018	07/28/92	Operate	1
Nine Mile Pt. 2	41092020	09/25/92	Operate	1
Nine Mile Pt. 2	41092023	11/05/92	Operate	1
Nine Mile Pt. 2	41093001	01/05/93	Operate	1
Nine Mile Pt. 2	41093001	08/17/93	Operate	1
Nine Mile Pt. 2	41093008	11/07/93	Cold shutdown	1
North Anna 1	33887013	06/14/87	Cold shutdown	1
North Anna 1	33888020	08/06/88	Operate	1
North Anna 1	33889006	03/23/89	Cold shutdown	1
North Anna 1	33889010	04/16/89	Cold shutdown	2
North Anna 1	33891010	04/23/91	Operate	1
North Anna 2	33990002	08/02/90	Operate	1
North Anna 2	33990009	10/28/90	Cold shutdown	1
North Anna 2	33991002	05/14/91	Operate	1

Table B-2. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Palo Verde 1	52888003	01/16/88	Operate	2
Palo Verde 1	52888010	07/06/88	Operate	2
Palo Verde 1	52888019	07/22/88	Cold shutdown	1
Palo Verde 1	52889016	09/02/89	Refuel	1
Palo Verde 1	52891004	03/20/91	Operate	1
Palo Verde 1	52893003	02/13/93	Operate	1
Palo Verde 2	52989001	01/03/89	Operate	2
Palo Verde 2	52992002	03/23/92	Operate	2
Palo Verde 2	52992004	06/19/92	Operate	2
Palo Verde 3	53088004	04/06/88	Operate	1
Palo Verde 3	53091006	08/24/91	Operate	1
Palo Verde 3	53091010	11/15/91	Hot standby	1
River Bend	45888005	02/11/88	Operate	1
River Bend	45889029	06/12/89	Cold shutdown	1
Salem 1	27290008	03/27/90	Operate	2
Salem 1	27291022	06/06/91	Operate	1
Salem 1	27291022	06/13/91	Operate	1
Salem 1	27292009	04/06/92	Refuel	1
Salem 1	27293012	06/09/93	Hot standby	1
Salem 1	27293016	10/21/93	Refuel	2
Salem 1	27293017	11/06/93	Refuel	1
Salem 2	31190037	09/22/90	Operate	1
Salem 2	31191012	08/26/91	Operate	1
Salem 2	31192001	01/04/92	Refuel	1
Salem 2	31192013	07/27/92	Operate	1
San Onofre 2	36189014	11/06/89	Cold shutdown	1

Table B-2. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Seabrook	44389010	08/15/89	Cold shutdown	1
Seabrook	44391008	06/27/91	Operate	2
Sequoyah 1	32787016	02/27/87	Cold shutdown	1
Sequoyah 1	32787019	03/18/87	Cold shutdown	1
Sequoyah 1	32787060	08/27/87	Cold shutdown	1
Sequoyah 1	32788026	06/29/88	Cold shutdown	1
Sequoyah 1	32790005	04/09/90	Refuel	1
Sequoyah 1	32790014	06/25/90	Operate	1
Sequoyah 1	32792027	12/31/92	Operate	2
Sequoyah 1	32793015	06/14/93	Refuel	1
Sequoyah 2	32888034	08/15/88	Operate	1
Sequoyah 2	32792027	12/31/92	Operate	2
South Texas 1	49887021	11/30/87	Cold shutdown	1
South Texas 1	49888026	03/30/88	Operate	1
South Texas 1	49888057	10/04/88	Cold shutdown	1
South Texas 1	49889006	01/21/89	Cold shutdown	1
South Texas 1	49890014	06/20/90	Operate	1
South Texas 1	49890026	12/19/90	Cold shutdown	1
South Texas 1	49891004	02/15/91	Refuel	1
South Texas 1	49891007	03/09/91	Cold shutdown	3
South Texas 1	49891013	04/12/91	Cold shutdown	1
South Texas 2	49989001	01/06/89	Cold shutdown	2
South Texas 2	49989003	02/03/89	Cold shutdown	1
South Texas 2	49989005	03/20/89	Start up	2
South Texas 2	49989009	04/05/89	Operate	1
South Texas 2	49989014	04/18/89	Cold shutdown	1
South Texas 2	49989017	07/13/89	Operate	1
St. Lucie 1	33590005	04/18/90	Cold shutdown	1

Table B-2. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
St. Lucie 2	38987001	03/03/87	Operate	1
St. Lucie 2	38992003	05/26/92	Operate	1
Summer	39587011	06/03/87	Hot standby	1
Summer	39589012	07/11/89	Operate	2
Summer	39590007	04/23/90	Refuel	1
Summer	39590008	05/05/90	Cold shutdown	1
Summer	39591010	11/06/91	Cold shutdown	1
Summer	39592008	11/14/92	Operate	1
Turkey Point 3	25087012	05/07/87	Cold shutdown	1
Turkey Point 3	25092009	08/24/92	Hot standby	3
Turkey Point 4	25187012	07/05/87	Hot standby	2
Turkey Point 4	25092009	08/24/92	Hot standby	3
Vogtle 1	42490006	03/20/90	Refuel	1
Vogtle 1	42490006	03/20/90	Refuel	2
Vogtle 1	42490006	03/20/90	Refuel	1
Vogtle 1	42493004	04/10/93	Refuel	1
Vogtle 2	42589023	07/20/89	Operate	1
Vogtle 2	42590002	03/20/90	Operate	1
Wash. Nuclear 2	39789016	05/14/89	Cold shutdown	1
Waterford 3	38290003	03/29/90	Operate	1
Waterford 3	38290012	08/25/90	Operate	1
Waterford 3	38292018	09/30/92	Refuel	1
Wolf Creek	48287030	07/20/87	Operate	1
Wolf Creek	48287048	10/14/87	Refuel	1
Wolf Creek	48290014	06/13/90	Operate	1

Table B-2. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Wolf Creek	48290023	10/23/90	Operate	1
Zion 1	29588015	07/15/88	Hot standby	1
Zion 1	29591017	11/08/91	Hot standby	1
Zion 2	30491002	03/21/91	Operate	1

Table B-2A. Emergency diesel generator unplanned demands for the plants *not* reporting per Regulatory Guide 1.108.

Plant name	LER number	Event date	Unit mode	Number of demands
Arkansas 1	31389040	12/05/89	Cold shutdown	1
Arkansas 1	31389040	12/06/89	Cold shutdown	1
Arkansas 1	31393002	03/09/93	Operate	1
Beaver Valley 1	33489013	11/12/89	Cold shutdown	1
Beaver Valley 1	33493013	10/12/93	Operate	3
Beaver Valley 2	41287036	11/17/87	Operate	2
Beaver Valley 2	41288002	01/27/88	Operate	1
Beaver Valley 2	41288004	02/01/88	Cold shutdown	1
Beaver Valley 2	41289012	04/27/89	Cold shutdown	1
Beaver Valley 2	41290019	11/05/90	Operate	1
Brunswick 1	32587006	03/03/87	Refuel	1
Brunswick 1	32588001	01/04/88	Operate	1
Brunswick 1	32589026	12/10/89	Operate	1
Brunswick 1	32593008	03/16/93	Cold shutdown	2
Brunswick 2	32489009	06/17/89	Operate	2
Brunswick 2	32491005	06/30/91	Operate	1
Brunswick 2	32491016	10/05/91	Refuel	1
Brunswick 2	32593008	03/16/93	Cold shutdown	2
Brunswick 2	32493011	11/22/93	Operate	1
Calvert Cliffs 1	31787012	07/23/87	Operate	3
Calvert Cliffs 1	31793003	06/10/93	Operate	3
Cooper	29887016	05/26/87	Startup	2
Cooper	29887017	07/07/87	Operate	2
Cooper	29887018	08/06/87	Operate	2
Cooper	29889020	05/29/89	Cold shutdown	1

Table B-2A. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Cooper	29893008	03/28/93	Cold shutdown	1
Cooper	29893022	05/14/93	Cold shutdown	1
Crystal River 3	30287021	10/14/87	Refuel	1
Crystal River 3	30287025	10/16/87	Refuel	1
Crystal River 3	30289023	06/16/89	Operate	2
Crystal River 3	30289025	06/29/89	Hot standby	1
Crystal River 3	30291010	10/20/91	Cold shutdown	1
Crystal River 3	30292002	03/27/92	Operate	2
Crystal River 3	30293002	03/29/93	Cold shutdown	2
Crystal River 3	30293004	04/08/93	Cold shutdown	1
Davis-Besse	34687011	09/06/87	Operate	1
Dresden 2	23790002	01/16/90	Operate	2
Dresden 2	23790011	10/27/90	Cold shutdown	1
Dresden 2	23792033	10/15/92	Operate	1
Dresden 3	24989001	03/25/89	Operate	2
Duane Arnold	33188016	10/17/88	Refuel	1
Duane Arnold	33189011	08/26/89	Operate	1
Duane Arnold	33190007	07/09/90	Refuel	2
Fitzpatrick	33388011	10/31/88	Refuel	2
Fort Calhoun	28587008	03/21/87	Refuel	2
Fort Calhoun	28590006	02/26/90	Refuel	2
Ginna	24488006	07/16/88	Operate	2
Ginna	24489002	05/06/89	Refuel	1
Ginna	24490009	06/09/90	Hot shutdown	1
Ginna	24491002	03/04/91	Operate	1
Ginna	24491002	03/07/91	Operate	1

Table B-2A. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Ginna	24492007	12/24/92	Operate	1
Indian Point 2	24787004	02/10/87	Operate	3
Indian Point 2	24790016	12/03/90	Operate	2
Indian Point 2	24791006	03/20/91	Refuel	3
Indian Point 2	24791010	06/22/91	Cold shutdown	2
Indian Point 3	28687009	05/15/87	Cold shutdown	2
Indian Point 3	28688006	10/09/88	Operate	1
Maine Yankee	30988006	08/13/88	Operate	2
Millstone 1	24589012	04/29/89	Refuel	1
Millstone 2	33688002	01/19/88	Refuel	1
Millstone 2	33688011	10/25/88	Operate	2
Millstone 2	33692012	07/06/92	Refuel	1
Nine Mile Pt. 1	22089002	03/08/89	Refuel	1
Nine Mile Pt. 1	22089002	03/11/89	Refuel	1
Nine Mile Pt. 1	22090023	11/12/90	Operate	2
Nine Mile Pt. 1	22093007	08/31/93	Operate	2
Oyster Creek	21989015	05/18/89	Operate	2
Oyster Creek	21992005	05/03/92	Operate	2
Palisades	25587012	04/17/87	Operate	1
Palisades	25587024	07/14/87	Operate	2
Palisades	25590020	11/10/90	Refuel	1
Palisades	25592029	04/04/92	Cold shutdown	1
Palisades	25592032	04/06/92	Cold shutdown	2
Palisades	25593005	07/20/93	Refuel	1
Peach Bottom 2	27787004	04/07/87	Cold shutdown	1

Table B-2A. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Peach Bottom 2	27788020	07/29/88	Refuel	2
Peach Bottom 2	27790006	04/02/90	Cold shutdown	1
Peach Bottom 2	27792010	07/04/92	Operate	1
Peach Bottom 3	27888009	08/31/88	Cold shutdown	1
Pilgrim	29387005	03/31/87	Cold shutdown	2
Pilgrim	29387014	11/12/87	Cold shutdown	2
Pilgrim	29389010	02/21/89	Refuel	2
Pilgrim	29391024	10/30/91	Hot standby	2
Pilgrim	29393004	03/13/93	Operate	2
Pilgrim	29393010	05/19/93	Refuel	2
Pilgrim	29393022	09/10/93	Operate	2
Point Beach 1	26692003	04/28/92	Refuel	1
Point Beach 1	26693007	07/26/93	Operate	1
Point Beach 2	30189002	03/29/89	Operate	2
Prairie Island 1	28290007	05/17/90	Operate	1
Quad Cities 2	26587013	10/19/87	Operate	1
Quad Cities 2	26592011	04/02/92	Refuel	1
Rancho Seco	31287028	05/14/87	Cold shutdown	1
Robinson 2	26192017	08/22/92	Operate	2
Surry 1	28089005	02/04/89	Cold shutdown	2
Surry 1	28089010	04/06/89	Cold shutdown	2
Surry 1	28089013	04/13/89	Cold shutdown	2
Surry 1	28089044	12/21/89	Operate	1
Surry 1	28090004	05/22/90	Operate	1
Surry 1	28090006	07/01/90	Operate	1

Table B-2A. (continued).

Plant name	LER number	Event date	Unit mode	Number of demands
Surry 1	28090017	12/02/90	Cold shutdown	2
Surry 1	28091018	08/26/91	Operate	2
Three Mile Isl 1	28987002	03/02/87	Refuel	1
Trojan	34487010	05/11/87	Refuel	1
Vermont Yankee	27187008	08/17/87	Refuel	2
Vermont Yankee	27191009	04/23/91	Operate	2
Vermont Yankee	27191012	04/23/91	Operate	2
Yankee-Rowe	02987008	05/31/87	Refuel	2
Yankee-Rowe	02987010	06/01/87	Refuel	2
Yankee-Rowe	02988002	03/22/88	Operate	1
Yankee-Rowe	02988003	03/26/88	Operate	1
Yankee-Rowe	02988008	05/17/88	Operate	2
Yankee-Rowe	02988010	11/16/88	Cold shutdown	1
Yankee-Rowe	02991002	06/15/91	Operate	3

B-3. EDG TRAIN FAILURES

The search of the SCSS and NUDOCs databases resulted in the identification of 446 events for all plants during the 1987 through 1993 time period in which at least one EDG train failure occurred. Table B-3 provides the column heading definitions for Tables B-4 and B-4A. Table B-4 lists the events for the plants reporting failures in accordance with Regulatory Guide 1.108. Table B-4A lists the events for the plants *not* reporting failures in accordance with Regulatory Guide 1.108.

EDG train failures that occurred prior to a plant's low-power license date or after the decommissioning date were excluded. The events that were identified by a Special Report are listed in Table B-4 with a 5-digit number that identifies plant docket and year of report. Unique numbering similar to the LER numbering requirements are not used for Special Reports.

The events for which the method of discovery is equal to "A" and "S(C)" and the failure mode was either, FTS, FTR, or MOOS, are events that were considered for calculations of the failure probabilities used for comparison with the PRA/IPEs.

Table B-3. Column heading abbreviations used in Tables B-4 and B-4A.

Column	Definition	
Unit Mode	Unit mode at the time of the failure	
	(PWRs)	PO = mode 1 = >5% Power,
		SU = mode 2 = startup,
		HS = mode 3 = hot standby > 350F,
		HD = mode 4 = hot shutdown 200-350F,
		CD = mode 5 = cold shutdown,
		RF = mode 6 = refuel
		UN = unknown
		U = plant at power = OUTINFO data were used to determine whether the plant was at power or shutdown, LER/SR was indeterminate.
		D = plant shut down = OUTINFO data were used to determine whether the plant was at power or shutdown, LER/SR was indeterminate.
	(BWRs)	PO = mode 1 = run mode,
		SU = mode 2 = start up,
		HS = not used for BWRs
		HD = mode 3 = hot shutdown >200F,
		CD = mode 4 = cold shutdown,
		RF = mode 5 = refuel
		UN = unknown

Table B-3. (continued).

Column	Definition
	U = plant at power = OUTINFO data were used to determine whether the plant was at power or shutdown, LER/SR was indeterminate. D = plant shut down = OUTINFO data were used to determine whether the plant was at power or shutdown, LER/SR was indeterminate.
EDG train manufacturer	AP = ALCO Power (GE of England) CB = Cooper Bessemer EM= Electro Motive (General Motors) FC = Fairbanks Morse/Colt NM= Nordberg Mfg. TD = Transamerica Delaval WC = Worthington Corp.
Number of failures	The number of failures listed in this column is the number of actual EDG train failures that occurred. If a component failed for one EDG train and the similar component was replaced on all the other EDG trains at the site for precautionary reasons, only one failure was recorded. The column also represents the failure of more than one EDG train or the same EDG train more than once. Failures in quick succession for the same reason are *not* considered multiple failures. Separate entries are used for unrelated failures from the same LER or Report.
Subsystem	A = air start system C = cooling system E = electrical (generator or breaker system, including power and control for them, including sequencer, load shed circuits) F = fuel system including the governor (i.e., all Woodward failures even if associated with the electric controls for it) H = HVAC I = instrument and controls relating to start or shutdown, including control circuit power L = lubrication oil system M = mechanical, i.e., overspeed trip etc.
Method of discovery	A = actual unplanned demand O = other than S or an A S = surveillance testing S(C) = cyclic surveillance testing
FLMD	Failure Mode

Table B-3. (continued).

Column	Definition
	FTS = failure to start
	FTR = failure to run
	MOOS = maintenance out of service
	RFR = restoration failure that identifies an EDG train failure that could result in an EDG train trip during restoration of the EDG train to non-emergency operating conditions, usually when ECCS actuations are reset
	RFP = restoration failure that identifies an EDG train parallel operation failure that could result in an EDG train trip during restoration of offsite power
	SIF = self-initiated failure
Recovered	Recovery (only applies to failures found during unplanned demands)
	T—True if operators recovered the failure
	F—False if not recovered

Table B-4. Emergency diesel generator failures for the plants reporting per Regulatory Guide 1.108.

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Arkansas 2	36888003	03/10/88	RF	FC	1	I	O	FTS	
Arkansas 2	36892004	04/24/92	CD	FC	1	F	S	FTR	
Braidwood 2	45788004	01/29/88	CD	CB	1	E	A	SIF	F
Braidwood 2	45788	08/03/88	U	CB	1	F	S	RFP	
Braidwood 2	45790004	04/16/90	RF	CB	1	F	S(C)	FTS	
Braidwood 2	45790	11/14/90	U	CB	1	E	S	FTS	
Braidwood 2	45793	09/28/93	U	CB	1	I	O	FTS	
Browns Ferry 2	26089023	07/23/89	CD	EM	1	I	S(C)	FTR	
Browns Ferry 2	26089026	08/10/89	CD	EM	1	A	O	FTS	
Byron 1	45488	05/16/88	PO	CB	1	F	S	RFP	
Byron 1	45489004	03/28/89	PO	CB	1	F	S	FTS	
Byron 1	45489005	05/01/89	PO	CB	1	F	S	FTS	
Byron 1	45491	09/22/91	CD	CB	1	A	S(C)	FTS	
Byron 1	45491	09/27/91	CD	CB	1	E	S(C)	FTS	
Byron 1	45492	07/01/92	PO	CB	1	F	O	RFP	
Byron 2	45587012	07/30/87	PO	CB	1	M	S	FTR	
Byron 2	45588003	03/29/88	PO	CB	1	A	O	FTS	
Byron 2	45588	06/15/88	PO	CB	1	E	S	RFP	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Byron 2	45588	10/05/88	PO	CB	1	F	S	RFP	
Byron 2	45592	03/20/92	D	CB	1	M	O	FTR	
Byron 2	45592	04/07/92	D	CB	1	F	O	FTR	
Callaway	48387002	04/01/87	PO	FC	1	E	S	FTS	
Callaway	48387002	04/01/87	PO	FC	1	F	O	FTR	
Callaway	48389001	02/07/89	PO	FC	1	F	S	FTR	
Callaway	48389	03/30/89	U	FC	1	C	O	FTR	
Callaway	48389	04/01/89	D	FC	1	E	S	FTS	
Callaway	48389008	06/23/89	PO	FC	1	I	A	MOOS	F
Callaway	48390	09/24/90	CD	FC	1	E	S(C)	FTS	
Callaway	48391	08/14/91	U	FC	1	F	S	FTS	
Callaway	48393	12/02/93	RF	FC	1	E	O	FTS	
Catawba 1	41387011	03/05/87	PO	TD	1	I	O	RFR	
Catawba 1	41388019	10/07/87	D	TD	1	I	S	FTS	
Catawba 1	41388019	11/13/87	D	TD	1	I	O	FTS	
Catawba 1	41387042	11/17/87	CD	TD	1	E	A	FTS	F
Catawba 1	41388019	12/01/87	D	TD	1	I	S(C)	FTS	
Catawba 1	41388	03/07/88	U	TD	1	E	O	FTS	
Catawba 1	41388019	03/22/88	PO	TD	1	I	S	FTS	
Catawba 1	41388019	04/12/88	PO	TD	1	I	S	FTS	
Catawba 1	41388019	04/19/88	U	TD	1	I	S	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Catawba 1	41388019	04/25/88	U	TD	1	I	S	FTS	
Catawba 1	41388019	05/05/88	U	TD	1	I	S	FTS	
Catawba 1	41389001	01/07/89	CD	TD	1	I	A	MOOS	F
Catawba 1	41389	01/27/89	D	TD	1	M	S	FTR	
Catawba 1	41389	08/09/89	PO	TD	1	E	O	RFP	
Catawba 1	41390	10/12/90	PO	TD	1	I	O	RFR	
Catawba 1	41391	04/15/91	RF	TD	1	I	O	RFR	
Catawba 1	41391	04/25/91	D	TD	1	C	S	RFR	
Catawba 1	41391	10/09/91	U	TD	1	F	O	FTS	
Catawba 1	41391	11/24/91	PO	TD	1	I	S	RFR	
Catawba 1	41393	12/03/93	RF	TD	1	I	S	RFR	
Catawba 1	41393	12/06/93	RF	TD	1	E	O	FTS	
Catawba 2	41488	01/15/88	D	TD	1	F	S(C)	FTS	
Catawba 2	41488	01/15/88	D	TD	1	I	O	FTS	
Catawba 2	41388019	01/15/88	U	TD	1	I	S	FTS	
Catawba 2	41488	03/14/88	HD	TD	1	F	S	FTS	
Catawba 2	41388019	04/12/88	PO	TD	1	I	S	FTS	
Catawba 2	41489	09/20/89	PO	TD	1	I	S	RFR	
Catawba 2	41490	04/11/90	U	TD	1	F	S	FTS	
Catawba 2	41491	01/15/91	U	TD	1	I	S	RFR	
Catawba 2	41491010	09/11/91	PO	TD	1	C	S	FTR	
Catawba 2	41491	10/19/91	RF	TD	1	I	S(C)	RFR	
Catawba 2	41491	11/07/91	RF	TD	1	I	S(C)	RFR	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Catawba 2	41493	01/13/93	PO	TD	1	I	S	RFR	
Catawba 2	41493	01/31/93	CD	TD	1	I	S(C)	RFR	
Catawba 2	41493	02/03/93	CD	TD	1	I	O	RFR	
Clinton	46189	10/30/89	U	EM	1	E	S	RFP	
Clinton	46190011	05/14/90	SU	EM	1	C	S	FTR	
Clinton	46191	04/04/91	U	EM	1	E	S	FTS	
Clinton	46192	03/28/92	RF	EM	1	F	O	FTS	
Clinton	46192	07/17/92	U	EM	1	E	S	FTS	
Clinton	46192	09/21/92	U	EM	1	E	S	FTS	
Clinton	46193	06/23/93	U	EM	1	E	S	RFP	
Clinton	46193	09/27/93	CD	EM	1	E	S(C)	FTS	
Comanche Peak 1	44592	05/28/92	U	TD	1	I	S	RFR	
Comanche Peak 1	44592	05/28/92	U	TD	1	I	O	RFR	
Cook 1	31592002	02/06/92	PO	WC	1	F	S	FTS	
Cook 2	31692008	09/28/92	CD	WC	1	L	S	FTS	
Diablo Canyon 1	27587014	08/25/87	PO	AP	1	E	A	SIF	F
Diablo Canyon 1	27588014	05/05/88	RF	AP	1	F	S(C)	FTR	
Diablo Canyon 1	27590	04/30/90	PO	AP	1	E	S	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Diablo Canyon 1	27590	09/20/90	PO	AP	1	F	O	FTS	
Diablo Canyon 2	32388012	10/10/88	RF	AP	1	I	A	MOOS	F
Diablo Canyon 2	32388	11/12/88	CD	AP	1	I	S(C)	FTS	
Diablo Canyon 2	32392	12/29/92	PO	AP	1	E	S	FTS	
Farley 1	34890008	11/12/90	PO	FC	1	E	S	RFP	
Fermi 2	34187	01/30/87	U	FC	1	I	S	FTS	
Fermi 2	34187	06/25/87	U	FC	1	E	O	RFP	
Fermi 2	34187	09/05/87	U	FC	1	F	S	RFR	
Fermi 2	34187	09/26/87	U	FC	1	F	S	RFR	
Fermi 2	34188	04/12/88	D	FC	1	F	S	RFP	
Fermi 2	34188	04/20/88	D	FC	1	F	S(C)	FTS	
Fermi 2	34188	04/25/88	D	FC	1	E	S(C)	FTS	
Fermi 2	34189023	09/24/89	RF	FC	1	I	A	MOOS	F
Fermi 2	34189	10/23/89	D	FC	1	E	S	RFP	
Fermi 2	34191002	02/14/91	PO	FC	1	F	S	RFP	
Fermi 2	34191002	02/15/91	PO	FC	1	F	S	RFP	
Fermi 2	34193	12/16/93	U	FC	1	F	S	FTS	
Grand Gulf	41687	03/05/87	U	TD	1	E	S	FTR	
Grand Gulf	41687	11/26/87	RF	TD	1	I	S	RFR	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Grand Gulf	41688	03/02/88	U	TD	1	L	S	RFR	
Grand Gulf	41688	03/30/88	U	TD	1	L	S	RFR	
Grand Gulf	41688	04/15/88	U	TD	1	C	S	FTR	
Grand Gulf	41688	06/08/88	U	TD	1	I	O	RFR	
Grand Gulf	41688015	09/15/88	PO	TD	1	C	O	FTR	
Grand Gulf	41688	12/14/88	U	TD	1	E	S	RFP	
Grand Gulf	41689	12/18/89	U	TD	1	E	S	FTR	
Grand Gulf	41690	11/27/90	U	TD	1	E	S	FTR	
Grand Gulf	41691	05/13/91	U	TD	1	E	S	FTS	
Grand Gulf	41692	01/28/92	U	TD	1	E	S	RFP	
Grand Gulf	41692	05/25/92	D	TD	1	E	O	FTR	
Grand Gulf	41692	06/23/92	U	TD	1	I	S	RFR	
Grand Gulf	41692	09/15/92	U	TD	1	I	S	RFR	
Grand Gulf	41692	10/14/92	U	TD	1	M	O	FTR	
Haddam Neck	21391	11/06/91	RF	EM	1	E	O	FTS	
Haddam Neck	21393006	05/25/93	RF	EM	1	E	S	FTR	
Hatch 1	32189015	10/09/89	PO	FC	1	F	S	FTS	
Hatch 2	36692004	03/16/92	PO	FC	1	F	O	FTR	
Hope Creek	35491	05/22/91	U	FC	1	F	S	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
LaSalle 1	37388005	04/22/88	RF	EM	1	F	S(C)	RFP	
LaSalle 1	37388012	06/08/88	RF	EM	1	F	S(C)	FTS	
LaSalle 1	37388012	06/08/88	RF	EM	1	F	O	FTR	
LaSalle 1	37391	04/03/91	RF	EM	1	F	S(C)	FTS	
LaSalle 2	37492	01/18/92	RF	EM	1	E	O	FTS	
Limerick 1	35288022	06/09/88	PO	FC	1	I	O	FTS	
Limerick 1	35288	11/07/88	U	FC	1	E	S	FTS	
Limerick 1	35290019	09/15/90	RF	FC	1	E	S(C)	FTS	
Limerick 1	35290022	10/03/90	RF	FC	1	E	O	FTS	
Limerick 1	35293013	10/26/93	PO	FC	1	A	S	FTS	
Limerick 2	35389005	08/03/89	CD	FC	1	L	S	FTR	
Limerick 2	35390021	12/06/90	PO	FC	1	E	S	RFP	
Limerick 2	35391005	04/01/91	CD	FC	1	E	S(C)	FTR	
Limerick 2	35391009	05/21/91	CD	FC	1	E	S(C)	FTR	
Limerick 2	35391	08/23/91	PO	FC	1	F	O	FTR	
Limerick 2	35392001	01/04/92	PO	FC	1	I	O	FTS	
Limerick 2	35392	07/30/92	PO	FC	1	F	S	FTS	
Limerick 2	35392	11/25/92	PO	FC	1	E	S	RFP	
Limerick 2	35392013	11/30/92	PO	FC	1	F	S	FTS	
Limerick 2	35393	01/02/93	PO	FC	1	F	S	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
McGuire 1	36987014	07/28/87	PO	NM	1	I	O	FTS	
McGuire 1	36987030	09/08/87	CD	NM	1	F	O	FTR	
McGuire 1	36987021	09/16/87	RF	NM	1	I	A	MOOS	F
McGuire 1	36988	05/19/88	PO	NM	1	L	S	RFR	
McGuire 1	36988	05/25/88	U	NM	1	I	O	RFR	
McGuire 1	36988	05/25/88	U	NM	1	L	S	FTR	
McGuire 1	36988	10/17/88	CD	NM	1	I	S	RFR	
McGuire 1	36988	11/05/88	RF	NM	1	E	S	RFP	
McGuire 1	36989	10/30/89	U	NM	1	F	S	FTR	
McGuire 1	36990	03/03/90	D	NM	1	C	O	RFR	
McGuire 1	36990	03/04/90	D	NM	1	I	O	RFR	
McGuire 1	36990017	06/26/90	PO	NM	1	F	S	FTS	
McGuire 1	36990017	06/26/90	PO	NM	1	F	O	FTS	
McGuire 1	36991	06/16/91	U	NM	1	C	O	FTR	
McGuire 2	36988010	06/01/88	CD	NM	1	I	S(C)	FTS	
McGuire 2	36988011	06/01/88	CD	NM	1	F	S(C)	FTR	
McGuire 2	37088	06/02/88	CD	NM	1	L	S(C)	FTR	
McGuire 2	36988014	06/24/88	RF	NM	1	I	A	FTS	F
McGuire 2	37088	06/24/88	RF	NM	1	L	O	FTR	
McGuire 2	37088	12/15/88	PO	NM	1	L	S	FTS	
McGuire 2	37089	03/28/89	U	NM	1	M	S	RFR	
McGuire 2	37089	07/27/89	RF	NM	1	E	O	FTR	
McGuire 2	37089	07/30/89	D	NM	1	L	S(C)	RFR	
McGuire 2	37089	09/28/89	U	NM	1	I	S	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
McGuire 2	37089	10/05/89	U	NM	1	I	S	FTS	
McGuire 2	37089	10/27/89	U	NM	1	A	S	FTS	
McGuire 2	37089012	11/08/89	CD	NM	1	E	S(C)	FTR	
McGuire 2	37090	10/10/90	RF	NM	1	I	S(C)	FTR	
McGuire 2	37091012	11/07/91	U	NM	1	C	S	FTR	
McGuire 2	37091	12/31/91	U	NM	1	I	S	FTS	
Millstone 3	42388	09/06/88	PO	FC	1	F	S	FTS	
Millstone 3	42392	02/18/92	U	FC	1	C	S	RFR	
Nine Mile Pt. 2	41088036	07/21/88	PO	CB	1	C	S	FTS	
Nine Mile Pt. 2	41088	12/21/88	D	CB	1	L	O	FTR	
Nine Mile Pt. 2	41089	02/15/89	D	CB	1	F	S	FTS	
Nine Mile Pt. 2	41089030	09/20/89	CD	CB	1	E	S	FTS	
Nine Mile Pt. 2	41089	12/02/89	D	CB	1	F	S	FTS	
Nine Mile Pt. 2	41090	01/29/90	D	CB	1	F	S	FTR	
Nine Mile Pt. 2	41090	09/30/90	RF	CB	1	E	O	FTS	
Nine Mile Pt. 2	41091	05/21/91	U	CB	1	F	O	FTR	
Nine Mile Pt. 2	41091	05/21/91	D	CB	1	I	S	RFR	
Nine Mile Pt. 2	41091	09/15/91	U	CB	1	E	O	RFP	
Nine Mile Pt. 2	41092006	03/23/92	RF	CB	1	I	A	MOOS	F
Nine Mile Pt. 2	41092	04/06/92	RF	CB	1	E	S	FTS	
Nine Mile Pt. 2	41092	04/29/92	RF	CB	1	F	S(C)	FTR	
Nine Mile Pt. 2	41092	04/30/92	RF	CB	1	F	S(C)	FTR	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Nine Mile Pt. 2	41092	08/13/92	U	CB	1	I	S	RFR	
Nine Mile Pt. 2	41093001	08/17/93	U	CB	1	I	A	MOOS	F
North Anna 2	33987001	02/09/87	PO	FC	2	F	O	FTS	
North Anna 2	33988004	05/20/88	PO	FC	1	E	S	FTS	
Palo Verde 1	52888	03/04/88	HS	CB	1	E	S	FTS	
Palo Verde 1	52889016	09/02/89	RF	CB	1	E	A	SIF	F
Palo Verde 2	52987	02/08/87	CD	CB	1	F	S	FTR	
Palo Verde 3	53087	10/13/87	HS	CB	1	F	S	FTS	
Palo Verde 3	53089004	01/04/89	PO	CB	1	M	O	FTR	
Palo Verde 3	53090003	03/28/90	PO	CB	1	F	O	FTS	
Perry	44087009	02/27/87	PO	TD	2	A	O	FTS	
Perry	44089	12/22/89	U	TD	1	E	S	FTS	
Perry	44091009	03/14/91	PO	TD	1	E	S	FTS	
Perry	44091009	03/14/91	PO	TD	1	F	S	RFP	
River Bend	45888	01/28/88	U	TD	1	L	S	FTS	
River Bend	45889	05/17/89	D	TD	1	I	S	RFR	
River Bend	45889	08/23/89	U	TD	1	I	S	RFR	
River Bend	45889	10/17/89	PO	TD	1	I	S	RFR	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
River Bend	45889	11/14/89	PO	TD	1	I	S	RFR	
River Bend	45891	02/20/91	U	TD	1	C	S	FTR	
River Bend	45891	08/05/91	U	TD	1	I	S	RFR	
River Bend	45891	11/12/91	PO	TD	1	I	S	RFR	
River Bend	45892	10/13/92	PO	TD	1	I	S	RFR	
River Bend	45893	07/15/93	D	TD	1	C	S	RFR	
Salem 2	31188	08/04/88	PO	AP	1	F	S	FTS	
Salem 2	31189	09/09/89	PO	AP	1	C	S	FTR	
Salem 2	31190	01/09/90	U	AP	1	F	S	FTS	
Salem 2	31190	05/02/90	RF	AP	1	M	S(C)	FTR	
Salem 2	31190	05/18/90	RF	AP	1	C	S(C)	FTR	
Salem 2	31190	05/21/90	RF	AP	1	C	S(C)	FTR	
Salem 2	31191	05/23/91	PO	AP	1	A	O	FTS	
Salem 2	31191	05/25/91	PO	AP	1	C	O	FTS	
Salem 2	31192	03/02/92	CD	AP	1	C	S(C)	FTR	
Salem 2	31192	03/05/92	CD	AP	1	F	O	FTS	
Salem 2	31192	09/24/92	PO	AP	1	M	S	FTR	
Seabrook	44391	09/11/91	RF	FC	1	A	O	FTR	
Seabrook	44391	09/16/91	RF	FC	1	A	S(C)	FTR	
Seabrook	44392410	12/16/92	PO	FC	1	E	S	FTS	
Seabrook	44393	12/16/93	U	FC	1	F	S	RFP	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Sequoyah 1	32787060	08/27/87	RF	EM	1	F	O	FTR	
Sequoyah 1	32787060	08/27/87	CD	EM	1	I	A	MOOS	F
Sequoyah 1	32789014	05/06/89	PO	EM	1	I	O	FTS	
Sequoyah 2	32893	08/21/93	D	EM	1	F	S	FTS	
Sequoyah 2	32893	12/28/93	U	EM	1	E	S	FTS	
South Texas 1	49888	03/16/88	D	CB	1	E	S	RFP	
South Texas 1	49888	07/07/88	U	CB	1	F	S	RFP	
South Texas 1	49888	08/13/88	HS	CB	1	I	S	RFR	
South Texas 1	49888	08/26/88	PO	CB	1	I	O	RFR	
South Texas 1	49888	10/27/88	PO	CB	1	I	O	FTS	
South Texas 1	49888	12/04/88	D	CB	1	E	S	RFP	
South Texas 1	49889	04/06/89	PO	CB	1	F	S	FTS	
South Texas 1	49889	05/23/89	PO	CB	1	F	O	RFP	
South Texas 1	49889	05/24/89	PO	CB	1	I	O	RFR	
South Texas 1	49889	06/08/89	U	CB	1	I	O	RFR	
South Texas 1	49889	08/05/89	CD	CB	1	C	O	RFR	
South Texas 1	49889	08/07/89	CD	CB	1	C	O	RFR	
South Texas 1	49889023	12/16/89	PO	CB	1	E	S	FTS	
South Texas 1	49890	02/09/90	PO	CB	1	E	S	FTR	
South Texas 1	49890	08/29/90	PO	CB	1	I	S	RFR	
South Texas 1	49891	01/17/91	RF	CB	1	F	S	RFP	
South Texas 1	49891	03/05/91	RF	CB	1	E	S(C)	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
South Texas 1	49891	12/12/91	PO	CB	1	E	S	RFP	
South Texas 1	49892	07/08/92	PO	CB	1	I	S	RFR	
South Texas 1	49892	10/07/92	D	CB	1	M	O	RFR	
South Texas 1	49892	10/08/92	D	CB	1	F	O	FTR	
South Texas 1	49892	10/14/92	D	CB	1	F	S	FTS	
South Texas 1	49892	10/16/92	RF	CB	1	M	S(C)	RFR	
South Texas 1	49892	12/09/92	HS	CB	1	F	S	FTR	
South Texas 1	49893	09/19/93	U	CB	1	E	S	FTS	
South Texas 2	49989	11/03/89	U	CB	1	F	S	FTS	
South Texas 2	49989	11/21/89	D	CB	1	E	S(C)	FTR	
South Texas 2	49989	11/28/89	CD	CB	1	M	S(C)	FTR	
South Texas 2	49990	11/26/90	CD	CB	1	F	S(C)	FTR	
South Texas 2	49991	07/10/91	PO	CB	1	L	O	FTS	
South Texas 2	49991	09/04/91	PO	CB	1	E	S	RFR	
South Texas 2	49991	09/13/91	PO	CB	1	E	S	FTS	
South Texas 2	49991	10/06/91	RF	CB	1	I	O	RFR	
South Texas 2	49991	10/30/91	RF	CB	1	F	S(C)	FTR	
South Texas 2	49991	12/06/91	RF	CB	1	I	O	RFR	
South Texas 2	49991	12/07/91	RF	CB	1	I	S	RFR	
South Texas 2	49991	12/24/91	PO	CB	1	I	O	RFR	
South Texas 2	49992	04/08/92	PO	CB	1	I	S	RFR	
South Texas 2	49992	06/10/92	PO	CB	1	I	S	RFR	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
St. Lucie 1	33589002	06/14/89	PO	EM	1	F	S	FTR	
St. Lucie 1	33591	10/21/91	CD	EM	1	C	S(C)	FTR	
St. Lucie 1	33591	11/29/91	RF	EM	1	E	S	FTS	
St. Lucie 1	33592	04/03/92	U	EM	1	E	S	FTS	
St. Lucie 1	33592	07/01/92	U	EM	1	I	O	RFR	
St. Lucie 2	38987	09/02/87	U	EM	1	F	S	FTS	
St. Lucie 2	38987	10/05/87	U	EM	1	F	S(C)	FTS	
St. Lucie 2	38988	01/06/88	U	EM	1	F	S	FTS	
St. Lucie 2	38989	03/15/89	D	EM	1	E	S	FTS	
St. Lucie 2	38989	03/15/89	D	EM	1	M	S	RFR	
St. Lucie 2	38989	03/21/89	D	EM	1	M	O	RFR	
St. Lucie 2	38989	04/06/89	D	EM	1	C	O	FTR	
St. Lucie 2	38990	01/03/90	U	EM	1	F	S	RFP	
St. Lucie 2	38991	01/16/91	U	EM	1	F	O	FTS	
St. Lucie 2	38991	06/26/91	U	EM	1	E	O	FTS	
Summer	39588	11/26/88	D	FC	1	I	S	FTS	
Susquehanna 1	38789024	09/16/89	PO	CB	1	M	S(C)	FTR	
Susquehanna 1	38789024	10/07/89	PO	CB	1	M	S(C)	FTR	
Susquehanna 1	38790018	08/30/90	PO	CB	2	M	O	FTR	
Susquehanna 1	38792	01/31/92	PO	CB	1	C	O	FTR	
Susquehanna 1	38792	12/04/92	PO	CB	1	F	S	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Susquehanna 2	38891006	04/22/91	CD	CB	1	M	S(C)	FTS	
Susquehanna 2	38892001	03/18/92	PO	CB	1	E	S	FTR	
Turkey Point 3	25088011	05/29/88	PO	EM	2	F	S	FTR	
Turkey Point 3	25088022	09/20/88	PO	EM	1	F	S	FTS	
Turkey Point 3	25092009	08/27/92	HS	EM	1	E	A	FTR	T
Turkey Point 4	25189011	09/15/89	PO	EM	1	L	O	FTR	
Turkey Point 4	25092009	08/24/92	HS	EM	1	E	A	FTR	T
Turkey Point 4	25193	02/25/93	U	EM	1	E	S	FTS	
Vogtle 1	42488	02/18/88	D	TD	1	F	O	FTS	
Vogtle 1	42488	09/23/88	U	TD	1	L	O	RFR	
Vogtle 1	42489	07/17/89	U	TD	1	E	S	FTS	
Vogtle 1	42490	01/03/90	U	TD	1	I	S	RFR	
Vogtle 1	42490006	03/20/90	RF	TD	1	I	A	FTR	T
Vogtle 1	42490006	03/20/90	RF	TD	1	I	A	MOOS	F
Vogtle 1	42490006	03/20/90	RF	TD	1	I	O	FTR	
Vogtle 1	42490	05/23/90	U	TD	1	I	S	FTS	
Vogtle 1	42490014	06/18/90	PO	TD	1	F	S	FTS	
Vogtle 1	42490	07/05/90	U	TD	1	A	S	FTS	
Vogtle 1	42490	08/29/90	U	TD	1	E	S	FTS	
Vogtle 1	42491	05/22/91	U	TD	1	E	S	FTR	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Vogtle 1	42491	10/04/91	RF	TD	1	E	S(C)	RFP	
Vogtle 1	42492010	11/18/92	PO	TD	1	A	S	FTS	
Vogtle 1	42492010	12/03/92	PO	TD	1	A	O	FTS	
Vogtle 2	42590	01/24/90	U	TD	1	A	S	FTS	
Vogtle 2	42590	01/25/90	U	TD	1	A	O	FTS	
Vogtle 2	42490	04/12/90	D	TD	1	A	S	FTS	
Vogtle 2	42490	07/11/90	U	TD	1	A	S	FTS	
Vogtle 2	42590	09/14/90	U	TD	1	F	O	FTR	
Vogtle 2	42590	10/09/90	RF	TD	1	I	S(C)	RFR	
Vogtle 2	42591003	01/29/91	U	TD	2	E	S	RFP	
Vogtle 2	42592	02/05/92	U	TD	1	E	S	RFP	
Vogtle 2	42593	02/01/93	U	TD	1	E	S	RFP	
Wash. Nuclear 2	39788018	05/22/88	RF	EM	1	I	O	FTS	
Wash. Nuclear 2	39790012	05/27/90	RF	EM	1	E	S(C)	FTR	
Waterford 3	38287	05/08/87	PO	CB	1	I	S	RFR	
Waterford 3	38287	06/22/87	PO	CB	1	I	S	RFR	
Waterford 3	38287	06/23/87	PO	CB	1	I	S	RFR	
Waterford 3	38287	08/15/87	PO	CB	1	I	S	RFR	
Waterford 3	38288	03/08/88	U	CB	6	I	S	RFR	
Waterford 3	38288	04/04/88	CD	CB	1	I	O	RFR	
Waterford 3	38288	09/09/88	PO	CB	1	F	O	FTR	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Waterford 3	38289	02/06/89	PO	CB	1	F	O	RFP	
Waterford 3	38289	04/03/89	PO	CB	1	F	S	RFP	
Waterford 3	38290	01/28/90	CD	CB	1	L	S	RFR	
Waterford 3	38290	11/12/90	PO	CB	1	F	S	RFP	
Waterford 3	38290	12/26/90	PO	CB	1	E	O	FTR	
Waterford 3	38291	03/18/91	CD	CB	1	M	S(C)	FTR	
Waterford 3	38291	04/21/91	D	CB	1	I	S	RFR	
Waterford 3	38291	06/19/91	U	CB	1	I	S	RFR	
Waterford 3	38291	08/20/91	U	CB	1	F	S	FTS	
Waterford 3	38291	11/11/91	PO	CB	1	H	S	RFR	
Waterford 3	38292018	09/30/92	RF	CB	1	I	A	MOOS	F
Wolf Creek	48287	12/11/87	D	FC	1	L	S(C)	FTR	
Wolf Creek	48287	12/19/87	RF	FC	1	E	S(C)	RFP	
Wolf Creek	48288	11/16/88	RF	FC	1	F	S	FTR	
Wolf Creek	48288	11/27/88	D	FC	1	F	S(C)	FTR	
Wolf Creek	48289	09/19/89	U	FC	1	C	O	FTR	
Wolf Creek	48292	06/08/92	PO	FC	1	C	S	FTR	
Zion 1	29587006	03/15/87	SU	CB	1	F	O	FTR	
Zion 1	29587006	03/15/87	SU	CB	1	I	O	RFR	
Zion 1	29588004	02/24/88	HS	CB	1	M	S(C)	FTR	
Zion 1	29590008	03/01/90	PO	CB	1	L	S	RFR	
Zion 1	29590023	11/06/90	PO	CB	1	I	O	FTS	

Table B-4. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Zion 1	29590023	11/06/90	PO	CB	1	I	S	RFP	
Zion 2	30491002	03/21/91	PO	CB	1	I	A	MOOS	F
Zion 2	30492004	07/15/92	PO	CB	1	C	S	FTR	

Table B-4A. Emergency diesel generator failures for the plants NOT reporting per Regulatory Guide 1.108.

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Beaver Valley 2	41293012	11/04/93	CD	FC	2	E	S(C)	FTS	
Brunswick 1	32589001	01/12/89	RF	NM	1	I	O	FTR	
Brunswick 2	32492001	01/06/92	PO	NM	1	F	O	FTS	
Calvert Cliffs 2	31888005	06/06/88	PO	FC	1	E	S	FTS	
Cooper	29889003	02/13/89	PO	CB	1	A	S	FTR	
Cooper	29889004	02/16/89	PO	CB	1	M	O	FTS	
Cooper	29889020	05/29/89	CD	CB	1	I	A	MOOS	F
Cooper	29893008	03/28/93	CD	CB	1	E	A	SIF	T
Crystal River 3	30287021	10/14/87	RF	FC	1	I	A	MOOS	F
Crystal River 3	30289025	06/29/89	HS	FC	1	I	A	MOOS	F
Crystal River 3	30291010	10/20/91	CD	FC	1	I	A	MOOS	F
Crystal River 3	30292002	03/27/92	HS	FC	1	C	A	FTR	F
Davis-Besse	34691007	12/06/91	PO	EM	1	I	S	FTS	
Davis-Besse	34691007	12/06/91	PO	EM	1	I	O	FTS	

Table B-4A. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Dresden 2	23793012	04/18/93	RF	EM	1	E	S(C)	FTS	
Duane Arnold	33187009	05/27/87	RF	FC	1	E	S(C)	FTS	
Duane Arnold	33188016	10/17/88	RF	FC	1	I	A	MOOS	F
Duane Arnold	33190007	07/09/90	RF	FC	1	I	A	MOOS	F
Duane Arnold	33193004	06/11/93	PO	FC	1	M	S	FTS	
Duane Arnold	33193008	09/16/93	CD	FC	1	E	S(C)	FTS	
Fort Calhoun	28587008	03/21/87	RF	EM	1	I	A	MOOS	F
Fort Calhoun	28587008	03/21/87	RF	EM	1	I	A	MOOS	T
Fort Calhoun	28587025	09/23/87	PO	EM	1	C	S	FTR	
Fort Calhoun	28590006	02/26/90	RF	EM	1	I	A	MOOS	F
Fort Calhoun	28590020	09/13/90	PO	EM	1	E	O	FTR	
Fort Calhoun	28591016	08/02/91	PO	EM	1	C	S	FTR	
Indian Point 2	24787004	02/10/87	PO	AP	1	I	A	MOOS	F
Indian Point 2	24788011	09/09/88	PO	AP	1	C	S(C)	FTR	
Indian Point 2	24791006	03/20/91	RF	AP	2	I	A	MOOS	F
Indian Point 2	24791010	06/22/91	RF	AP	1	E	S	FTR	
Indian Point 2	24792006	03/23/92	PO	AP	1	F	O	FTR	
Indian Point 2	24793004	03/04/93	RF	AP	2	F	O	FTR	
Indian Point 2	24793009	08/10/93	PO	AP	1	I	O	FTS	
Indian Point 3	28687009	05/15/87	CD	AP	1	E	A	FTS	F

Table B-4A. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Indian Point 3	28688008	08/17/88	PO	AP	1	F	O	RFP	
Indian Point 3	28689006	03/21/89	RF	AP	1	I	S	FTS	
Indian Point 3	28690002	02/03/90	PO	AP	1	E	S	FTS	
Indian Point 3	28690005	08/09/90	PO	AP	1	I	O	FTS	
Indian Point 3	28691002	12/05/90	RF	AP	1	I	O	FTS	
Indian Point 3	28692001	12/16/91	PO	AP	1	E	S	FTS	
Indian Point 3	28692007	06/10/92	RF	AP	1	E	O	FTS	
Indian Point 3	28692010	06/25/92	CD	AP	1	I	O	FTS	
Indian Point 3	28692011	07/06/92	CD	AP	1	I	S	FTS	
Indian Point 3	28693042	10/09/93	CD	AP	2	H	O	FTR	
Indian Point 3	28693053	12/02/93	CD	AP	3	C	O	FTR	
Millstone 1	24591004	03/07/91	CD	FC	1	L	S	FTS	
Millstone 2	33691009	08/21/91	PO	FC	1	F	S	RFP	
Millstone 2	33691009	08/23/91	PO	FC	1	F	S	RFP	
Millstone 2	33692012	07/06/92	RF	FC	1	E	A	SIF	F
Nine Mile Pt. 1	22087012	07/24/87	PO	EM	1	F	O	FTS	
Nine Mile Pt. 1	22089002	03/08/89	RF	EM	2	I	A	MOOS	F
Oyster Creek	21987044	10/30/87	CD	EM	1	I	O	FTS	

Table B-4A. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Oyster Creek	21989019	09/11/89	PO	EM	1	I	S	RFP	
Palisades	25593001	01/06/93	PO	AP	1	M	O	FTS	
Peach Bottom 2	27788020	07/29/88	RF	FC	2	I	A	MOOS	F
Peach Bottom 2	27790034	11/12/90	PO	FC	1	E	O	FTR	
Peach Bottom 2	27791020	06/07/91	PO	FC	1	F	O	FTR	
Peach Bottom 2	27792010	07/04/92	PO	FC	1	E	A	FTS	
Peach Bottom 2	27793	08/03/93	PO	FC	1	F	S	FTR	
Peach Bottom 2	27793	10/12/93	PO	FC	1	F	S	FTR	
Pilgrim	29387005	03/31/87	RF	AP	1	I	A	MOOS	F
Pilgrim	29391005	03/25/91	PO	AP	1	E	S	FTR	
Point Beach 1	26688010	10/26/88	PO	EM	1	I	S	FTS	
Point Beach 1	26693002	02/18/93	PO	EM	1	I	S	RFP	
Prairie Island 1	28287001	02/04/87	PO	FC	1	C	S	FTR	
Prairie Island 2	30693003	07/19/93	PO	CL	2	H	O	FTR	
Quad Cities 1	25490003	02/13/90	PO	EM	1	F	S	FTS	
Quad Cities 1	25492021	08/11/92	PO	EM	1	F	S	FTR	
Quad Cities 1	25492021	08/25/92	PO	EM	1	F	S	RFP	

Table B-4A. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Quad Cities 2	26587001	01/03/87	RF	EM	1	I	O	FTS	
Quad Cities 2	26592011	04/02/92	CD	EM	1	I	A	MOOS	F
Quad Cities 2	25492010	04/07/92	CD	EM	2	I	O	FTS	
Rancho Seco	31287022	07/29/87	CD	EM	1	C	S	FTR	
Robinson 2	26187023	08/26/87	PO	FC	1	M	S	FTS	
Robinson 2	26187028	11/05/87	PO	FC	1	A	S	FTS	
Robinson 2	26188005	02/13/88	RF	FC	1	M	O	FTS	
Robinson 2	26192006	04/13/92	RF	FC	1	F	S	FTR	
Robinson 2	26193019	11/22/93	RF	FC	1	A	S	FTS	
Surry 1	28089010	04/06/89	CD	EM	1	I	A	MOOS	F
Surry 1	28089013	04/13/89	CD	EM	1	I	A	MOOS	F
Surry 1	28091017	05/09/91	PO	EM	1	F	O	FTS	
Surry 1	28091018	08/26/91	PO	EM	1	F	A	FTS	T
Surry 2	28191007	08/02/91	PO	EM	1	F	O	FTS	
Three Mile Isl 1	28989002	11/02/89	PO	FC	1	C	S	FTR	
Three Mile Isl 1	28993006	07/01/93	PO	FC	1	L	O	FTR	

Table B-4A. (continued).

Plant name	LER/SR number	Event date	Unit mode	EDG manufacturer	Number of failures	Subsystem	Method of discovery	FLMD	Recovered
Trojan	34487010	05/11/87	RF	EM	1	I	A	MOOS	F
Vermont Yankee	27192017	05/29/92	PO	FC	1	M	S	FTR	
Vermont Yankee	27192017	05/29/92	PO	FC	1	M	O	FTR	
Yankee-Rowe	02987008	05/31/87	HD	EM	1	I	A	MOOS	F
Yankee-Rowe	02988010	11/16/88	RF	EM	1	I	A	MOOS	F
Yankee-Rowe	02991001	02/26/91	PO	EM	1	F	S	FTS	
Yankee-Rowe	02991005	11/05/91	CD	EM	2	I	S	FTS	

B-4. UNRELIABILITY EVENTS

Those events for which a demand frequency could be determined or estimated were analyzed from an engineering and statistical approach. Based on this analysis, events that could be used in determining EDG train unreliability were selected. Only plants required to report EDG train failures during testing per Regulatory Guide 1.108 were used in the cyclic test contribution to unreliability. Table B-5 lists these events with a short description of the event.

The first section of the table presents a list of the EDG train failures that occurred during an unplanned demand. This list includes the FTS, FTR and MOOS events. No CCF events were observed during an unplanned demand. The second section is a list of the CCF events that occurred during cyclic surveillance testing. The third list is of the FTR events found during cyclic surveillance testing. The fourth section lists the FTS events found during cyclic surveillance testing.

Table B-5. Summary of EDG train failure events used for unreliability calculations.

Plant name	Failure mode	LER number	Event date	Description
Unplanned Demand Failures				
Catawba 1	FTS (Not Recovered)	41387042	11/17/87	A malfunction of a switch assembly resulted in loss of power to a 4.16-KV essential bus, causing the EDG to start and load the bus. The associated essential 600-V load centers did not energize because a timer drift resulted in the load shed signal being still available when the sequencer tried to close the supply to the 600-V bus. Normal power was restored to the bus 20 minutes after the start of the event.
McGuire 2	FTS (Not Recovered)	36988014	06/24/88	While the plant was shutdown in preparation for a modification to a 2B offsite power feed, an operator aligned all four 6.9-KV busses to the wrong offsite power feed (2B instead of 2A). When the 2B feed was de-energized for the modification, all four buses de-energized and both EDGs received unplanned demands. EDG 2A tripped in less than 30 seconds after starting. Investigation concluded that the most likely cause of the EDG trip was slow response of lube oil pressure switches due to air or sediment in the sensing lines. The slow response caused a false low lube oil pressure signal. Eight minutes after the EDG trip, offsite power was restored to the bus.
Turkey Point 3	FTR (Recovered)	25092009	08/27/92	EDG A for Unit 3 tripped after 3.5 days of operation during Hurricane Andrew. No cause for the trip was identified, and the EDG was restored to operation in 2.5 hours with no further trips experienced.
Turkey Point 4	FTR (Recovered)	25092009	08/24/92	EDG A for Unit 4 tripped after 7 hours of operation during troubleshooting efforts to isolate a ground on dc control power. The procedure for ground isolation used was intended to be used when offsite power was available and caused the trip. Power from the EDG was immediately restored to the bus.
Vogtle 1	FTR (Recovered)	42490006	03/20/90	During a refueling outage on Unit 1, a truck struck a support for an offsite power supply transformer causing a loss of offsite power. The loss of offsite power resulted in an EDG start and loading of its safety bus; however, the EDG tripped after only 80 seconds of operation. Nineteen minutes following this trip, an attempt to restart the EDG was successful but again ended with a trip after 70 seconds of operation. Fifteen minutes after this second trip, the EDG was started using the emergency start button and continued to run throughout the remainder of the event. The most likely cause of the EDG trip was intermittent actuation of the high jacket water temperature switches.

Table B-5. (continued).

Plant name	Failure mode	LER number	Event date	Description
Callaway 1	MOOS (Not Recovered)	48389008	06/23/89	During a plant shutdown the main generator was being shutdown as required by procedure when a relay failed in the control circuit causing a loss of power to safety-related buses. An EDG was out of service for maintenance when the safety-related buses lost power.
Catawba 1	MOOS (Not Recovered)	41389001	01/07/89	An improperly installed relay caused a loss of safety-related buses when a reactor coolant pump was started. An EDG was out of service for maintenance when the safety-related buses lost power.
Zion 2	MOOS (Not Recovered)	30491002	03/02/91	During a surveillance test of the firewater system, the deluge valves were inadvertently opened and sprayed water on the auxiliary and main transformers. This caused a main generator trip and loss of safety-related buses. An EDG was out of service for maintenance when the safety-related buses lost power.
Cyclic Surveillance CCF				
Catawba 1	FTS	41388019	12/01/87	During ESF testing, EDG 1B tripped approximately 70 seconds after starting. Investigation determined that the low-low lube oil pressure trip device did not operate properly. During a 7 month period, the licensee had 10 failures for the same reason, and was not able to find a root cause. In May 1988, the licensee determined the cause of all the failures to be a design problem with the pressure sensor. All of these failures could occur during an emergency start since the low lube oil trip is not bypassed. Since all the failures occurred within a short period of time for the same design problem, these are considered as a CCF event.
Salem 2 (2 Events)	FTR	SR 31190	05/18/90	A jacket water leak developed on a threaded connection for EDG 2A during a 24-hour load test. Three days later during a 24-hour load test of EDG 2B, a jacket water leak developed from a cracked threaded nipple. This is considered a CCF since even though the leaks were not in the same exact location, they were both vibration induced and occurred within a short period of time. Other leaks had occurred in the past, one on the same nipple as this failure. In both events, the operator secured the tests due to the jacket water leaks, though the leakage was within the make-up system capacity.
Susquehanna 1 (2 Events)	FTR	38789024	10/07/89	During a 24-hour surveillance test, EDG C experienced a crankcase overpressurization. Three weeks earlier, EDG B also experienced a crankcase overpressurization. No single

Table B-5. (continued).

Plant name	Failure mode	LER number	Event date	Description
				root cause was determined for either occurrence, but potential causal factors were identified and corrective action was taken to improve the existing design.
Cyclic Surveillance FTR				
Browns Ferry 2	FTR	26089023	07/23/89	During a surveillance of the accident signal logic, arcing and smoke were noticed coming from inside the engine control panel. When an attempt was made to shutdown the EDG, the EDG would immediately restart. The EDG was secured using the emergency fuel cutoff lever. A diode failure caused a voltage transient, resulting in fusing of contacts in the pinion failure relay. This failure sealed in the fast start signal to the EDG.
Diablo Canyon 1	FTR	27588014	05/05/88	During a 24-hour load test, the EDG load decreased below acceptance criteria. Operators were able to shift fuel filters and maintain EDG operation to complete the test. Investigation showed a high differential pressure across the fuel filter, which was caused by fungus in the fuel system. The same fungus condition existed in the other EDGs day tanks and in the main storage tank.
Limerick 2	FTR	35391005	04/01/91	During a LOOP test, EDG 21 was manually tripped when its output voltage exceeded acceptance criteria. The EDG had successfully powered and rejected the RHR pump load. As part of the procedure in restoring loads, the RHR pump is restarted. After starting the pump, the EDG output voltage increased above the acceptance criteria. A potential transformer fuse that was not fully engaged caused the loss of voltage control.
Limerick 2	FTR	35391009	05/21/91	During a LOOP test, EDG 24 was manually tripped when its output voltage exceeded acceptance criteria following starting of an RHR pump. A loose wire in the potential transformer sensing network caused the loss of voltage control.
McGuire 2	FTR	36988011	06/01/88	After numerous troubleshooting runs, an operability test was run with the EDG operating for 131 minutes and the EDG was declared operable. Several hours later when running the ESF blackout test, the EDG successfully started and loaded the bus but tripped on overspeed after 14 minutes of operation. The overspeed was the result of all of the oil leaking from the governor, causing the governor to supply excess fuel. Improper installation of the governor was determined to be the cause of the oil leak.
McGuire 2	FTR	SR 37088	06/02/88	During an ESF test, the EDG was secured after 21 minutes as the result of a lube oil cooler leak. Approximately 100 gallons of lube oil sprayed into the EDG room. The leak was caused by a torn gasket that had been recently installed.

Table B-5. (continued).

Plant name	Failure mode	LER number	Event date	Description
McGuire 2	FTR	37089012	11/08/89	During a 24-hour run, EDG 2B was manually tripped after 18 hours of operation owing to a loss of voltage control caused by two blown fuses in the voltage regulator control circuitry.
McGuire 2	FTR	SR 37090	10/10/90	During a 24-hour surveillance test run, EDG 2B tripped with no alarms after 2.5 hours of operation. Water from heavy rains had entered the EDG room from the air intake plenum and led to a short circuit in the control panel.
Nine Mile Pt. 2 (2 Events)	FTR	SR 41092	04/29/92	During a 24-hour run, EDG 1 was secured owing to a fuel oil leak after 8 hours of operation. The leak was caused by a crack in the fuel injector pump valve delivery holder. The following day when the test was again being run, a different fuel injector pump valve delivery holder developed a leak after 4 hours of operation, and the test was again terminated.
St. Lucie 1	FTR	SR 33591	10/21/91	During a 24-hour surveillance run, EDG 1B tripped on high discharge water temperature after 5.5 hours of operation. The radiator fan pulley shaft broke owing to high stress.
Salem 2	FTR	SR 31190	05/02/90	During a 24-hour endurance run, the load of EDG 2B decreased from 2860 KW to 700 KW and could not be raised. The failure of the turbocharger bearing resulted in brittle failure of a compressor blade and seizure of the turbocharger. The failure occurred after the EDG was running for 20 minutes.
Salem 2	FTR	SR 31192	03/02/92	During a 24-hour endurance run, a jacket water leak developed on EDG 2A, and the test was terminated after 20 minutes of operation owing to the size of the leak. The leak was caused by a cracked fitting.
Seabrook	FTR	SR 44391	09/16/91	During an 18-month ESF surveillance test, EDG 1B was shutdown after 56 minutes of operation when two air lines on the air start manifold were severed. Investigation also identified broken air start lines on four cylinders. Licensee concluded this condition would have resulted in equipment damage. Excessive vibration caused the failures.
South Texas 2	FTR	SR 49989	11/21/89	During a 24-hour load test, EDG 22 was secured after 11.5 hours of operation owing to overheating of the voltage regulator transformer. The overheating was caused by induced current in a mounting bolt that was missing an insulator.

Table B-5. (continued).

Plant name	Failure mode	LER number	Event date	Description
South Texas 2	FTR	SR 49989	11/28/89	During a 24-hour load test run of EDG 22, a master connecting rod failed, and the EDG tripped. The rod failure was caused by fatigue owing to an improperly drilled oil passage. During performance of the endurance test, a loud knocking was heard in the EDG by maintenance workers after 10 hours of operation. The workers evacuated the area and the engine tripped.
South Texas 2	FTR	SR 49990	11/26/90	During a LOOP-ESF test, EDG 23 was secured owing to a spraying fuel leak. The leak was caused by a crack in the threaded portion of the delivery valve holder. The SR does not give any indication of how long the EDG was run before the failure was identified and the EDG was tripped. The problem of cracks in the delivery valve holder was a known problem for Cooper Bessemer EDGs and was addressed by the user group. This particular event was considered a failure since the crack resulted in a spraying of fuel on a hot exhaust header, constituting a fire hazard.
South Texas 2	FTR	SR 49991	10/30/91	While performing an 8-hour run prior to a surveillance inspection, EDG 22 developed a fuel leak on a high-pressure supply line. The leak gradually increased into a spray with a fire hazard potential, and the EDG was shutdown. The SR does not indicate how long the EDG ran before the leak developed and had to be secured.
Wash. Nuclear 2	FTR	39790012	05/27/90	During a 24-hour full load run, EDG 1 was manually tripped after 6 hours of operation owing to failure of the generator slip ring end bearing. The bearing failure caused excessive vibration, rumbling, and a small fire. The bearing failure was caused by an extra O-ring groove in the thrust bearing bracket, resulting in oil starvation.
Waterford 3	FTR	SR 38291	03/18/91	During a run as a prerequisite for the 18-month inspection, an overpressurization occurred on EDG A after 3 hours of operation. The cause of the crankcase overpressurization was stuck piston rings. Operators tripped the EDG and exited the room. All 10 cylinder relief assemblies lifted, filling the room with oil vapor.
Wolf Creek	FTR	SR 48287	12/11/87	During a 24-hour run, a lube oil fitting began leaking on EDG A. The EDG had operated for 10 hours when a lube oil line leak was reported by operations. Maintenance attempted to stop the leak by tightening the fittings, but the leak worsened. The EDG was secured since it was thought the leak could ultimately result in damage or failure from an excessive leak.

Table B-5. (continued).

Plant name	Failure mode	LER number	Event date	Description
Wolf Creek	FTR	SR 48288	11/27/88	During a 24-hour run, a fuel oil leak developed on a fitting of EDG B. The leak continued to increase. When a mist was seen coming from the leak, the EDG was secured, and shortly after a fire was noticed in the vicinity of the leak. The EDG was secured after 13 hours of operation.
Zion 1	FTR	29588004	02/24/88	During the endurance run for EDG 0, the EDG was manually shutdown 15 minutes after being loaded owing to a sudden drop in generator load and excessive vibration. The turbocharger blower shaft had broken owing to a failure of the blower bearing sleeve that resulted from overheating of the bearings.
Cyclic Surveillance FTS				
Braidwood 2	FTS	45790004	04/16/90	EDG 2A was started in preparation for an 18-month surveillance. Shortly after starting, the EDG speed began oscillating, and the EDG was shutdown. The cause was identified as failure of a dropping resistor in the governor unit.
Byron 1	FTS	SR 45491	09/22/91	During a undervoltage sequencer test, EDG 1B failed to start for two minutes after receiving a start signal. A second attempt to start the EDG was unsuccessful. A failure of the turning gear interlock valve prevented air supply to the starting air valves. The valves leaked sufficiently that after two minutes air pressure was unavailable to actuate the starting air valves.
Byron 1	FTS	SR 45491	09/27/91	During a start for an ESF actuation test, EDG 1B failed to indicate proper voltage. Investigation determined a fuse for the voltage control and metering circuit had blown.
Callaway	FTS	SR 48390	09/24/90	During EDG sequencer testing, EDG B started but failed to sequence on any loads. A plunger bolt that actuates a switch to start the load sequencer was found out of adjustment. The out of adjustment was caused three days earlier by improper movement of a test link that was used in the blackout test.
Catawba 2	FTS	SR 41488	01/15/88	While performing a load rejection test, EDG 2B could not be paralleled to the bus owing

Table B-5. (continued).

Plant name	Failure mode	LER number	Event date	Description
				to oscillations. The oscillations were caused by the governor being out of adjustment.
Clinton	FTS	SR 46193	09/27/93	During an integrated ECCS test, EDG 1B failed to reach the required voltage of 3740 VAC. Voltage reached only 3595 VAC. Insufficient contact pressure for contacts on the voltage regulating potentiometer caused the failure.
Diablo Canyon 2	FTS	SR 32388	11/12/88	During performance of the 4-KV bus auto transfer verification surveillance test, EDG 1-3 failed to start. Dirty contacts on the second level undervoltage relay prevented the EDG from starting.
Fermi 2	FTS	SR 34188	04/20/88	During an ECCS test, EDG 13 could not be loaded to full load. The EDG is required by the surveillance to be loaded at 2500 KW , but it could only be loaded to 1500 KW. The cause was the governor load limit knob was set improperly. The licensee concluded that the knob was changed by an unauthorized person since the last EDG test about one month prior.
Fermi 2	FTS	SR 34188	04/25/88	EDG 11 failed when attempting to start 5 minutes after being shutdown from a 24-hour run. The EDG came up to speed but failed to generate voltage when the exciter failed to flash the generator field. The cause of the failure was intermittent operation of the relay that resets the field flashing circuit.
LaSalle 1	FTS	37388012	06/08/88	EDG 0 tripped on underfrequency after running loaded for approximately one minute. The EDG had run loaded for 27 hours, shutdown, and started within five minutes after the shutdown. The EDG started and loaded the bus but experienced a frequency oscillation that did not dampen out prior to the trip. A combination of high oil temperature and a governor speed adjustment problem caused the frequency oscillations. Although the EDG ran for about one minute after starting, this is considered as a fail to start since the oscillation occurred immediately after the start and did not dampen out.
LaSalle 1	FTS	SR 37391	04/03/91	During an undervoltage auto-start test, the 1B EDG failed to start. The cause of the failure was a defective governor-run solenoid.
Limerick 1	FTS	35290019	09/15/90	During a loss of offsite power test, EDG 13 was manually tripped owing to an overvoltage condition. The overvoltage condition was caused by failure of the voltage regulator rectifier bank. The LER indicates this overvoltage condition occurred immediately after the start; therefore, this is considered a FTS.

Table B-5. (continued).

Plant name	Failure mode	LER number	Event date	Description
McGuire 2	FTS	36988010	06/01/88	During a blackout test, EDG 2A failed to start. The cause was determined to be intermittent failure of contacts in the EDG start timing relay.
St. Lucie 2	FTS	SR 38987	10/05/87	Following a successful 24-hour run, EDG 2B failed while starting during a loss of offsite power test. The EDG was manually tripped when the voltage fluctuated and the frequency dropped while the EDG was being loaded. The cause of the failure was determined to be a mechanical malfunction of the governor.
South Texas 1	FTS	SR 49891	03/05/91	During a 24-hour load test run, the EDG 11 output breaker tripped. The failure was caused by a faulty voltage regulator. The SR only states that during the performance of the 24-hour load test the output breaker tripped. Therefore, it is not clear if the EDG ran before the failure. It is assumed the voltage regulator had already failed at the start. The SR states that during subsequent troubleshooting starts the failure occurred immediately after starting.
Susquehanna 2	FTS	38891006	04/22/91	During a loss of offsite power test, EDG A failed to reach rated speed and load the safety-related bus. The cause of the failure could not be determined, though it is suspected a sticky pneumatic valve caused the failure. After replacing the pneumatic valve, subsequent tests of the EDG were performed satisfactorily.

B-5. COMMON CAUSE FAILURE EVENTS

All failure events were evaluated to identify the common cause failure (CCF) events. Since all plants are required to report common cause failures per 10 CFR 50.73, this subsection was not limited to only those plants required to report per Regulatory Guide 1.108, but includes all plants. From all the events reviewed, 34 CCF events were identified. Many LERs and Special Reports reported only one actual failure, but the information available indicated that failure of a second EDG train would have occurred owing to the same cause if a start and run had been attempted. If the cause of the actual failure would have clearly caused failure of another EDG train, then the event was identified as a CCF. If, however, the report did not clearly identify that another EDG train would have also failed due to the same cause, the event was not considered a CCF. Similarly, for reports that identified failures discovered prior to an EDG train start demand (e.g., the condition was found during inspection) and no actual start or run failure occurred, a CCF was identified in only those cases for which a second failure could be certain. For purposes of this CCF study, a personnel error resulting in more than one inoperable EDG train, even without any component malfunction, is considered a CCF event.

All CCF events identified in this study are listed in Table B-6. The Cause and Coupling Factor are all discussed in Reference B-1, Common Cause Failure Data Collection and Analysis System. The number of failures listed in the table is the number of failures specifically discussed in the report. In some cases, multiple failures of the same component are discussed in the report, but for purposes of defining a CCF event only one failure was listed for each component. An actual failure was a reported failure of the EDG train to start or run. An expected failure indicates that the licensee discovered a condition that would have prevented correct operation of one or more EDG train.

Table B-6. Common cause failure events.

Plant name	LER/SR number	Event description	Number & type of failures	Cause	Coupling factor
Beaver Valley 2	41293012	During testing, both EDG trains failed automatic loading capability owing to malfunction of the digital solid state timer associated with the automatic load sequencing circuitry. The condition existed because of inadequate post modification testing.	2 actual	Design deficiency	Hardware design (component)
Catawba 1 Catawba 2	41388019	Repeated failures of the 1A, 1B, 2B EDG trains were caused by a defective design of the low lubrication oil pressure trip sensor. The EDG train failures, all found during surveillance testing, were fail to start, or start and immediately trip. (There were a total of six failures on the 1A EDG train and two failures on the 1B EDG System.) For CCF events, the number of actual failures cannot exceed the number of different EDG trains that failed, even though they failed more than once. The expected failure is for the 2A EDG train.	2 actual	Manufacturing deficiency	Hardware design (component)
Clinton	46190011	EDG train A tripped on high temperature because service water valves to heat exchangers were not set to provide adequate flow. EDG train B valves were also set wrong.	1 actual 1 expected	Inadequate procedure	Operation procedure
Duane Arnold	33187009	EDG train B stopped during a test run owing to an incorrect setpoint on a newly installed phase differential overcurrent relay. Both EDG trains had the same setpoint.	1 actual 1 expected	Inadequate procedure	Maintenance/test procedure
Fort Calhoun	28587025	EDG train 2 tripped owing to high coolant temperature caused by a partially open exhaust damper that failed because a pilot valve was stuck. Water intrusion in the instrument air system left residue on the valve. Similar conditions were found in EDG train 1, but no actual failure occurred.	1 actual 1 expected	Internal contamination	Internal environment
Fort Calhoun	28590020	The EDG train 1 voltage regulator failed during testing, owing to excessive heat in the control cabinet. The licensee assumed that EDG train 2 would also be susceptible to the same failure mode.	1 actual 1 expected	Design deficiency	External environment
Fort Calhoun	28591016	An exhaust damper roll pin failure on the 2 EDG train was discovered during testing when the jacket water temperature increased rapidly. The damper pin on the 1 EDG train was cracked but not broken. Laboratory testing determined probable cause was a manufacturing defect.	1 actual 1 expected	Manufacturing deficiency	Hardware quality (manufacturing)
Grand Gulf	41688015	Tubes in the EDG train 2 intercooler had been ruptured by the diffuser plate in the left bank. This caused a cooling water leak such that the EDG train would not run unattended. A crack was found on the EDG train 1 intercooler, but no leak yet existed.	1 actual 1 expected	Design error	Hardware design (component)

Table B-6. Cont.

Plant name	LER/SR number	Event description	Number & type of failures	Cause	Coupling factor
Grand Gulf	SR 41688002	Failure of power element in temperature control valve for 11 EDG train jacket water cooler resulted in high lubrication oil temperature. Power elements for both EDG trains were replaced owing to past history of frequent failures.	1 actual 1 expected	Manufacturing deficiency	Hardware design (component)
Haddam Neck	21393006	EDG train A failed to continue running 22 hours into a 24-hour test owing to a short on voltage suppression devices caused by inadequate cooling in the excitation cabinet. EDG train B parts were replaced when the EDG train A parts were replaced because of excessive dust accumulation, age related wear, and lack of ventilation.	1 actual 1 expected	Ambient environmental stress	Hardware design (component)
Indian Point 2	24793004	Two of three EDG trains started on the loss of a 480-V bus. During recovery, fuel oil transfer pumps 21 and 22 did not start owing to dirty contacts on the level switch and a blown fuse, respectively.	2 actual 1 out of service	Inadequate procedure	Maintenance/test schedule
Indian Point 3	28690005	Control power fuses were blown on the 32 EDG train owing to poor maintenance practices and less than adequate documentation of the jacket water train and pressure switch. Prior to the 32 EDG train failure EDG train 31 had experienced blown power fuses, but had subsequently tested satisfactorily.	1 actual 1 expected 1 out of service	Inadequate procedure	Maintenance/test procedure
Indian Point 3	28692010	A fuse blew in the 31 EDG train control panel during CO_2 operation in conjunction with EDG train exhaust fan operation. A simulated CO_2 actuation blew the fuse in the 33 EDG train control panel. The condition resulted from a design deficiency during installation of the CO_2 system.	1 actual 2 expected	Design deficiency	Hardware design (component)
Indian Point 3	28693042	Room ventilation exhaust fan motors tripped during operation. All fans were tested, and it was discovered that current was too high owing to a design change to install an overload heater. Administrative controls and inadequate maintenance testing program contributed to problem.	2 actual 1 expected	Inadequate procedure	Maintenance/test procedure
Indian Point 3	28693053	Service water valves failed to open during a post-maintenance test, rendering all EDG trains inoperable. The primary cause was improper maintenance on the solenoid valves to the flow control valves.	3 actual	Failure to follow procedure	Maintenance/test staff
McGuire 1	36990017	During an operability test, EDG train 1A failed to fully load owing to paint on the fuel pump rack connections to the governor. Paint was also found on the EDG train 1B fuel pump rack. Owing to the nature of the events, this expected failure was considered an actual failure in Table B-4.	1 actual 1 expected	Inadequate procedure	Maintenance/test staff

Table B-6. Cont.

Plant name	LER/SR number	Event description	Number & type of failures	Cause	Coupling factor
Millstone 2	33691009	The 12U EDG train exhibited erratic load control owing to intermittent failure of the electronic control unit in the governor system. Both EDG trains exhibited the same erratic operation during troubleshooting testing.	2 actual	Setpoint drift	Hardware design (component)
North Anna 2	33987001	The load limit setting was set too low on both EDG trains, which could have prevented the EDG trains from maintaining the required voltage and frequency during load sequencing. If the load were to reach maximum design load, the EDG train will trip. The load limits had not been reset to the correct settings following a special test. This event was considered a failure in Table B-4 because sufficient information was available to predict EDG train failures under maximum load conditions.	2 expected	Failure to follow procedure	Operation procedure
Perry	44087009	Two air start solenoid valves failed, preventing starts of both EDG trains. No conclusive cause was found for solenoid failures. The solenoids had been identified for replacement, but the work was not performed prior to the start failures.	2 actual	Ambient environmental stress	Hardware design (component)
Prairie Island 2	30693003	Ventilation to the EDG train enclosures for both the D5 and D6 EDG trains was secured for filter maintenance, rendering the EDG trains inoperable. Temperatures could have exceeded qualification limits.	2 actual	Failure of other component	Maintenance/ test procedure
Quad Cities 2	25492010	Loss of the 125-VDC bus resulted in both the 2 and 1/2 EDG trains inoperable (incapable of auto-start) for four minutes. The loss of the dc bus was caused by a contractor technician accidentally opening a fusible disconnect on battery bus 1.	2 actual	Unintentional personnel error	Hardware design (system)
Quad Cities 1	25492021	Fluctuations in power and slow loading was caused by air trapped in the governor lines. Both the 1 and the 1/2 EDG trains were affected, 2 weeks apart.	2 actual	Construction/ installation error	Hardware quality (installation)
Robinson 2	26193019	B EDG train was inoperable owing to a test procedure that required air to be applied to the distributor while the EDG train was running, which resulted in damage to the air distributor such that the EDG train would not start. It is assumed that the A EDG train would have also failed if the run time during the previous test had been 45 min instead of 10 min with the air start system on.	1 actual 1 expected	Inadequate procedure	Maintenance/test procedure
Salem 2	SR 31190	Jacket water leaks during load tests were caused by a loosened fitting (vibration induced) and a cracked thread on the nipple (vibration induced fatigue).	2 actual	Ambient environmental stress	Hardware design (system)
Sequoyah 1 Sequoyah 2	32787060	Oil passages on the hydraulic actuator on the 1A-A EDG train were clogged with RTV (silicone sealant), causing the EDG train to trip on overspeed. No other failures were found from the RTV, but actuators on all four EDG trains were replaced and RTV will no longer be	1 actual (on Unit 1) 3 expected (both Units)	Manufacturing deficiency	Hardware design (component)

Table B-6. Cont.

Plant name	LER/SR number	Event description	Number & type of failures	Cause	Coupling factor
		used on the actuators.			
South Texas 2	SR 49991	Both EDG trains tripped when taken out of the emergency mode owing to foreign material under the seat of check valves, allowing a decrease in control air pressure. This is a restoration failure.	2 actual	Internal contamination	Maintenance/ test schedule
Susquehanna 1[a] Susquehanna 2	38789024	EDG train C crankcase overpressurization occurred (w/smoke in diesel bay) owing to a combination of causes. EDG train B had a similar problem 3 weeks earlier. A combination of causes were responsible, but maintenance was the dominant focus of corrective actions.	2 actual	Inadequate procedure	Maintenance/ test procedure
Susquehanna 1 Susquehanna 2	38790018	EDG train B was inoperable owing to high chromium content in lubrication oil from sand intrusion during maintenance work. The same symptoms were discovered on EDG train D, which was out of service.	2 actual	Inadequate procedure	Maintenance/ test procedure
Three Mile Isl. 1	28989002	The EDG train 1A radiator gear drive bearing seized because of inadequate lubrication from sludge formation in the lubrication lines. A similar condition was found on the 1B EDG System. The cause was an inadequate inspection/maintenance procedure for the lubrication oil system.	1 actual 1 expected	Inadequate procedure	Maintenance/ test procedure
Turkey Point 3	25088011	During a fuel pump surveillance test, the fuel oil tank isolation valve (single valve to both EDG trains) was found locked closed instead of locked open. This was caused by a chemistry technician not following the sampling procedure. The only fuel available to the EDG trains was in the day tank for each EDG train.	2 actual	Failure to follow procedure	Hardware design (system)
Vogtle 1 Vogtle 2	SR 42490005	Air valve pistons sticking prevented the 1B, 2A, and 2B EDG trains from starting. The cause was determined to be inadequate manufacturing tolerances. (There were two additional failures of the 2A EDG System.) Only 3 of the 4 EDG trains on site failed; therefore, CCF failures indicate 3 actual. Table B-4 shows all 5 failures, 3 of which were on the 2A-EDG train.	3 actual (on both Units) 1 expected (on Unit 1)	Manufacturing deficiency	Hardware quality (manufacturing)
Vogtle 1 Vogtle 2	SR 42491004	Wiring diagram error and subsequent installation error resulted in EDG train 1B tripping shortly after start. Review of wiring discrepancy on other EDG trains revealed that the same error existed for 1A, 2A, and 2B. This deficiency would not prevent the EDG trains from starting in an emergency start, but would be a restoration failure.	1 actual (on Unit 1) 3 expected (on both Units)	Design deficiency	Hardware design (component)
Vogtle 2	42591003	Both EDG trains failed to operate properly in parallel with the grid owing to excessive reactive power. This condition was caused by improper sizing of potential transformers feeding the voltage regulator circuits.	2 actual	Construction/ installation error	Hardware design (component)

Table B-6. Cont.

Plant name	LER/SR number	Event description	Number & type of failures	Cause	Coupling factor
Yankee-Rowe	02991005	Testing determined EDG trains 1 and 3 were inoperable owing to excessive arcing across contacts (one on each EDG train), caused by incorrect starting contactor coils installed (240/480 VAC vs. 125 VDC). The EDG trains were capable of starting on an emergency signal, but probably would not have restarted if they had been shut down for any reason.	2 actual 1 out of service	Construction/ installation error	Hardware quality (installation)

a. There was only one CCF event coded for each of the two LERs at Susquehanna. Owing to the design of five shared EDG trains for both units, the emergency power system is modeled as a one-unit plant site.

B-6. REFERENCES

B-1. A. Mosleh, et al., *Common Cause Failure Systems: Volume 2, Definition and Classification of Common cause Failure Events*, Draft NUREG/CR-6268, October 1994.

Appendix C

Failure Probabilities and Unreliability Trends

Appendix C

Failure Probabilities and Unreliability Trends

This appendix contains results from the statistical analysis of EDG train data that lead to estimates of probabilities for each failure mode, including distributions that characterize any variation observed in the data. Three types of detailed analyses are given: a plant-specific analysis for probability of individual failure modes; an investigation of the possible relation between plant low-power license date and EDG train performance, as measured by unreliability and by failures per year; and an investigation of whether overall performance changed during the seven years of the study.

C-1. BASIC EVENT FAILURE PROBABILITIES

Industry patterns in the EDG train failure modes are discussed in the first subsection below. The second contains plant-specific distributions for those cases where empirical Bayes distributions describing between-plant variability were found.

C-1.1 Analysis of Individual Failure Modes

Much of the detailed analysis of the EDG train operational data was limited by the realization that only a subset of the plants having diesels report testing problems according to Regulatory Guide 1.108 (RG-1.108). Since testing data were of necessity restricted to this subset of plants, a question considered early in the study was the feasibility of restricting the entire study to those plants following the RG-1.108 criteria. For each failure mode, statistical tests for significant differences among the unplanned demand data for the reporting and nonreporting plants were evaluated. In no case did the chi-square statistics reveal a significant difference between the unplanned demand data used to estimate EDG train unreliability. However, because the data from reporting plants contained information from cyclic surveillance tests, which results in a significantly larger data set, the study was restricted to the subset of reporting plants. Section C-4 contains observations about the nonreporting plant data.

Table C-1 contains results from the initial assessment of data for the eleven failure modes, including point estimates and confidence bounds for the probability of failure for each mode. Note that the point estimate and bounds do not consider any special sources of variation (e.g., year, plant unit, EDG manufacturer). These results are plotted in Figure C-1.

Table C-2 summarizes the results from testing the hypothesis of constant probabilities across groupings for each failure mode based on data source, plant mode, calendar years, plants, and EDG manufacturer. Statistical evidence of differences between these groupings was found, as discussed below.

Plant Mode. The only significant difference between power operation and shutdown operations failure probabilities was for the MOOS failure mode.

Table C-1. Point estimates and confidence bounds for EDG train failure modes (RG-1.108 plants).

Failure mode	Type of demand	Failures f	Demands d	Probability[a]
Maintenance out of service (MOOS)	Unplanned, not shutdown	3	112	(0.007, 0.027, 0.068)
	Unplanned, shutdown	8	83	(0.049, 0.101, 0.160)
	Pooled	11	195	(0.032, 0.056, 0.092)
Common cause failure (CCF)	Unplanned	0	39	(0.000, 0.000, 0.074)
	Cyclic tests	4	297	(0.005, 0.013, 0.031)
	Pooled	4	336	(0.004, 0.012, 0.027)
Self-initiated failure (SIF)	Unplanned	3	146	(0.006, 0.021, 0.052)
Failure to start (FTS)	Unplanned	2	181	(0.002, 0.011, 0.034)
	Cyclic tests	17	1364	(0.008, 0.012, 0.019)
	Pooled	19	1545	(0.008, 0.012, 0.018)
Failure to recover from FTS (FRFTS)	Unplanned	2	2	(0.224, 1.000, 1.000)
Failure to run--early (FTR_E) (0 to 0.5 h)	Unplanned	1	179	(0.000, 0.006, 0.026)
	Cyclic tests[b]	11	665	(0.009, 0.016, 0.027)
	Pooled	12	844	(0.008, 0.014, 0.023)
Failure to run--middle (FTR_M) (0.5 to 14 h)	Cyclic tests[b]	15	654	(0.014, 0.023, 0.035)
Failure to run--late (FTR_L) (14 to 24 h)	Cyclic tests[b]	1	639	(0.000, 0.002, 0.007)
Failure to recover from FTR (FRFTR)	Unplanned	0	3	(0.000, 0.000, 0.632)
Restoration failure-reset (RFR)	Unplanned	0	179	(0.000, 0.000, 0.017)
	Cyclic tests	6	638	(0.004, 0.009, 0.018)
	Pooled	6	817	(0.003, 0.007, 0.014)
Restoration failure-power (RFP)	Unplanned	0	179	(0.000, 0.000, 0.017)
	Cyclic tests	3	632	(0.001, 0.005, 0.012)
	Pooled	3	811	(0.001, 0.004, 0.010)

a. The middle number is the point estimate, f/d, and the two end numbers form a 90% confidence interval.

b. For three events (four failures), run times were not known well enough to classify the events. The average number of FTR_E failures was 11. Use of averages due to this uncertainty also applies for cyclic failures and demands for FTR_M and FTR_L.

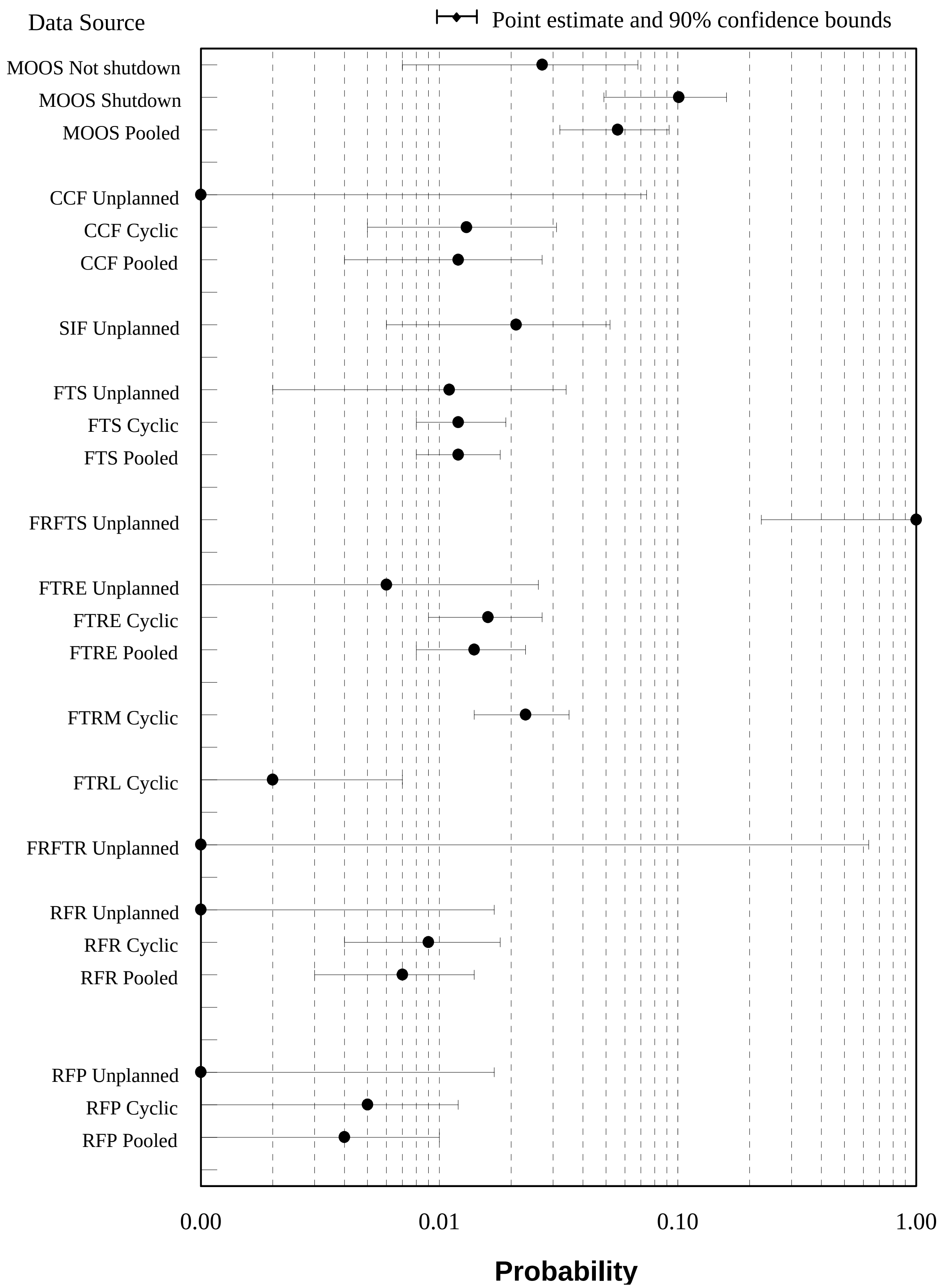

Figure C-1. Point estimates and confidence bounds for EDG train failure modes for RG-1.108 reporting plants.

Table C-2. Evaluation of differences between groups for EDG train failure modes (RG-1.108 plant data).

		P-values for test of variation[a]					
Failure mode	Type of demand	Between data sources	Between plant modes	Between years	Between plants	Between EDG manufacturers	Entities with relatively high chi-square statistics[b]
Maintenance	Pooled	—	0.037	NS	NS	NS	
out of service (MOOS)	Unplanned (not shutdown)	—	—	NS	0.018[c]	NS	Zion 2, but data are sparse
	Unplanned (shutdown)	—	—	NS	NS	NS	
Common cause failure (CCF)	Unplanned	—	NF	NF	NF	NF	
	Cyclic tests	—	—	NS	NS	NS	
	Pooled	NS	NS	NS	NS	NS	
Self-initiated failure (SIF)	Unplanned	—	NS	NS	0.016[c]	NS	Braidwood 2, but data are sparse
Failure to start (FTS)	Unplanned	—	NS	NS	NS	NS	
	Cyclic tests	—	—	0.019	NS	NS	1988
	Pooled	NS	NS	0.011	NS	NS	1988
Failure to recover from FTS (FRFTS)	Unplanned	—	NF	NF	NF	NF	
Failure to run , early (FTR_E)	Unplanned	—	1F	1F	1F	1F	
	Cyclic tests	—	—	NS	0.043	0.001	Salem 2, ALCO Power, Nordberg Mfg.
	Pooled	NS	NS	NS	NS	0.011	ALCO Power, Nordberg Mfg.
Failure to run, middle (FTR_M)	Cyclic tests	—	—	NS	0.001	NS	South Texas 2
Failure to run, late (FTR_L)	Cyclic tests	—	—	NS	NS	<0.001	Nordberg Mfg.
Failure to recover from FTR (FRFTR)	Unplanned	—	NF	NF	NF	NF	
Recovery failure during reset (RFR)	Unplanned	—	NF	NF	NF	NF	
	Cyclic tests	—	—	NS	<0.001	0.002	Catawba 2; Transamerica Delaval
	Pooled	NS	NS	NS	<0.001	0.002	Catawba 2; Transamerica Delaval
Recovery failure upon power	Unplanned	—	NF	NF	NF	NF	
restoration (RFP)	Cyclic tests	—	—	NS	NS	NS	
	Pooled	NS	NS	NS	NS	NS	

a. —, not applicable; NS, not significant (P-value >0.05); NF, no failures or no successes (thus, no test); 1F, only one failure.

b. Years, plants, and EDG manufacturers with an unusual failure probability (compared to others in the group) are flagged. The entities that dominate the chi-square statistic are listed for those cases in which the p-values were less than 0.05. Unless noted otherwise, probabilities for the flagged entities were higher than average.

c. This chi-square test may be unreliable in this case because so few failures occurred.

Year. Among failures to start on unplanned and cyclic test demands, seven of nineteen occurred in 1988 and five occurred in 1991. No other significant differences related to year were identified.

Plant. There were significant plant-to-plant differences in failure probabilities, particularly for failures to run in the middle period. South Texas 2 with two or three failures (depending on the actual run times) in less than eight demands dominates. The Zion 2 and Braidwood 2 data associated with high chi-square statistics for maintenance during operations and for self-initiated failure, respectively, each represent just one failure in just one demand. Salem 2 and McGuire 2 had the highest probability of diesel failure in the first half-hour of running. Catawba 2 had three of the six failures in restoration reset during cyclic testing.

EDG Manufacturer. There were significant EDG manufacturer differences in failure probabilities for failure to run and for recovery failures during reset. For early failures to run (in the first half-hour), Nordberg Mfg. and ALCO Power diesels had the highest failure probabilities. The single failure on a cyclic test that was known to occur after 14 hours of running was on a Nordberg Mfg. diesel. Transamerica Delaval diesels had four of the six RFR failures.

More specific descriptions of the particular data that were used to estimate unreliability for each failure mode and the rationale for choosing that data are discussed in subsections below. The type of modeling selected to calculate the distributions that characterize sampling and/or between-group variation is also discussed. All of these results are based on data from the RG-1.108 plants.

C-1.1.1 Maintenance Out of Service

Three maintenance out of service (MOOS) events occurred among 112 unplanned demands while plants were in the power operations mode. In comparison, 8 MOOS events occurred among 83 unplanned demands while plants were in shutdown modes (including hot standby). The MOOS rate when the plants were shutdown was almost three times the MOOS rate when plants were operating. Table C-1 and Figure C-1 show this difference, and Fisher's exact test found this difference was nearly statistically significant (P-value=0.0568).[a] Therefore, the MOOS data were differentiated by plant mode throughout the reliability analysis, and the power operations (i.e., not shutdown) rate was used in the reliability estimates.

For the power operations mode data, the chi-square statistical analysis detected a significant difference among plants, but there were too few failures for the test to be reliable. Plant-specific empirical beta distributions could not be formed. Therefore, a simple Bayes beta distribution describing approximately the same variation as the confidence interval was derived. This distribution was used in the variance propagation to quantify the EDG MOOS rate when the plants were in the power operations mode.

For the shutdown mode RG-1.108 plant data, the chi-square statistical analysis did not detect any significant differences in any of the grouping variables (e.g., years, plants).

C-1.1.2 Common Cause Failure

No common cause failures (CCF) were observed in the 39 unplanned demands that demanded two or more trains. Four CCF events were identified during cyclic testing. They are discussed briefly below.

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a. When the non-RG-1.108 plants are included, the difference is highly significant (P-value<0.0001).

In the cyclic tests, the separate diesel trains are not tested simultaneously. In two of the four CCF events among RG-1.108 plants, just one train failure was observed. In each of these events, the plant units had two dedicated EDG trains and no swing diesels. The potential for loss of the system existed if there would have been a simultaneous demand for both trains. One of these two events was a failure to start, while the other was a recovery failure on power restoration.

The remaining CCF failures occurred in plants with EDG train configurations involving more than two EDG trains (one plant unit had three dedicated diesel trains and the other had five swing diesels). In each event, two failures occurred over a period of several days as the individual diesels were tested. However, in each of these events a single failure mechanism was involved. Both events were detected during the loaded run phase (i.e., FTR), and represent train failures and not a system loss.

Comparisons of operational data CCF results to PRA/IPEs is not straightforward owing to the various EDG train configurations and different techniques used in risk assessments to model CCF. For this reason, no attempt was made to directly compare the operational data CCF results with CCF statistics based on PRA/IPE information. In the unreliability analysis, the CCF events were treated as train failures and included in the individual failure modes.

For the four failures, the statistical tests showed no significant differences between the unplanned demand and cyclic test data; thus, these were pooled. The tests also showed no significant differences across years, plants, or EDG manufacturers. However, an empirical Bayes distribution was identified reflecting variation in the failure data when grouped by diesel manufacturer.

C-1.1.3 Self-initiated Failure

Self-initiated failures are caused by train configuration problems. Only those unplanned demands and failures that could have occurred during plant operations were considered for SIF failure probability estimates. Estimates were derived to describe a phenomena seen in the operational data. The events were not used in the unreliability estimation process because they do not correspond to failure mechanisms typically modeled in fault trees.

No empirical Bayes distributions or differences across years or diesel manufacturers were found for the self-initiated failure mode. Among plants, the failure data varied from no failures in ten opportunities (at South Texas 2) to one failure in one opportunity (at Braidwood 2). The apparent statistical significance of the Braidwood 2 result is muted by the fact that the data are sparse and multiple tests are being made.

C-1.1.4 Failure to Start

From an engineering standpoint, each cyclic surveillance test contains two sequences that reliably and realistically simulate an EDG train unplanned start demand. Significant differences were not found in the data for unplanned and testing demands, so these data were pooled.

Empirical Bayes distributions describing variation were found for both plant and year. Among years, 1988 had 7 of 19 failures. This difference is highly significant. The 1988 failures occurred at five different units. The distribution reflecting variation in plant unit was selected for the unreliability analysis because it was slightly broader than the year distribution, and it fit the data better (no plants were flagged in the goodness of fit test for the beta-binomial model).

C-1.1.5 Failure to Recover from FTS

Just two of the nineteen failures to start occurred on unplanned demands. They were not recovered. There were no between-group differences in the data. For unreliability evaluations, the simple Bayes beta distribution was used to model failure to recover from FTS.

C-1.1.6 Failure to Run

As explained in Appendix A, Section A-2.1.5, the probability of failure to run was found to depend on the different lengths of the missions, in spite of the fact that mission times were unknown for most of the operational data. Careful review of the cyclic test and unplanned demand failure data allowed determination of run times for most, though not all, of the events. Run times for successful unplanned demands were known only rarely, but were assumed to be at least 0.5 hours. Twenty-four hours was assumed for the mission time of the cyclic tests. To investigate the dependence of failures on run times, the known run times before failure were plotted as a function of the fraction of the set of such times that are less than or equal to each observed time. The cumulative curve that results can be approximated by three straight segments, with breaks at approximately 1/2 hour and 14 hours. Therefore, the failure rate was modeled as being constant in each of the time periods 0 to 1/2 hour, 1/2 hour to 14 hours, and 14 to 24 hours. No conclusions were drawn about the failure rate after 24 hours. The cyclic test data were used for all three time periods while the unplanned demands were applicable only for the first half hour. They were not used for the later time periods because the mission times varied greatly and were often unknown.

As explained in Section A-2.1.5, the failure to run analysis was also complicated by the fact that running times prior to failure were unknown for three events, involving four failures. Thus, these events could not be clearly classified as early, middle, or late failures. The uncertainty was considered by performing analyses for each possible scenario for these events, then combining the results to form a "mixture" distribution. This processing was performed as described in Appendix A to characterize between-plant performance and between-year performance.

Early failures to run. Empirical Bayes distributions reflecting variation in plants and years were found in every data set for the early failures to run, i.e., in every possible combination for the uncertain events. Significant chi-square test results for differences in data groupings were found only 33% of the time for years and 39% of the time for plants. Salem 2 had the highest failure probability in those data sets for which its two uncertain failures occurred in the early period (together with its two known early failures to run). The combined beta distribution reflecting variation between plants was selected for the unreliability analysis.

The early failures to run were also analyzed using fractional failures for the uncertain events to see if differences in mode, data source (unplanned versus cyclic tests) or EDG manufacturer exist. The chi-square tests found that significant differences exist between EDG manufacturers. ALCO Power and Nordberg Mfg. have relatively high rates (an average of 3.88 failures in 78 demands for ALCO Power diesels and 2 failures in 28 demands for Nordberg Mfg). The ALCO Power diesel failures occurred at Salem 2, and the Nordberg failures occurred at McGuire 2. The mixture method was not implemented in this study to identify possible distributions for variation in manufacturers. The computed beta distribution for plants was judged to sufficiently reflect the overall variation and uncertainty. A gamma distribution was also derived from this beta distribution to describe the rate of failure for the 0 to 0.5-hour period.

Middle Failure to Run. Thirteen of the cyclic test failures to run were known to have occurred during the middle period, from 0.5 to 14 hours after the diesel was loaded and running. As many as four additional events may have occurred in this period, depending on the timing of the three uncertain events.

For every data scenario, significant differences were noted between plant units in the FTR_M data. The average P-value was 0.001. A higher rate was found for South Texas 2, though the rate is not significant when multiple testing is considered. The average of the empirical Bayes beta distributions found for each data scenario, as described in Section A-2.1.4, was used for the unreliability calculations. This distribution reflects variation among plants, as well as the uncertainty introduced by the unknown failure times.

The uncertain event analysis also considered variation in years. Significant differences between years based on chi-square tests were not found in any of the data scenarios. Empirical Bayes distributions for variation in year were found just 33% of the time. Use of fractional failures for the uncertain data in a test for differences among EDG manufacturers found no significant differences in the 0.5- to 14-hour period.

Late Failure to Run. One cyclic failure was known to have occurred in the period from 14 to 24 hours. Two of the three uncertain events might have occurred during this period, though the probability of these occurrences, based on the pattern of known cyclic failure times, is small (1/23 for each). One of the uncertain events had one failure; the other had two. Therefore, the average number of failures is 1.125, based on the common occurrence of one failure, the 1/23 potential of two failures (one known, one unknown), the 1/23 potential of three failures (one known, two in the unknown time event), and the (1/23)*(1/23) possibility of four failures having occurred in this time interval. The first and second moments of the simple Bayes distributions arising from these four cases were averaged according to these probabilities, and a beta distribution was fit to the resulting moments. This distribution was used as described in Section A-2.1.5 for the unreliability estimates. The distribution entered the calculations only for unreliabilities for mission times exceeding 14 hours. A gamma distribution was also derived from the beta distribution to describe the rate of failure for the 14 to 24-hour period.

A statistical test for differences in groups using the fractional failures and demands arising from the uncertain data show a significantly higher rate for Nordberg Manufacturing diesels. The known failure occurred for this manufacturer (at McGuire 2), and there were just 18 demands. The other six manufacturers among the RG-1.108 plants had from 18 to 194 demands and either no failures or a small probability of failure from the uncertain data.

C-1.1.7 Failure to Recover from FTR

Recoveries from FTR are only reliably attempted on unplanned demands. Of the three FTR events on unplanned demands at RG-1.108 plants, none were recovered.[a] These data are not sufficient to draw conclusions about any between-group differences. Therefore, a simple Bayes beta distribution was used for unreliability evaluations.

C-1.1.8 Restoration Failure during Reset

Statistical tests show no significant differences between the unplanned demand and cyclic test data for recovery failure during reset; thus, these were pooled. Significant between-group differences and empirical Bayes distributions were found for both plant and EDG manufacturer. Three of the six failures occurred at one plant, Catawba 2. Catawba diesels are made by Transamerica Delaval. One other RFR failure occurred in a Transamerica Delaval diesel (at Vogtle 2). All four of these failures were caused by instrumentation problems, while the other two RFR failures were not in instrumentation subsystems.

The empirical Bayes beta distribution describing variation among plants was used for unreliability evaluations because it was wider (had a higher upper 95 percentile).

C-1.1.9 Restoration Failure upon Power Restoration

Statistical tests show no significant differences between the unplanned demand and cyclic test data for recovery failure upon power restoration; thus, these were pooled. The tests also show no significant differences across years, plants, or EDG manufacturers. Therefore, a simple Bayes beta distribution was used for unreliability evaluations.

C-1.1.10 Summary of Beta Distributions for Individual Failure Modes

Table C-3 describes the beta distributions used to model each of the eleven failure modes. This table differs from Table C-1 and Figure C-1 because it gives Bayesian distributions and intervals rather than confidence intervals. The Bayesian distributions allow the results for the failure modes to be combined to give an uncertainty distribution on the unreliability.

Table C-3 includes distributions for the four failure modes not used in the unreliability calculations: common-cause failure, self-initiated failure, and the two restoration failure modes. Also, it gives the original beta distributions derived for the probability of failure during the complete mission time (0.5 hours, 13.5 hours, and 10 hours, respectively, for FTR_E, FTR_M, and FTR_L). These distributions were used in the unreliability calculations explained in Section A-2.1.5.

An overlap exists between Table C-3 and Table 3 in the body of the report. Table 3 describes Bayesian distributions modeling the statistical variability observed in the data for those failure modes used to estimate EDG train unreliability. However, for the three failure to run modes, Table 3 provides gamma distributions for failure rates. The gamma distributions were derived from the beta distributions, as explained in Section A-2.1.5. They are given in Table 3 (and in the next section) for use by those wishing to make failure rate comparisons.

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a. Note that just one of these three failures was used in the failure unreliability analysis. The other two occurred during the middle and late periods rather than in the first half-hour.

C-1.2 Plant-Specific Distributions for Failure Probabilities

This section provides plant-specific or manufacturer-specific failure probabilities and rates for the five failure modes where such variation could be modeled, namely, FTS, FTR_E, FTR_M, CCF, and RFR. Gamma distributions and rates are provided for the two failure to run modes; the others have beta distributions and probabilities. All the distributions are based on plants except for CCF, for which the distribution is on EDG manufacturer. All the tables listed in this section are based on plants that report in accordance with RG-1.108.

Plant-specific failure probabilities for FTS are shown in Table C-4. For the column labeled "Empirical Bayes mean and 90% interval" in the table, the middle number is the mean of the empirical Bayes beta distribution and the end points include 90% of the Bayes probability, leaving 5% in each tail. Methods for deriving the distributions are given in Section A-2.1.4 of Appendix A. The table also shows the raw counts and 90% confidence intervals. For the column labeled "90% confidence interval," the middle number is the point estimate, the fraction of demands that resulted in failure, and the end points form the confidence interval. Note that the empirical Bayes intervals are more consistent with each other than the confidence intervals are, because the empirical Bayes method pulls the extreme plants toward the general population. If the data from a plant are solely relevant for estimating the failure probability for that plant, the confidence intervals should be used. If instead, the plants belong to a population with individual differences, the empirical Bayes intervals should be used.

Probabilities for common cause failure for each diesel manufacturer are in Table C-5. These tables are in the same format and have the same basic interpretation as Table C-4.

Plant-specific empirical Bayes gamma distributions are given in Tables C-6 and C-7 for early and middle failure to run rates. Confidence intervals are not given in these tables since the distributions were derived by mixing the results of eighteen possible scenarios for the status of three events whose failure times were not known, as described in Section A-2.1.5 of Appendix A. The average number of failures and demands used to assess each probability distribution are given.

Nondegenerate empirical Bayes distributions were not found for the other failure modes. Therefore, for each of these modes that was used in the unreliability estimating process, the generic distribution based on pooling the data from all the RG-1.108 plants was used.

Table C-3. EDG failure mode data and Bayesian probability distributions (based on data from RG-1.108 plants).

Failure mode	Failures	Demands	Modeled variation	Distribution[a]	Bayes mean and 90% interval
Maintenance (MOOS) (not shutdown)	3	112[b]	Sampling	Beta(3.5, 109.5)	(0.0097,0.0310,0.0615)
Common cause failure (CCF)	4	336[c]	Between manufacturer	Beta(3.8, 297.6)	(0.0041,0.0124,0.0244)
Self-initiated failure (SIF)	3	146[d]	Sampling	Beta(3.5, 143.5)	(0.0075,0.0238,0.0474)
Fail to start (FTS)	19	1545[e]	Between plant	Beta(0.9, 70.2)	(0.0005,0.0124,0.0386)
Fail to recover from FTS (FRFTS)	2	2[f]	Sampling	Beta(2.5, 0.5)	(0.4307,0.8333,0.9991)
Fail to run--early (FTR_E) (0-0.5 h)	12	844[g]	Between plant	Beta(0.2, 18.1)	(0.0000,0.0127,0.0630)
Fail to run--middle (FTR_M) (0.5-14 h)	15	654[h]	Between plant	Beta(0.2, 9.1)	(0.0000,0.0247,0.1226)
Fail to run--late (FTR_L) (14-24 h)	1	639[i]	Sampling	Beta(1.4, 566.7)	(0.0003,0.0025,0.0067)
Fail to recover from FTR (FRFTR)	0	3[j]	Sampling	Beta(0.5, 3.5)	(0.0006,0.1250,0.4441)
Restoration failure--reset (RFR)	6	817[e]	Between plant	Beta(0.1, 9.6)	(0.0000,0.0078,0.0470)
Restoration failure--power (RFP)	3	811[e]	Sampling	Beta(3.5, 808.5)	(0.0013,0.0043,0.0086)

a. For the three fail to run modes, gamma distributions were derived from the beta distributions shown in this table, as explained in Section A-2.1.5. The resulting gamma distributions are presented in Table 3 of the main report.

b. Based on unplanned demand data.

c. Based on failures during unplanned or cyclic test demands for which an attempt was made to start more than one diesel.

d. Based on unplanned demands that occurred at power or could have occurred at power.

e. Based on both unplanned and cyclic test data.

f. Of the 19 failures to start, two occurred on unplanned demands.

g. Based on both unplanned demand and cyclic test data, with allowances made for three events for which the exact failure time was unknown.

h. Based on cyclic test data, with allowances made for three events for which the exact failure time was unknown.

i. Based on cyclic test data, with allowances made for two events for which the exact failure time was unknown and could have occurred late.

j. Among unplanned demands at RG-1.108 plants, a failure occurred in the early period and 2 beyond the early time frame. All three were used for the recovery failure for FTR.

Table C-4. Probability of FTS, by plant (RG-1.108 plants)

Plant	*f*	*d*	90% confidence interval[a]	Beta distribution Alpha	Beta distribution Beta	Empirical Bayes mean and 90% interval[b]
Arkansas 2	0	17	(0.000, 0.000, 0.162)	0.82	80.98	(0.000, 0.010, 0.032)
Braidwood 1	0	20	(0.000, 0.000, 0.139)	0.81	83.16	(0.000, 0.010, 0.031)
Braidwood 2	1	16	(0.003, 0.063, 0.264)	1.39	62.92	(0.002, 0.022, 0.057)
Browns Ferry 2	0	12	(0.000, 0.000, 0.221)	0.83	77.08	(0.000, 0.011, 0.034)
Byron 1	2	24	(0.015, 0.083, 0.240)	1.63	52.09	(0.004, 0.030, 0.076)
Byron 2	0	22	(0.000, 0.000, 0.127)	0.81	84.57	(0.000, 0.009, 0.030)
Callaway	1	21	(0.002, 0.048, 0.207)	1.47	70.39	(0.002, 0.020, 0.053)
Catawba 1	2	22	(0.016, 0.091, 0.259)	1.58	49.44	(0.004, 0.031, 0.078)
Catawba 2	1	24	(0.002, 0.042, 0.183)	1.51	74.84	(0.002, 0.020, 0.051)
Clinton	1	20	(0.003, 0.050, 0.216)	1.45	68.90	(0.002, 0.021, 0.054)
Comanche Peak 1	0	20	(0.000, 0.000, 0.139)	0.81	83.16	(0.000, 0.010, 0.031)
Comanche Peak 2	0	0	(no data)	0.88	70.20	(0.000, 0.012, 0.039)
Cook 1	0	18	(0.000, 0.000, 0.153)	0.82	81.72	(0.000, 0.010, 0.032)
Cook 2	0	22	(0.000, 0.000, 0.127)	0.81	84.57	(0.000, 0.009, 0.030)
Diablo Canyon 1	0	27	(0.000, 0.000, 0.105)	0.80	87.91	(0.000, 0.009, 0.029)
Diablo Canyon 2	1	27	(0.002, 0.037, 0.164)	1.55	79.23	(0.002, 0.019, 0.049)
Farley 1	0	28	(0.000, 0.000, 0.101)	0.79	88.55	(0.000, 0.009, 0.029)
Farley 2	0	23	(0.000, 0.000, 0.122)	0.81	85.25	(0.000, 0.009, 0.030)
Fermi 2	2	45	(0.008, 0.044, 0.133)	2.07	81.51	(0.005, 0.025, 0.058)
Grand Gulf	0	24	(0.000, 0.000, 0.117)	0.80	85.93	(0.000, 0.009, 0.030)
Haddam Neck	0	21	(0.000, 0.000, 0.133)	0.81	83.87	(0.000, 0.010, 0.031)
Harris	0	26	(0.000, 0.000, 0.109)	0.80	87.26	(0.000, 0.009, 0.029)
Hatch 1	0	30	(0.000, 0.000, 0.095)	0.79	89.82	(0.000, 0.009, 0.028)
Hatch 2	0	16	(0.000, 0.000, 0.171)	0.82	80.23	(0.000, 0.010, 0.032)
Hope Creek	0	50	(0.000, 0.000, 0.058)	0.74	101.43	(0.000, 0.007, 0.024)
LaSalle 1	2	19	(0.019, 0.105, 0.296)	1.50	45.53	(0.004, 0.032, 0.082)
LaSalle 2	0	12	(0.000, 0.000, 0.221)	0.83	77.08	(0.000, 0.011, 0.034)
Limerick 1	1	40	(0.001, 0.025, 0.113)	1.68	97.52	(0.002, 0.017, 0.042)
Limerick 2	0	32	(0.000, 0.000, 0.089)	0.78	91.07	(0.000, 0.009, 0.028)
McGuire 1	0	23	(0.000, 0.000, 0.122)	0.81	85.25	(0.000, 0.009, 0.030)
McGuire 2	2	29	(0.012, 0.069, 0.202)	1.75	58.89	(0.004, 0.029, 0.070)
Millstone 3	0	26	(0.000, 0.000, 0.109)	0.80	87.26	(0.000, 0.009, 0.029)
Nine Mile Pt. 2	0	27	(0.000, 0.000, 0.105)	0.80	87.91	(0.000, 0.009, 0.029)
North Anna 1	0	30	(0.000, 0.000, 0.095)	0.79	89.82	(0.000, 0.009, 0.028)
North Anna 2	0	23	(0.000, 0.000, 0.122)	0.81	85.25	(0.000, 0.009, 0.030)
Palo Verde 1	0	27	(0.000, 0.000, 0.105)	0.80	87.91	(0.000, 0.009, 0.029)
Palo Verde 2	0	30	(0.000, 0.000, 0.095)	0.79	89.82	(0.000, 0.009, 0.028)
Palo Verde 3	0	19	(0.000, 0.000, 0.146)	0.81	82.45	(0.000, 0.010, 0.031)
Perry	0	20	(0.000, 0.000, 0.139)	0.81	83.16	(0.000, 0.010, 0.031)
River Bend	0	18	(0.000, 0.000, 0.153)	0.82	81.72	(0.000, 0.010, 0.032)
Salem 1	0	39	(0.000, 0.000, 0.074)	0.77	95.25	(0.000, 0.008, 0.026)
Salem 2	0	40	(0.000, 0.000, 0.072)	0.77	95.82	(0.000, 0.008, 0.026)
San Onofre 2	0	29	(0.000, 0.000, 0.098)	0.79	89.19	(0.000, 0.009, 0.029)
San Onofre 3	0	32	(0.000, 0.000, 0.089)	0.78	91.07	(0.000, 0.009, 0.028)
Seabrook	0	15	(0.000, 0.000, 0.181)	0.82	79.46	(0.000, 0.010, 0.033)
Sequoyah 1	0	20	(0.000, 0.000, 0.139)	0.81	83.16	(0.000, 0.010, 0.031)
Sequoyah 2	0	23	(0.000, 0.000, 0.122)	0.81	85.25	(0.000, 0.009, 0.030)
South Texas 1	1	41	(0.001, 0.024, 0.111)	1.69	98.87	(0.002, 0.017, 0.042)

Table C-4. (continued).

Plant	*f*	*d*	90% confidence interval[a]	Beta distribution Alpha	Beta	Empirical Bayes mean and 90% interval[b]
South Texas 2	0	26	(0.000, 0.000, 0.109)	0.80	87.26	(0.000, 0.009, 0.029)
St. Lucie 1	0	21	(0.000, 0.000, 0.133)	0.81	83.87	(0.000, 0.010, 0.031)
St. Lucie 2	1	22	(0.002, 0.045, 0.198)	1.48	71.88	(0.002, 0.020, 0.052)
Summer	0	27	(0.000, 0.000, 0.105)	0.80	87.91	(0.000, 0.009, 0.029)
Susquehanna 1	0	24	(0.000, 0.000, 0.117)	0.80	85.93	(0.000, 0.009, 0.030)
Susquehanna 2	1	16	(0.003, 0.063, 0.264)	1.39	62.92	(0.002, 0.022, 0.057)
Turkey Point 3	0	24	(0.000, 0.000, 0.117)	0.80	85.93	(0.000, 0.009, 0.030)
Turkey Point 4	0	21	(0.000, 0.000, 0.133)	0.81	83.87	(0.000, 0.010, 0.031)
Vogtle 1	0	24	(0.000, 0.000, 0.117)	0.80	85.93	(0.000, 0.009, 0.030)
Vogtle 2	0	18	(0.000, 0.000, 0.153)	0.82	81.72	(0.000, 0.010, 0.032)
Wash. Nuclear 2	0	29	(0.000, 0.000, 0.098)	0.79	89.19	(0.000, 0.009, 0.029)
Waterford 3	0	22	(0.000, 0.000, 0.127)	0.81	84.57	(0.000, 0.009, 0.030)
Wolf Creek	0	24	(0.000, 0.000, 0.117)	0.80	85.93	(0.000, 0.009, 0.030)
Zion 1	0	38	(0.000, 0.000, 0.076)	0.77	94.66	(0.000, 0.008, 0.026)
Zion 2	0	20	(0.000, 0.000, 0.139)	0.81	83.16	(0.000, 0.010, 0.031)
RG-1.108 Population	19	1545	(0.008, 0.012, 0.018)[c]	0.88	70.20	(0.000, 0.012, 0.039)[d]

a. The middle number is the maximum likelihood estimate, *f/d*, and the end numbers form a 90% confidence interval.

b. The middle number is the Bayes mean, a/(a+b), and the end numbers form a 90% interval.

c. This confidence interval is too short, because it assumes no variation between plants.

d. This empirical Bayes interval models the substantial variation between plants, but not the randomness of events within a plant.

Table C-5. Probability of CCF by manufacturer (based on RG-1.108 plant data).

Plant	*f*	*d*	90% confidence interval[a]	Beta distribution Alpha	Beta distribution Beta	Empirical Bayes mean and 90% interval[b]
ALCO Power	1	25	(0.002, 0.040, 0.176)	0.88	59.54	(0.001, 0.015, 0.045)
Cooper Bessemer	1	82	(0.001, 0.012, 0.057)	2.42	192.73	(0.003, 0.012, 0.028)
Electro Motive	0	73	(0.000, 0.000, 0.040)	0.91	90.38	(0.000, 0.010, 0.031)
Fairbanks Morse/Colt	0	85	(0.000, 0.000, 0.035)	0.77	78.70	(0.000, 0.010, 0.032)
Nordberg Mfg.	0	14	(0.000, 0.000, 0.193)	1.83	152.26	(0.002, 0.012, 0.029)
Transamerica Delaval	2	47	(0.008, 0.043, 0.128)	0.54	32.43	(0.000, 0.017, 0.061)
Worthington Corp.	0	10	(0.000, 0.000, 0.259)	1.81	148.68	(0.002, 0.012, 0.029)
RG-1.108 Population	4	336	(0.004, 0.012, 0.027)[c]	3.75	297.55	(0.004, 0.012, 0.024)[d]

a. The middle number is the maximum likelihood estimate, *f/d*, and the end numbers form a 90% confidence interval.

b. The middle number is the Bayes mean, a/(a+b), and the end numbers form a 90% interval.

c. This confidence interval is too short, because it assumes no variation between manufacturers.

d. This empirical Bayes interval models the substantial variation between manufacturers, but not the randomness of events within a manufacturers.

Table C-6. Hourly failure rates for FTR_E (the early period 0 to 0.5 h), by plant (RG-1.108 plants).

Plant	Failures	Demands[a]	Gamma distribution Alpha	Beta	Empirical Bayes mean and 90% interval[b]
Arkansas 2	0	9	0.25	14.37	(0.000, 0.017, 0.084)
Braidwood 1	0	12	0.25	15.86	(0.000, 0.016, 0.076)
Braidwood 2	0	7	0.25	13.35	(0.000, 0.019, 0.090)
Browns Ferry 2	0.4[c]	6	0.38	7.72	(0.000, 0.050, 0.210)
Byron 1	0	10	0.25	14.87	(0.000, 0.017, 0.081)
Byron 2	0	12	0.25	15.86	(0.000, 0.016, 0.076)
Callaway	0	10	0.25	14.87	(0.000, 0.017, 0.081)
Catawba 1	0	10	0.25	14.87	(0.000, 0.017, 0.081)
Catawba 2	0	11	0.25	15.37	(0.000, 0.016, 0.078)
Clinton	0	9	0.25	14.37	(0.000, 0.017, 0.084)
Comanche Peak 1	0	12	0.25	15.86	(0.000, 0.016, 0.076)
Comanche Peak 2	0	0	0.25	9.79	(0.000, 0.025, 0.123)
Cook 1	0	10	0.25	14.87	(0.000, 0.017, 0.081)
Cook 2	0	12	0.25	15.86	(0.000, 0.016, 0.076)
Diablo Canyon 1	1	15	1.10	15.23	(0.005, 0.072, 0.209)
Diablo Canyon 2	0	16	0.25	17.76	(0.000, 0.014, 0.068)
Farley 1	0	16	0.25	17.76	(0.000, 0.014, 0.068)
Farley 2	0	13	0.25	16.34	(0.000, 0.015, 0.074)
Fermi 2	0	23	0.24	20.96	(0.000, 0.012, 0.057)
Grand Gulf	0	12	0.25	15.86	(0.000, 0.016, 0.076)
Haddam Neck	0	13	0.25	16.34	(0.000, 0.015, 0.074)
Harris	0	16	0.25	17.76	(0.000, 0.014, 0.068)
Hatch 1	0	15	0.25	17.29	(0.000, 0.014, 0.069)
Hatch 2	0	8	0.25	13.87	(0.000, 0.018, 0.087)
Hope Creek	0	26	0.24	22.29	(0.000, 0.011, 0.053)
LaSalle 1	0	9	0.25	14.37	(0.000, 0.017, 0.084)
LaSalle 2	0	6	0.25	12.83	(0.000, 0.019, 0.094)
Limerick 1	0	19	0.25	19.15	(0.000, 0.013, 0.062)
Limerick 2	2	16	1.67	13.25	(0.018, 0.126, 0.317)
McGuire 1	0	13	0.25	16.34	(0.000, 0.015, 0.074)
McGuire 2	2	15	1.64	12.62	(0.018, 0.130, 0.329)
Millstone 3	0	14	0.25	16.82	(0.000, 0.015, 0.071)
Nine Mile Pt. 2	0	17	0.25	18.23	(0.000, 0.014, 0.066)
North Anna 1	0	18	0.25	18.69	(0.000, 0.013, 0.064)
North Anna 2	0	13	0.25	16.34	(0.000, 0.015, 0.074)
Palo Verde 1	0	17	0.25	18.23	(0.000, 0.014, 0.066)
Palo Verde 2	0	18	0.25	18.69	(0.000, 0.013, 0.064)
Palo Verde 3	0	11	0.25	15.37	(0.000, 0.016, 0.078)
Perry	0	10	0.25	14.87	(0.000, 0.017, 0.081)
River Bend	0	10	0.25	14.87	(0.000, 0.017, 0.081)
Salem 1	0	24	0.24	21.41	(0.000, 0.011, 0.056)
Salem 2	2.8[d]	22	1.66	10.92	(0.021, 0.152, 0.382)
San Onofre 2	0	15	0.25	17.29	(0.000, 0.014, 0.069)
San Onofre 3	0	16	0.25	17.76	(0.000, 0.014, 0.068)
Seabrook	0	9	0.25	14.37	(0.000, 0.017, 0.084)
Sequoyah 1	0	14	0.25	16.82	(0.000, 0.015, 0.071)
Sequoyah 2	0	13	0.25	16.34	(0.000, 0.015, 0.074)
South Texas 1	0	25	0.24	21.85	(0.000, 0.011, 0.054)

Table C-6. (continued).

Plant	Failures	Demands[a]	Gamma distribution Alpha	Beta	Empirical Bayes mean and 90% interval[b]
South Texas 2	1.4[e]	17	1.18	12.80	(0.007, 0.093, 0.261)
St. Lucie 1	0	11	0.25	15.37	(0.000, 0.016, 0.078)
St. Lucie 2	0	11	0.25	15.37	(0.000, 0.016, 0.078)
Summer	0	17	0.25	18.23	(0.000, 0.014, 0.066)
Susquehanna 1	0	12	0.25	15.86	(0.000, 0.016, 0.076)
Susquehanna 2	0	7	0.25	13.35	(0.000, 0.019, 0.090)
Turkey Point 3	0	14	0.25	16.82	(0.000, 0.015, 0.071)
Turkey Point 4	0	13	0.25	16.34	(0.000, 0.015, 0.074)
Vogtle 1	1	14	1.09	14.60	(0.005, 0.074, 0.216)
Vogtle 2	0	10	0.25	14.87	(0.000, 0.017, 0.081)
Wash. Nuclear 2	0	15	0.25	17.29	(0.000, 0.014, 0.069)
Waterford 3	0	12	0.25	15.86	(0.000, 0.016, 0.076)
Wolf Creek	0	14	0.25	16.82	(0.000, 0.015, 0.071)
Zion 1	1	20	1.15	18.32	(0.004, 0.063, 0.179)
Zion 2	0	10	0.25	14.87	(0.000, 0.017, 0.081)
RG-1.108 Population	11.6	844.0	0.25	9.79	(0.000, 0.025, 0.123)

a. Demands from unplanned and cyclic surveillance tests.

b. The middle number is the Bayes mean, a/b, and the end numbers form a 90% interval.

c. The time of one failure was completely unknown. The failure was given a subjective probability of 9/23 of having occurred in the first half hour, because of the 23 failures with known times on cyclic tests, 9 occurred in the first half hour. See Section A-2.1.5.

d. The time of one event (two failures) was completely unknown. The event was treated in the same manner as the uncertain Browns Ferry event. See Section A-2.1.5.

e. The time of one failure was before 14 hours, but otherwise unknown. The failure was given a subjective probability of 9/22 of having occurred in the first half hour, because of the 22 failures with known times < 14 hours on cyclic tests, 9 occurred in the first half hour. See Section A-2.1.5.

Table C-7. Hourly failure rate for FTR_M (the middle period 0.5 to 14.0 h), by plant (RG-1.108 plants).

Plant	Failures	Demands[a]	Gamma distribution Alpha	Beta	Empirical Bayes mean and 90% interval[b]
Arkansas 2	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Braidwood 1	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Braidwood 2	0	7	0.24	232.60	(0.000, 0.001, 0.005)
Browns Ferry 2	0.6[c]	5.6	0.60	158.52	(0.000, 0.004, 0.014)
Byron 1	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Byron 2	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Callaway	0	9	0.24	257.97	(0.000, 0.001, 0.005)
Catawba 1	0	9	0.24	257.97	(0.000, 0.001, 0.005)
Catawba 2	0	11	0.24	283.09	(0.000, 0.001, 0.004)
Clinton	0	9	0.24	257.97	(0.000, 0.001, 0.005)
Comanche Peak 1	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Comanche Peak 2	0	0	0.26	143.38	(0.000, 0.002, 0.009)
Cook 1	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Cook 2	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Diablo Canyon 1	0	11	0.24	283.09	(0.000, 0.001, 0.004)
Diablo Canyon 2	0	9	0.24	257.97	(0.000, 0.001, 0.005)
Farley 1	0	12	0.24	295.57	(0.000, 0.001, 0.004)
Farley 2	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Fermi 2	0	18	0.23	369.83	(0.000, 0.001, 0.003)
Grand Gulf	0	12	0.24	295.57	(0.000, 0.001, 0.004)
Haddam Neck	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Harris	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Hatch 1	0	15	0.24	332.82	(0.000, 0.001, 0.003)
Hatch 2	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Hope Creek	0	24	0.23	443.41	(0.000, 0.001, 0.003)
LaSalle 1	0	6	0.25	219.78	(0.000, 0.001, 0.005)
LaSalle 2	0	6	0.25	219.78	(0.000, 0.001, 0.005)
Limerick 1	0	19	0.23	382.12	(0.000, 0.001, 0.003)
Limerick 2	0	14	0.24	320.43	(0.000, 0.001, 0.004)
McGuire 1	0	10	0.24	270.56	(0.000, 0.001, 0.004)
McGuire 2	1	9	1.25	252.43	(0.000, 0.005, 0.014)
Millstone 3	0	12	0.24	295.57	(0.000, 0.001, 0.004)
Nine Mile Pt. 2	2	10	2.11	247.84	(0.002, 0.008, 0.020)
North Anna 1	0	12	0.24	295.57	(0.000, 0.001, 0.004)
North Anna 2	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Palo Verde 1	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Palo Verde 2	0	12	0.24	295.57	(0.000, 0.001, 0.004)
Palo Verde 3	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Perry	0	10	0.24	270.56	(0.000, 0.001, 0.004)
River Bend	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Salem 1	0	15	0.24	332.82	(0.000, 0.001, 0.003)
Salem 2	1.1[d]	15	0.80	201.91	(0.000, 0.004, 0.013)
San Onofre 2	0	14	0.24	320.43	(0.000, 0.001, 0.004)
San Onofre 3	0	16	0.24	345.17	(0.000, 0.001, 0.003)
Seabrook	1	6	1.20	203.18	(0.000, 0.006, 0.017)
Sequoyah 1	0	6	0.25	219.78	(0.000, 0.001, 0.005)
Sequoyah 2	0	10	0.24	270.56	(0.000, 0.001, 0.004)

Table C-7. (continued).

Plant	Failures	Demands[a]	Gamma distribution Alpha	Beta	Empirical Bayes mean and 90% interval[b]
South Texas 1	0	14	0.24	320.43	(0.000, 0.001, 0.004)
South Texas 2	2.6[e]	7.6	2.21	179.33	(0.002, 0.012, 0.028)
St. Lucie 1	1	10	1.26	268.30	(0.000, 0.005, 0.013)
St. Lucie 2	0	9	0.24	257.97	(0.000, 0.001, 0.005)
Summer	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Susquehanna 1	2	12	2.17	281.62	(0.002, 0.008, 0.018)
Susquehanna 2	0	7	0.24	232.60	(0.000, 0.001, 0.005)
Turkey Point 3	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Turkey Point 4	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Vogtle 1	0	10	0.24	270.56	(0.000, 0.001, 0.004)
Vogtle 2	0	8	0.24	245.32	(0.000, 0.001, 0.005)
Wash. Nuclear 2	1	14	1.28	329.72	(0.000, 0.004, 0.011)
Waterford 3	1	10	1.26	268.30	(0.000, 0.005, 0.013)
Wolf Creek	2	10	2.11	247.84	(0.002, 0.008, 0.020)
Zion 1	0	17	0.23	357.51	(0.000, 0.001, 0.003)
Zion 2	0	10	0.24	270.56	(0.000, 0.001, 0.004)
RG-1.108 Population	15.3	654.4	0.26	143.38	(0.000, 0.002, 0.009)

a. Demands from cyclic surveillance tests only.

b. The middle number is the Bayes mean, a/b, and the end numbers form a 90% interval.

c. The time of one failure was completely unknown. The failure was given a subjective probability of 13/23 of having occurred in the 0.5- to 14.0-h period because, of the 23 failures with known times on cyclic tests, 13 occurred in the 0.5- to 14.0-h period. See Section A-2.1.5. The average number of demands also is not an integer because of uncertainty about whether the failure occurred in the first period, and hence reduced the number of demands for FTR_M.

d. The time of one event (two failures) was completely unknown. The event was treated in the same manner as the uncertain Browns Ferry event. See Section A-2.1.5.

e. The time of one failure was before 14 hours, but otherwise unknown. The failure was given a subjective probability of 13/22 of having occurred in the middle run period because, of the 22 failures with known times < 14 hours on cyclic tests, 13 occurred between 0.5 and 14 hours into the test. See Section A-2.1.5.

C-2. INVESTIGATION OF RELATION TO PLANT LOW-POWER LICENSE DATE

The possibility of a trend in EDG train performance with plant age as measured by a plant's low-power license date was investigated. This evaluation was performed for unreliabilities, for the rate of unplanned demands, and for the rate of failures.

Table C-9 shows the EDG unreliability by plant for the RG-1.108 plants, along with the plant low-power license date. The details of calculating the plant-specific unreliabilities deserve some attention. The unreliabilities calculated for Section 3.1.2 of the main report are not used because the failure probabilities for four of the seven failure modes in the calculation were generic, not plant-specific. Therefore, the trend study estimates were obtained as described in Section A-2.1.4. First, the RG-1.108 population data for a failure mode were pooled and a diffuse prior with the RG-1.108 population mean (more specifically, a constrained noninformative prior) was formed for each failure mode. For each plant, each of these priors was updated with plant-specific failures and demands from the study period to obtain plant-specific posterior distributions for each failure mode. The resulting updated distributions were combined for each plant as described in Sections A-2.1.5 and A-2.2 to yield plant-specific unreliabilities for EDG that were very sensitive to the plant data.

A simple approach for seeking trends is to plot the plant-specific unreliability against the plant low-power license date. Such a plot is shown in the main body of this report, with 90% uncertainty bars plotted vertically. The 90% intervals were not used in the trend calculations, but are shown as a matter of interest. Linear regression (least squares fitting) was used to see if there was a trend, here and in the work described in the next section. A straight line was fitted to the unreliability (shown as dots in the plot), and a straight line was also fitted to log(unreliability). The log fit was selected if it accounted for substantially more of the variation, as measured by R^2, or if it were needed to produce a plot with regression confidence limits greater than zero. If the simple model fit as well as the log model, the simple model was chosen for simplicity.

The regression-based confidence band shown as dashed lines on the plots applies to every point of the fitted line simultaneously. The methodology for the confidence bounds was developed by Working, Hotelling, and Scheffé, and is described in References C-1 and C-2 as well as many other statistics books that treat linear regression. The regression line as a whole lies within the band with 90% confidence when the data being plotted are normally distributed.

The slope of the trend line was not statistically significant for the unreliabilities or the logs of the unreliabilities.

The above result used only those failures that occurred during unplanned demands and cyclic surveillance tests, for which demand counts are available. To make use of all the data, the plant-specific rate of failures per diesel per calendar year for the study period was estimated. Rates were also estimated for unplanned demands. The simplest normalizing technique was used: the rate for a plant was estimated as the quotient (number of events)/(number of calendar years in the study for the plant times the number of diesel generators), with calendar time estimated as described in Section A-1.2.3 of Appendix A. Maintenance out of service events were excluded from the failure rate assessment.

As with the unreliabilities, plant-specific rates were plotted against the plant low-power license date and a trend line was fitted to rate and to log(rate). For both failure and demand rates, use of log models was necessary to avoid negative regression prediction limits. For log models of rates, a refinement to the methodology helps stabilize the simultaneous confidence intervals. The method, described in the *Example 2: Poisson Regression* section of Ref. C-2, weights the log rates inversely according to their variances.

An additional detail of the methodology deserves mention. The log model cannot be used directly when a rate is zero. Rather than simply use an (arbitrary) fraction of a failure or demand divided by exposure time to estimate a non-zero rate for these cases, all the data for a particular rate were adjusted uniformly. The constrained noninformative prior distribution (see Section A-2.1.4) with a mean value equal to the RG-1.108 population mean for the rate (total event count plus 0.5 divided by total time) was used as a prior distribution and updated with plant-specific data. The resulting plant-specific mean was used for the rate. It was strictly positive, and therefore its logarithm was defined. For the EDG train rates, this adjustment effectively added approximately 0.5 to each failure count and, depending on the rate under consideration, between 1.3 and 2.4 years to each exposure time. This process, explained further in Section A-3, results also in the calculation of 90% Bayesian uncertainty bounds for each rate. These bounds are shown in the plots as a matter of interest.

Tests for variation between plants for both failure rates and unplanned demand rates show significant variation in both cases. The P-values for the chi-square tests were less than 0.0001. However, the only significant trend with respect to plant age was with the plant failure rates. A significant trend (P-value=0.0070) was found in the failure rate as a function of plant age. The rate tends to be higher for the newer plants. No trends were found with unplanned demands.

Table C-9. Plant-specific unreliability based on constrained noninformative priors and a 24-hour mission time, by low-power license date (RG-1.108 plants).

Plant	Low-power license date	Bayes mean and 90% interval
Haddam Neck	06/30/67	(0.001, 0.038, 0.129)
Turkey Point 3	07/19/72	(0.001, 0.034, 0.114)
Turkey Point 4	04/10/73	(0.001, 0.031, 0.104)
Zion 1	10/19/73	(0.001, 0.037, 0.122)
Zion 2	11/14/73	(0.008, 0.102, 0.275)
Browns Ferry 2	08/02/74	(0.001, 0.044, 0.138)
Hatch 1	10/13/74	(0.001, 0.039, 0.130)
Cook 1	10/25/74	(0.001, 0.037, 0.123)
St. Lucie 1	03/01/76	(0.001, 0.042, 0.134)
Salem 1	12/01/76	(0.000, 0.030, 0.102)
Farley 1	06/25/77	(0.001, 0.035, 0.121)
Cook 2	12/23/77	(0.001, 0.038, 0.129)
North Anna 1	04/01/78	(0.000, 0.035, 0.120)
Hatch 2	06/13/78	(0.001, 0.041, 0.133)
Arkansas 2	09/01/78	(0.001, 0.040, 0.133)
Sequoyah 1	02/29/80	(0.001, 0.035, 0.116)
North Anna 2	04/11/80	(0.001, 0.036, 0.122)
Salem 2	04/13/80	(0.001, 0.041, 0.126)
Farley 2	10/23/80	(0.001, 0.040, 0.131)
McGuire 1	06/12/81	(0.001, 0.036, 0.122)
Sequoyah 2	06/25/81	(0.001, 0.034, 0.115)
San Onofre 2	02/16/82	(0.001, 0.039, 0.130)
LaSalle 1	04/17/82	(0.010, 0.065, 0.156)
Grand Gulf	06/16/82	(0.001, 0.039, 0.131)
Susquehanna 1	07/17/82	(0.001, 0.044, 0.137)
Summer	08/06/82	(0.001, 0.033, 0.109)
San Onofre 3	11/15/82	(0.001, 0.039, 0.130)
McGuire 2	03/03/83	(0.012, 0.068, 0.160)
St. Lucie 2	04/06/83	(0.004, 0.050, 0.137)
Diablo Canyon 1	11/08/83	(0.001, 0.040, 0.131)
LaSalle 2	12/16/83	(0.001, 0.041, 0.134)
Wash. Nuclear 2	12/20/83	(0.001, 0.041, 0.133)
Susquehanna 2	03/23/84	(0.005, 0.056, 0.150)
Callaway	06/11/84	(0.014, 0.109, 0.266)
Limerick 1	10/26/84	(0.003, 0.048, 0.139)
Byron 1	10/31/84	(0.009, 0.066, 0.160)
Catawba 1	12/06/84	(0.010, 0.067, 0.162)
Waterford 3	12/18/84	(0.001, 0.038, 0.125)
Palo Verde 1	12/31/84	(0.001, 0.029, 0.095)
Wolf Creek	03/11/85	(0.001, 0.039, 0.121)
Fermi 2	03/20/85	(0.006, 0.053, 0.139)
Diablo Canyon 2	04/26/85	(0.004, 0.044, 0.119)
River Bend	08/29/85	(0.001, 0.038, 0.130)
Millstone 3	11/25/85	(0.000, 0.037, 0.128)
Palo Verde 2	12/09/85	(0.001, 0.030, 0.098)
Catawba 2	02/24/86	(0.004, 0.052, 0.145)
Perry	03/18/86	(0.001, 0.040, 0.132)

Table C-9. (continued).

Plant	Low-power license date	Bayes mean and 90% interval
Hope Creek	04/11/86	(0.000, 0.033, 0.118)
Clinton	09/29/86	(0.004, 0.054, 0.147)
Harris	10/24/86	(0.001, 0.031, 0.104)
Nine Mile Pt. 2	10/31/86	(0.010, 0.086, 0.217)
Byron 2	11/06/86	(0.001, 0.036, 0.122)
Vogtle 1	01/16/87	(0.001, 0.041, 0.133)
Palo Verde 3	03/25/87	(0.001, 0.035, 0.116)
Braidwood 1	05/21/87	(0.001, 0.036, 0.122)
South Texas 1	08/21/87	(0.002, 0.044, 0.130)
Braidwood 2	12/18/87	(0.004, 0.054, 0.148)
South Texas 2	12/16/88	(0.002, 0.042, 0.126)
Vogtle 2	02/09/89	(0.001, 0.037, 0.123)
Seabrook	05/26/89	(0.001, 0.040, 0.127)
Limerick 2	07/10/89	(0.001, 0.043, 0.136)
Comanche Peak 1	02/08/90	(0.001, 0.033, 0.110)
Comanche Peak 2	02/02/93	(0.001, 0.044, 0.139)

C-3. ANALYSIS BY YEAR, 1987–1993

The analyses of Section C-2 were modified to evaluate if there was a time trend during the period of the study (i.e., through calendar time). Unreliability was considered as well as failure rates and unplanned demand rates.

Table C-10 shows the unreliability estimated by year. The estimates are obtained by pooling the data from all the RG-1.108 plants during any one calendar year and updating the constrained noninformative prior described in Section A-3 for each failure mode with data from each year. Maintenance, failure to start, and the three FTR probabilities are included, as well as recovery from failures to start and from failures to run. Shutdown data were excluded in the estimation of the maintenance out of service probability. The failures used to estimate the unreliability were those for which failure opportunities (demands) can be counted. The linear model method to test for a trend was the same as described in Section C-2, except that the time variable was calendar year instead of low-power license date. The linear model was selected in preference to the logarithmic fit, but the slope of the trend is not statistically significant. That is, there was no trend in unreliability during the study period.

Rates for each calendar year were also analyzed by pooling the data from all the RG-1.108 plants during each calendar year. The counts were normalized by the number of diesel years of data associated with each calendar year for the RG-1.108 plants. A total of 952.5 diesel years of data were involved in these rate assessments. Maintenance events (MOOS) were excluded from the failure rate evaluation. No Bayesian adjustment was required to account for zero rates. The fitted line and its regression limits were not found to be negative, so linear rather than logarithmic fits were selected.

The results of the rate analyses are shown in main body of the report. The individual rate bounds shown for information are 90% confidence limits based on a constant occurrence rate in time. A chi-squared test shows that failure rates per diesel year differ significantly from one year to the next in the study period. However, no trend was found in the failure rates.

Calendar year trends show, particularly in the unplanned demand rate per plant year a statistically significant trend, which was found to be decreasing (P-value=0.0058). The trend was less significant when the data were normalized per diesel year (P-value=0.0771). Overall, the unplanned demand rates from year to year were more similar than the failure rates. The slope of the trend line when normalized by plant year rather than diesel year was significantly different from zero, but it was not large. Chi-square tests for differences in the unplanned demand rates per diesel year and per plant year found no significant differences.

Table C-10. Year-specific unreliability based on constrained noninformative priors and a 24-hour mission time.

Year	Bayes mean and 90% interval
87	(0.003, 0.031, 0.082)
88	(0.015, 0.045, 0.088)
89	(0.007, 0.060, 0.151)
90	(0.003, 0.031, 0.081)
91	(0.016, 0.059, 0.121)
92	(0.000, 0.016, 0.055)
93	(0.008, 0.062, 0.157)

C-4. RESULTS FOR NON-RG-1.108 PLANTS

For the main analysis described in this report, only plants reporting according to Regulatory Guide 1.108 were included. Only for these plants were data for single-diesel failures on cyclic surveillance tests available. Comments on the statistical analysis findings from tests on unplanned demand data that include all plants having diesels follows.

C-4.1 Failure Mode Comparison

Early in the study, tests for differences between RG-1.108 plants and non-RG-1.108 plants were conducted for each failure mode. Three failures on unplanned demands (one failure to start and two self-initiated failures) were excluded because they could not occur during operations. These failures all occurred at non-RG-1.108 plants. For the early failure to run mode, with uncertain counts in three events due to unknown failure times, the average numbers of failures and demands were used in the chi-square tests. For all the modes that were used in the unreliability analysis, no significant differences in data from the two groups of plants were found. Of course, the middle and late failure to run modes were not included in these tests, since only cyclic test data were used for these analyses. Furthermore, differences may exist that were not detected in the statistical tests. The data are sparse in several cases, and the completeness of even the unplanned demand data for the non-RG-1.108 plants is hard to ascertain.

The maintenance out of service failure mode deserves further discussion. While no differences were observed during operational periods, which were used for the unreliability analysis, significant differences were noted for shutdown periods. The non-RG-1.108 plants experienced 21 failures out of 82 unplanned demands during shutdown periods. The RG-1.108 reporting plants experienced 8 failures in 83 demands. Fisher's exact test for this difference has a p-value of 0.018, indicating that the nonreporting plants have a higher outage probability during shutdown periods. Variation between plants exists for shutdown MOOS probabilities among the non-RG-1.108 plants.

The data for recovery from failure to start and from failure to run are sparse, regardless of whether the RG-1.108 plant data are included. Therefore, no statistically significant differences were noted. The results are somewhat different; however for the two groups of plants. For recovery from failure to start the point estimate among RG-1.108 plants is 1.0 for the probability of failure (2 recovery failures out of 2 unplanned demand failures), while it is 0.5 for the non-RG-1.108 plants (1 out of 2). Conversely, for recovery from failure to run, the point estimate of the probability of failure to recover is 0.0 for the RG-1.108 plants and 1.0 for the non-RG-1.108 plants. The sole failure to recover from failure to run occurred at a non-RG-1.108 plant.

C-4.2 Unreliability Comparisons

No empirical Bayes distributions for unreliability analysis were found using data from just non-RG-1.108 plants. The unplanned demand data for these plants were too sparse. No mode used in the unreliability analysis had more than two failures. Unreliability estimates were constructed for comparison with other plants using simple Bayes distributions based on the pooled data that reflects sampling variation only. With just one failure to run among these data, the failure to run probability was not split into three time periods as with the data that included cyclic surveillance tests. The results of the comparisons are in the main text.

C-4.3 Trend Analysis Comparisons

The total data were analyzed for trends by low-power license date and calendar year using both the cyclic test data from RG-1.108 plants and the unplanned demand data from all the plants. The results were the same as for the RG-1.108 plants. In 1532.7 diesel years of data, significant differences were found between plants for overall failure rates per year and unplanned demand rates by plant year and by diesel year (the P-values were <0.0001 in every case). Increasing trends were observed in the failure rates, with a P-value of 0.0001.

Similarly, the addition of unplanned demand data for the non-RG-1.108 plants had little effect on the analysis by calendar year. Significant between-year differences were found for the failure rates (P-value=0.0014). Decreasing trends were found for the unplanned demand rates when normalized by plant year (P-value=0.01); the P-value was 0.0408 when normalized by diesel year. No other trends or significant differences were found in the calendar time analysis.

C-5. REFERENCES

C-1. M. E. Engelhardt, *Modeling Patterns in Continuous Data Using Linear and Related Models*, DRAFT INEL-95/0120, 1995.

C-2. C. L. Atwood, *Modeling Patterns in Count Data Using Loglinear and Related Models*, DRAFT INEL-95/0121, 1995.