ELECTRIC POWER RESEARCH INSTITUTE

Plant Engineering: Emergency Diesel Generator Excitation System End of Expected Life Guidance

2013 TECHNICAL REPORT

Plant Engineering: Emergency Diesel Generator Excitation System End of Expected Life Guidance

EPRI Project Manager
C. Mengers

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

3002000568
Final Report, December 2013

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Lucius Pitkin Inc.

Acknowledgments

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Lucius Pitkin Inc.
304 Hudson Street
New York, NY 10013

Principal Investigator
S. Cherukuri

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Plant Engineering: Emergency Diesel Generator Excitation System End of Expected Life Guidance. EPRI, Palo Alto, CA: 2013. 3002000568.

Product Description

This report provides guidance to nuclear plant personnel in determining the point in the life of the exciter-voltage regulator (EVR) system of the emergency diesel generators when long-term planning is advisable to preclude end-of-life failure of the system or repeated subcomponent failures, leading to increased costs and/or outage times. This report provides results of a review of historical industry operating experience and consultations with subject matter experts regarding the issues affecting the expected life of the system. In addition, this report develops a probabilistic failure model that can be used to assess the vulnerability of an EVR system in service to an end-of-life situation. It also recommends actions that can be taken in response to failures and to possibly extend the expected life of the system.

Background

Industry focus on emergency diesel generators has been previously directed toward the mechanical elements of the system, owing to the performance trends of the equipment in the past 20 years. The electronic equipment, mainly the EVR system, has been relatively more reliable, but recently, failures in the system have been increasingly frequent during test runs. Therefore, this report focuses exclusively on the EVR system, providing guidance and recommendations to preclude failure and decrease in overall system reliability, as well as options for long-term planning to preclude end-of-life failure and obsolescence-related issues.

Objectives

The objective of this report is to identify the failure modes affecting the EVR system and how they impact the expected life of the overall system. The report also aims to provide guidance and recommendations for plant personnel to engage in long-term planning to preclude failures and obsolescence.

Approach

The guidance provided in this report was obtained by performing a comprehensive review of the historical failure data, developing a probabilistic failure model, consulting with subject matter experts, and reviewing existing research and literature.

Applications, Value, and Use

End-of-life guidance documents can be used by plant personnel in the long-term planning for replacement or refurbishment of EVR systems.

Results and Findings

Using historical operating data, probabilistic failure models, and subject matter expert input, the report describes the onset of end-of-life failure modes, problem areas, obsolescence issues and recommendations for retrofits, condition monitoring, and assessment of the system's vulnerability to an end-of-life situation.

Keywords

Aging
Emergency diesel generator
Exciter
Expected life
Obsolescence
Voltage regulator

Abstract

Exciter-voltage regulator (EVR) systems in emergency diesel generators have shown high reliability, with more than 90% of the originally installed systems still in service. However, in recent years, these systems have been experiencing increasing failures of subcomponents during monthly tests and 24-hour endurance test runs. The industry is also facing the issue of obsolescence, with 40% of EVR systems becoming obsolete. The objective of this report is to provide guidance to plant personnel on end-of-expected-life scenarios for the EVR system and recommend ways to extend the life and increase the reliability of the systems. It also aims to provide recommendations on condition monitoring and options to deal with obsolescence. This report examines the failures reported in the industry, develops a probabilistic failure model based on the failure data, and describes subject matter expert input on these topics.

Table of Contents

List of Figures

List of Tables

Section 1: Introduction

1.1 Purpose

Emergency diesel generators (EDGs) have been a key industry issue since the early 1980s because of their importance to plant safety. Industry initiatives from the U.S. Nuclear Regulatory Commission, the Institute of Nuclear Power Operations (INPO), the Nuclear Energy Institute, the Electric Power Research Institute (EPRI), and the EDG owners groups have helped the industry to improve EDG system performance over the past 20 years.

Industry initiatives that have had a significant impact on EDG system performance include the establishment of improved technical specifications that reduce wear and tear on the engines, the establishment of EDG reliability programs, and the development of performance-based maintenance programs that minimize intrusive EDG inspections. Owing to performance trends of the equipment over the last 20 years, much of the industry's attention was focused on mechanical aspects of EDG system performance. Although overall performance has improved, recent aging and obsolescence issues indicate that more attention to electrical and electronic control system performance is needed. One such electrical system critical to successful EDG operation is the excitation-voltage regulator system.

Voltage regulators maintain a constant generator terminal voltage for emergency operation and control the volt-ampere reactive (var; a unit of reactive power) output from the generator when it is in parallel with the grid for testing purposes. These voltage regulators, typically of 1950–1960 vintage, have recently experienced aging and obsolescence problems that have heightened awareness among nuclear utilities because of the threat to overall EDG performance and availability. More than 40% of U.S. nuclear power plant EDG voltage regulators are obsolete. The industry's situation is complicated by parts shortages, limited or nonexistent manufacturer support, and limited station knowledge of EDG voltage regulator issues or operating principles, making troubleshooting difficult.

From an end-of-expected-life perspective, the exciter-voltage regulator (EVR) system is different from other major systems and components. First, it is essentially an electronic circuit consisting of several subcomponents with few moving parts. These subcomponents are all somewhat equal in functional importance, are relatively inexpensive, and require little time and effort to replace if a replacement part is available. Therefore, there is no single subcomponent or failure mode that has a major impact on the useful life of the EVR system as a whole. Second, other than during a loss of offsite power event or a loss-of-coolant accident event, which are rare, the EDG system is operated only occasionally, during monthly tests and in some cases, 24-hour endurance tests. Therefore, operational stressors that traditionally affect electronic components such as electrical, thermal, and mechanical stresses have a lesser impact on the EVR system.

However, other issues—such as degradation of capacitors, transformers, relays, and diodes—arise from infrequent operation. The elapsed time also contributes to engineers and operators not being aware of the issues and insufficient maintenance practices. In recent years, these factors, in combination with the traditional stressors that arise during the occasional EDG runs, have caused an increase in failures of the EVR system and, therefore, a decrease in EDG reliability

Therefore, it is important that system managers understand how the EVR system reliability is affected by various failure modes and to make contingency plans. The end of useful life of the whole system will not occur based on a single subcomponent failure, but as these failures become increasingly frequent and probable, if spare parts and vendor support are not available, options to retrofit the system or to acquire third-party support to existing systems, must be evaluated.

1.2 Areas of Focus

Earlier EPRI reports on the EVR system include a generic document on maintenance issues and five others that describe model-specific voltage regulators and their functional and support circuits [1–6]. These EPRI reports also provide details on tuning, as well as guidance on bench testing, potential failure modes, troubleshooting steps, preventive maintenance, and specific obsolescence issues.

In addition to these areas, this report presents results from an extensive review of operating experience (OE) describing failures of EDG EVR systems in the U.S. nuclear industry from 1974 to 2012. Trends and key observations from these failures were noted. Based on these data, a generic probabilistic failure model was developed that encompassed all EVR systems and subcomponents. Separate probabilistic models were also developed for the most failure-prone EVR systems.

For the probabilistic models, the Weibull analysis technique is used to estimate progressions of probability of failure with operating time. Because the operating time of an EVR system is rarely greater than 60 hours a year, a traditional aging and degradation model would not provide a good estimate of likelihood of failure. This is also true because the stressors involved in EVR system failures are not independent but are aided by external factors such as operational errors, manufacturing defects, and lack of proper preventive maintenance (PM). These external factors are random in nature and are difficult to simulate in a traditional aging and degradation model. Probabilistic models, such as the Weibull method, are helpful in such a scenario because the focus is more on the time from installation to failure, rather than predicting the physical behavior of the stressors.

This report also provides a qualitative comparison of EVR system OE between commercial nuclear applications and other commercial applications such as rail, municipal power plants, industrial power plants, and fossil power plants.

1.3 Exciter-Voltage Regulators in U.S. Nuclear Power Plants

Currently, nine different EVR systems are installed on EDGs across the U.S. commercial nuclear power fleet. The nine EVR systems and quantities that exist are presented in Table 1-1. A listing of all U.S. operating nuclear plants with their EDGs and EVR types is provided in the EPRI report *Emergency Diesel Generator Voltage Regulator Maintenance Issues* (1011232) [1]. This listing has been updated with known EVR replacements.

Table 1-1
Emergency diesel generator exciter-voltage regulators in U.S. nuclear plant service

Type	Number
Basler SBSR	80
Basler SER	18
Basler SR8A	28
Basler Vickers (EMD Mag Amp)	28
Portec	56
GE Static	10
EM	6
WNR/WPRX	6
Jeaumont-Snyder	1
Siemens' THYRIPART	2

1.4 Common Elements in Exciter-Voltage Regulator Systems

In a typical EVR system, the voltage regulator circuit senses the generator output voltage and compares a rectified sample of that voltage with a set reference voltage. The difference in the two voltages provides the error signal that is amplified and used to control the excitation field current in the exciter circuit to maintain the generator output voltage at the desired level. A majority of exciters in U.S. nuclear power plants are static exciters, with only four plants that have a variant of the GE Static systems using brushless, rotating-type exciters.

Regardless of the type, EVR systems share common elements, which can be categorized as follows:

- **Magnetics.** Primarily power potential transformers (PPTs), power current transformers (PCTs), linear reactors, saturable transformers (in some models), and magnetic amplifiers (in some types)
- **Circuitry.** Power path components including diodes, bridge rectifiers, silicon-controlled rectifiers (SCRs), capacitors, and so on
- **Motor-operated potentiometers (MOPs)**, known as *motor-operated controllers* in Basler terminology
- **Relays and contactors.** Relays and their mechanical contacts, including the K1, K2, and other relays
- **Wiring and connections.** Wires and connections between subcomponents in the exciter and voltage regulator circuits.

Section 2: Review of Operating Experience

2.1 Results from Operating Experience Review

EDG EVR systems that are in the scope of this study were examined broadly in INPO's Equipment Performance and Information Exchange (EPIX) and Nuclear Plant Reliability Data System (NPRDS) databases[1] [7].

The search was performed using combinations of keywords such as "EDG," "failure," "voltage regulator," "exciter," "emergency diesel generator," and so on. Several hundred results were shown, each of which was reviewed, and only the failures that occurred in the EVR system were selected.

Events that resulted in the EDG being declared inoperable for any amount of time or in an unsuccessful surveillance test were identified. The event reports were studied to identify the subcomponent that led to the failure, the mechanism and stressors, external factors involved, and the root cause. In some of the failure events reported, a root cause analysis was not performed, or the results of such an analysis were not available at the time of reporting. Where possible, a best estimate was made to identify these factors.

In general, the OE review revealed that most failures were due to external factors, not just by a conventional aging or degradation mechanisms. A variety of such external factors involved lack of PM, inherent design issues, design errors (such as undersizing), manufacturing defects, and operational errors. These factors have been identified based on the available information. Table 2-1 presents a summary of the resulting OE and the factors that contributed to the failure (listed in the "Cause Category" column).

[1] The INPO Operating Experience database, including EPIX and NPRDS data, is available only to INPO members.

Table 2-1
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
5/27/1979	3	EMD Mag Amp/Basler Vickers	Magnetics	Design error	EDG failed during a planned 24-hour simultaneous full load test	A design error present on both 'A' and 'B' EDGs, which could result in overheating these transformers at sustained high load operation. The primary of the wye-delta exciter potential transformer (EPT) was connected to the EDG in a four-wire wye configuration such that the normal third harmonic generator currents circulated through the EPT via a common neutral.
9/4/1985	11	Basler SBSR	Circuitry	Unknown (possibly voltage spike)	EDG failed to develop voltage	A review of the data sheets showed no previous fuse failures. The subject fuse was replaced, and the surveillance procedure was performed satisfactorily. No action was found to be required at that time. This failure is not indicative of a generic problem or an adverse trend.
1989	20	EMD Mag Amp/Basler Vickers	Circuitry	Operational error	Unknown	Rectifier failure due to reversal of Battery terminals.
2/1/1990	1	Portec	Circuitry	Manufacturing defect	EDG would not pick up load due to low excitation during the performance of the monthly surveillance	The failure was due to a defective remote firing module, which is a piece part of the exciter circuit. The cause of the remote firing module failure is unknown.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
1/12/1994	21	Portec	MOP	Manufacturing defect	Voltage control was erratic	The automatic voltage regulator module, a piece part of the voltage regulator circuit, had spikes on the output. This caused the voltage regulator to control erratically. The module was sent to the manufacturer for root cause analysis. The analysis found that a manufacturing defect caused a loose wiper connection in the voltage sensing circuit.
9/30/1994	9	Westinghouse	Magnetics	Operational error	EDG exciter power transformer caught fire during post-maintenance testing and balancing run	Because there was no blown-fuse indication, the normal full and above-full power runs for routine testing were conducted subsequently without knowing that the fuses had blown and resulted in "single phasing" the potential transformers. The condition of the damaged transformer exciter windings was consistent with progressive insulation breakdown caused by sustained current well in excess of the secondary winding ampacity.
2/27/1995	25	EMD Mag Amp/Basler Vickers	Magnetics	Unknown	EDG failure during surveil-lance testing indicated by kvars spiking high	Troubleshooting identified a magnetic amplifier unit (part of exciter) had failed. The part was replaced and post-maintenance testing commenced. Root cause not known.
3/27/1995	5	Portec	Relay/contactor	Operational error	Test personnel discovered lockout relay had overheated and was considered inoperable	The lockout relay is a high coil current relay. Repetitive cycling during testing and troubleshooting caused overheating and swelling of the coil's insulation, which resulted in binding failure. A contributing cause is that personnel performing the testing were focused on other concerns and appeared unaware of the consequences of repetitive circuit operation.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
6/18/1996	12	Basler SBSR	MOP	Unknown (possibly PM deficiency)	Erratic vars during testing	Erratic vars probably caused by failure of printed circuit board or MOP.
1/29/1996	10	Portec	Relay/contactor	Operational error	Operator noted a burned smell and smoke coming out of EDG exciter cabinet during post-mainten-ance test run	Latch and reset coils of the K1 relay to be energized simultaneously, resulting in a burned out reset coil. The relay was latched in manually to perform the test. This resulted in current being applied to the field flash circuit for about 15 minutes instead of the normal duration of 1 to 5 seconds, causing overheating of the exciter cabinet components. Although it overheated, no damaged components were noted.
11/2/1998	26	EMD Mag Amp/Basler Vickers	Relay/contactor	Wear	EDG failed during testing as a result of fault in exciter circuit	The electrical fault in the exciter cabinet was initiated by degradation of the contact between the spring finger and the contact block on the load side of the phase C EPT fuse. This resulted in the EDG excitation system trying to compensate for the loss of the phase C EPT voltage. This progressed into a phase-to-phase fault in the upper compartment that migrated toward the current source (the lower compartment) where the conditions were right for a significant fault and explosion.
1998	9	Portec	Magnetics	Design issue		Failure of operational amplifier in voltage regulator circuit.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
5/16/1998	13	Westinghouse	Circuitry	Unknown (possibly manufacturing defect)	Large var step increase during testing	The cause of the var step changes was thought to have been relay spiking. The voltage raise/lower switch operates two different relays that connect gate voltages to the electronic adjuster logic board to momentarily enable the counting circuit to count up or down and thus adjust the analog output voltage to the Westinghouse type WNR static EVR for the EDG. These relays had no suppression across the coils. Without suppression, dropping a relay out caused contact arcing and a corresponding inductive spike in the power circuit for the relay. The inductive spike was caused by the collapsing magnetic field of the relay.
3/16/1999	14	Westinghouse	Circuitry	Manufacturing defect	EDG failed to develop output voltage during testing	Testing of the failed diodes determined the cause for failure to be inadequate attachment of the diode leads to the silicon die (inadequate die attach). Testing of other diodes that had not failed identified that several of them also had inadequate die attach. Laboratory test results showed that the inadequate die attach was a manufacturing defect, which significantly reduced the electrical characteristics below the published rating. This caused the diodes to degrade over time under normal service conditions until they failed in a random fashion.
4/15/2000	12	Portec	Magnetics	Manufacturing defect	An acrid burning odor was noted corning from the back of the control panel during surveil-lance test	Linear reactors found to be failing in Portec unit due to manufacturing/design defect. Unit replaced with Basler.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
10/29/2000	20	Portec	Wiring/connections	Unknown (possibly PM deficiency)	Erratic vars during testing	A broken wire in the voltage regulator circuit caused erratic vars due to constant firing of the SCR module.
8/29/2000	16	Westinghouse	Relay/contactor	Unknown (possibly wear)	The local annunciators 6D, Engine Trouble Shutdown, and 7D, Generator Protective Relay were received. It was found the volts/Hertz relay had tripped	Failure of relay in shutdown circuit caused incorrect operation.
8/16/2001	24	Basler SBSR	Wiring/connections	PM deficiency	2A DG POT VOLT FREQ LO alarm was annunciated, even though all EDG parameters were normal during post-maintenance testing	MOP wire chafed due to rubbing with sharp edge. The chafed section of wire caused the circuit to become grounded and resulted in the unexpected alarm.
12/13/2001	18	Portec	Circuitry	Operational error	EDG test failure indicated by low output voltage	Incorrect operation led manual voltage regulator to interfere with performance of the automatic voltage regulator, causing failure of an SCR.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
6/10/2003	16	Basler SER	Relay/contactor	Wear	During monthly test, the K-1 relay did not open when the exciter shutdown/reset switch was placed to "STOP." This caused the generator field to prematurely flash	It was discovered that the pads on the auxiliary contact were severely worn. This prevented the open coil from energizing and repositioning the K1 relay. The wear on the pads resulted from arcing that occurred when the contacts changed state.
10/15/2003	19	Portec	Magnetics	External grid disturbance	Large increase in kvars and generator excitation close to operating limits	The local capacitor bank on the 230 kV system at the local substation was switched during the test, which lowered local area network voltage from 243 kV to 237 kV or 4375 V to 4250 V as read by plant display information system at the 4 kV switchgear. Because the EDG is running "in parallel" with the high-voltage transmission network along a predetermined voltage droop control characteristic, a change in network system voltage results in an increase in generator excitation. The EDG's static EVR responded automatically to raise reactive power from 1200 kVar to 2400 kVar. Generator field current increased from 133 amps DC to 147 amps DC without operator action.
8/20/2003	31	Portec	Circuitry	Unknown	One of the four EDGs exhibited a voltage decrease during an unloaded portion of the normal monthly surveillance testing	Component-level repairs of the voltage regulator were attempted but were unsuccessful. After the voltage regulator unit as a whole was replaced, the diesel was successfully returned to service.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
12/1/2004	16	Basler SR8A	Circuitry	Unknown (possibly dried up capacitor)	EDG failed during 24-hour endurance run	Inspection of the EDG found that the exciter module capacitor inside panel 1PL07J had failed.
12/20/2005	25	Basler SBSR	Wiring, connections, magnetics	PM deficiency	EDG exciter cabinet cable connection overheated	Thermography performed in the exciter cabinet revealed the termination point for control rectifiers (CR51 and CR54) was significantly warmer than adjacent rectifiers. After the PT was completed, visual inspections of the termination, hardware, and wire showed signs of heating.
2/21/2005	15	Basler SER	MOP	PM deficiency	EDG did not reach required frequency during testing	Loose MOP connection was found to be the root cause.
7/28/2005	30	GE Static	Relay/contactor	Design error	The EDG operability was questioned due to concerns that the set point for the installed EDG differential overcurrent protective devices (87DP relays) was not appropriate	Replacement of the EDG 87DP differential overcurrent relays, in 1982, without adequate confirmation that the trip setting of the new model was appropriate. This reduced the margin between the 87DP relay trip set point and the normal operating current, thereby reducing the EDGs' tolerance to electrical disturbances. The PPTs were found to be undersized, as well.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
3/25/2006	21	Basler SBSR	Wiring/connections	PM deficiency	EDG 24-hour surveillance test failed after 9 hours as kvars dropped	Burned wires in the exciter circuit led to unsuccessful testing. The cause of the short circuit appears to be original manufacturer installation, where a wire bundle was pushed tight behind a bare lug of the AC output of the saturable transformer. Over time, the wire insulation either cracked or rubbed off, causing direct contact of the control current circuit with the bare lug.
8/12/2006	23	Basler SR8A	MOP	PM deficiency	Erratic vars during testing	Dirty wiper on the output voltage adjustment potentiometer R3 caused erratic mvars output. This has been a common industry problem.
11/26/2006	36	Portec	Circuitry	Unknown (possible design issue)	Exciter field failed to flash while EDG was at rated speed during testing	Failure of excitation circuit.
1/4/2007	35	Basler SBSR	Magnetics	PM deficiency	EDG failure during surveillance testing indicated by kvars spiking high	Poor quality feedback signal to the voltage regulator due to tarnished potential transformer (PT) secondary link and misaligned PT primary stabs. Attributed to no PM to periodically inspect or clean the fuses or fuse holders within the PT drawer or the solid link on the secondary side of the potential transformer.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
1/17/2007	17	Basler SER	Relay/contactor	Wear	During EDG testing, the operator found loss of excitation even after pushing the exciter shutdown reset switch	The apparent cause of the K-1 auxiliary contact failure was determined to be a damaged operating mechanism (lever). The operating lever was bent and altered the mechanism travel length between the auxiliary contact and the main contactor latching roller mechanism. This allowed the auxiliary contact to open early. It also prevented the main contactor roller assembly from moving to the fully latched position before power was removed from the main coil. Therefore, at the time the power was removed, there was not sufficient magnetic force and momentum to complete the seating and latching of the main contacts.
4/9/2007	22	Portec	Magnetics	Design issue	EDG tripped during surveillance testing due to a lockout on the generator output breaker	Apparent cause is a spontaneous winding failure in the X2 exciter reactor. Visual inspections revealed discoloration, burn pattern, and charred wiring protruding from the interior of the reactor while external wiring connected to the lead wiring was unaffected. Failure of winding insulation produced a turn-to-turn short. Age is assumed to be the major contributor to the failure.
6/19/2007	37	Basler SBSR	Circuitry	PM deficiency	EDG failed to start at required time	Attributed to problem with voltage regulator caused by inadequate PM.
7/21/2008	22	Basler SER	MOP	PM deficiency	EDG experienced reactive power and load swings during 24-hour surveillance testing	Failure attributed to erratic operation of potentiometers.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
11/12/2008	22	Portec	Magnetics	Design issue	EDG tripped during testing	EDG tripped when the phase C linear reactor in the DG excitation control system failed. Problem attributed to original manufacturing defect. Winding insulation failed, causing two adjacent windings to short.
4/29/2008	21	Westinghouse	Wiring/connections	PM deficiency	EDG tripped on exciter ground overcurrent during test run	The cause of the event is that the cable insulation on the Generator Excitation DC Field Lead became worn under a metal clamp that secured the field lead where the field lead contacted the metal frame of the Generator rotor. Through vibration and the centrifugal forces of rotation, the insulation wore to the point where an intermittent ground developed. The ground only became solid after applying a 1000 VDC while the engine was running.
3/29/2009	34	Basler SBSR	MOP	PM deficiency	During surveillance run, EDG load experienced erratic swings and loss of excitation alarm was received	Apparent cause is a faulty pot in the R14 resistor in automatic voltage regulator circuit card.
6/17/2009	25	Basler SR8A	MOP	PM deficiency	Erratic vars during testing	Event attributed to erratic operation of R3 potentiometer due to poor contact surface continuity - likely due to deterioration from oxidation of the metal contact surfaces.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
9/2/2009	13	Portec	Relay/contactor	Wear	During EDG test run, the K1 voltage shunt contactor unlatched prematurely, producing a generator output voltage when none should exist	It appears the K1 contactor operate coil overheated and open circuited, most likely due to an intermittent reset coil actuation (spring operated switching contact) allowing the operate coil to remain continuously energized.
10/12/2009	24	Portec	Relay/contactor	Wear	During a monthly EDG 'A' surveillance run, it was discovered that the static EVR bridge transfer switch experienced elevated temperatures	Contacts 1 and 2 became misaligned, resulting in less contact surface area and increased heat generation of the contact surface with the nominal current of the voltage regulator excitation system.
2010	35	Basler SBSR	Relay/contactor	Wear		Age-related mechanical contact degradation.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
4/19/2010	37	Basler Vickers	Circuitry	PM deficiency	When field was flashed, the synchroscope began turning slowly in the SLOW direction, then began operating erratically after adjusted - incoming voltage had come up to ~120 V then went to 0 V	Attributed to aging rectifier that failed. No PM existed for rectifier.
6/17/2010	34	EM	Circuitry	PM deficiency	Voltage regulator did not respond as expected when operators went to lower voltage (voltage continued to drop and could not be adjusted higher) during surveillance test	The apparent cause of the failure was resistor R1 was found failed open due to general corrosion. The resistor was found to have a broken wire that was wrapped around the core, and was not addressed in PM activities.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
2005	35	GE Static	Brushes	PM deficiency	During the performance of the surveillance test, sparking was observed coming from the diesel generator inner ring brushes	After maintenance run of EDG on 9/12/10, brushes on the inner ring (brushes 1 and 2) were found below desired tolerance.
6/25/2010	27	Portec	Circuitry	PM deficiency	EDG tripped after being fully loaded for approximately 18 minutes	EDG tripped after being fully loaded for approximately 18 minutes. There may have been a ~200 kW variation in load prior to the trip. Diode CR2, which is located in one phase of a rectifier bridge sensing network, was found short-circuited. Attributed to aging.
3/17/2010	26	Westinghouse WNR	Relay/contactor	Wear	After a slow start, one hour loaded surveillance run of the EDG while shutting down the generator/engine, the 5B control relay contact associated with the exciter shut-down failed to appropriately shut down the EVR system, resulting in a valid volts/hertz and NE1061861DG (lockout) - protective relay actuations	The cause of the 5B relay contact failing to make up is age degradation due to the moveable contacts being slightly bent, in combination with the spring pressure not being able to make up consistently.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
4/19/2011	37	Basler SBSR	Circuitry	PM deficiency	The electrical power generated by DG2 became erratic during execution of the sequential load test surveillance. When load was added to the bus, the voltage dropped to unacceptable levels	The failure was caused by a random failure of an electronic component on the secondary side of the T3 isolation transformer in the voltage regulator assembly. The replacement of the existing 1960s-era voltage control system with a modern, more reliable voltage regulation system which was originally scheduled to occur by RE26 was delayed. Voltage regulator scheduled to be replaced.
2005	25	Portec	Circuitry	Operational error	Voltage started fluctuating immediately after EDG was started	Root cause attributed to change in resistance setting of range (R4) potentiometer on the automatic voltage regulator due to locking collar not being tightened due to lack of procedural guidance, which caused output voltage to be low. Also attributed to lack of RCM program for remote gate firing modules. Degradation of the GE H11C1 Photo SCR optocouplers resulted in two (U2 and U3) of the three optocouplers in remote gate firing module 2 becoming unstable under maximum shunting conditions, causing field and output voltage fluctuations.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
2/22/2011	25	Portec	Magnetics	Possible voltage spike, PM deficiency	EDG failed to reach rated voltage	The root cause investigation determined that a 741 series operational amplifier (op amp) denoted as U1 on the IPP board had failed in such a way that its output voltage was high at all times, regardless of any input voltage changes. The failure of this op amp (output voltage high and not responsive to the input voltage) would cause the EDG output voltage to go to a low value.
10/18/2011	39	Portec	Circuitry	Possible design issue	EDG 4A tripped from 110% load on loss of excitation during the 24-hour technical specification surveillance run while connected to the grid	Data showed initial drop in voltage and current followed by sudden current spike prior to trip. The CR4 diode was found shorted, which is located in one phase of the rectifier bridge sensing network. Based on the natural effects of temperature on diodes and industry OE, it can be concluded that increased heat on the subject diodes is accelerating the diode failure rate.
12/3/2012	36	Basler SBSR	Circuitry	Possible voltage spike, aging	EDG was secured by the operator via the emergency shutdown pushbutton after a minor adjustment to the governor resulted in a sudden unexpected load increase	Failed selenium rectifier CR57 due to possible voltage spike and high-temperature operation.

Table 2-1 (Continued)
Summary of operating experience

Event Date	Years to Failure	Model	Subcomponent Category	Cause Category	Failure Description	Cause Description
8/25/2012	28	Basler SER	Relay/contactor	Wear	Exciter failed to generate voltage during EDG test run	The apparent cause of the A DG exciter failure to start is an internal failure of the K1 contactor due to the degradation of the mechanical latch assembly coil contacts over time.
10/30/2012	39	Basler SBSR	Magnetics	Possible voltage spike	EDG static excitation system failed during testing	Static excitation system failed during post-installation testing. A root cause investigation was under way but was not completed at the time of report. On-site troubleshooting test results identified unexpected high voltages across the DC control winding of saturable transformers, which may be the cause of the failures.

2.2 Observations from Operating Experience Review

The following observations are made from the failure events reviewed:

- The largest percentage of failures occurred in the circuitry components, followed by magnetics and relays/contactors. Figure 2-1 shows the percentages of failures in each component category. There was one failure in exciter brushes, but it was excluded from the chart because a large majority of EVRs currently in service are of the static exciter type, which does not use brushes.

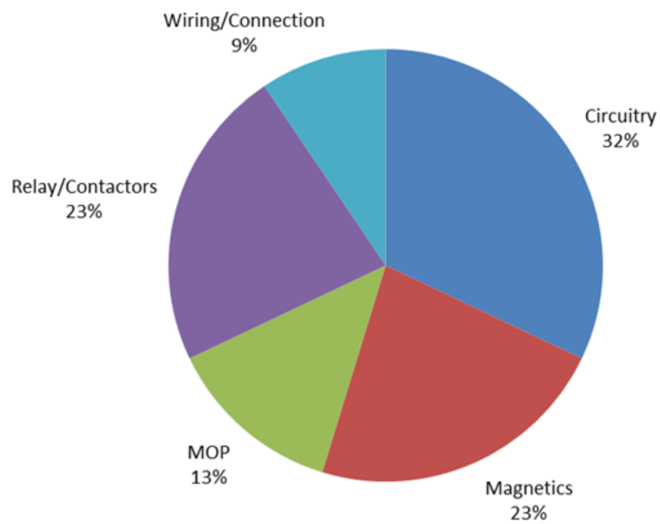

Figure 2-1
Failure summary of subcomponents

- Of the installed EVR system, the Portec had the highest failure count, followed by the GE Static and Basler SER. Westinghouse EVRs have the highest percentage failure, followed by Portec. Figure 2-2 shows the failure count and percentage of installed EVR types.

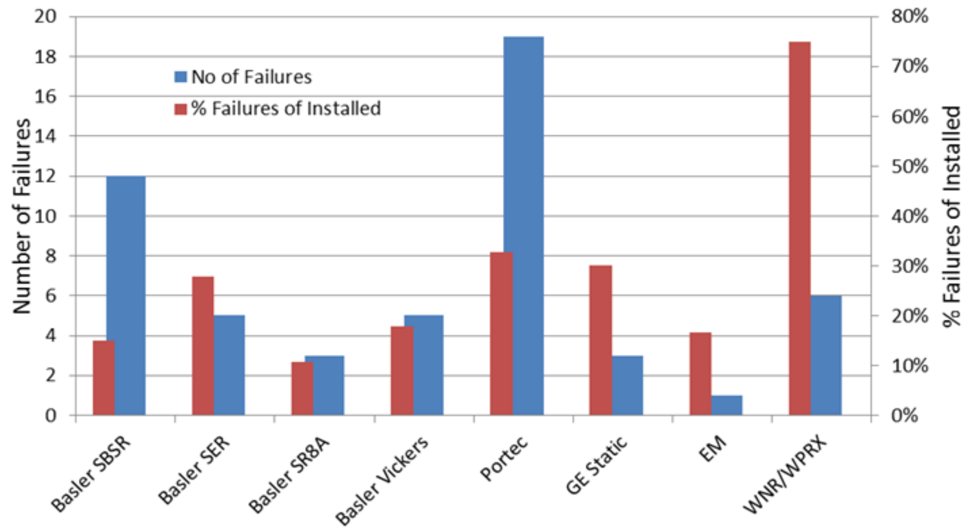

Figure 2-2
Failure percentage of exciter-voltage regulator models

- Only eight occurrences of an aging-related mechanism were found, all of which were attributed to wear of relays and contactors. This is expected because relay contacts are the only moving parts in the EVR system.
- More failures (16) were attributed to deficiencies in PM than any other root cause.
- Of the 10 failures attributed to transformers, more than half (six) occurred in Portec systems. This is likely due to the inherent design issue in Portec systems that make the magnetics vulnerable to accelerated aging and degradation. This is described in Section 3.
- Six failures were attributed to operational errors, and four were attributed to manufacturing defects. Design issues inherent to the operating principles of the system (such as Portec magnetics issue) and design errors (such as undersizing) contributed to six failures.

Section 3: End-of-Expected-Life Considerations

3.1 Probabilistic Models

3.1.1 Probabilistic Versus Deterministic Models

The EVR system is different from other major systems, structures, and components, in the respect that it is essentially a closed-loop circuit consisting of a number of electrical subcomponents such as transformers, relays, rectifiers, and diodes. Therefore, even if the failure of any one subcomponent will lead to the failure of the unit as a whole, no one subcomponent can be considered crucial in a way that its failure will significantly impact the service life of the entire system. This is especially the case because the subcomponents can be replaced with relatively little time and effort, if a spare is available. However, failure of any of the subcomponents during emergency service has great safety implications because the EDG system supplies power to shut down the reactor during a loss of offsite power event. Therefore, it is important to analyze the reliability of the EVR systems in service.

A deterministic approach would involve performing accelerated aging tests on components to develop equations to determine service life of a particular component. To make this estimation accurate, it is important to simulate the real plant conditions, including the most impactful stressors, during testing. The majority of reported failures were caused by external factors such as deficiency in PM, design errors, operational errors, manufacturing defects, and so on. These external factors played a larger role in the failures than the operational age of the subcomponent itself. These factors are hard to simulate in accelerated aging tests because they are random in occurrence.

Taking this into consideration, it is more valuable to perform a probabilistic reliability-based analysis. The objective of such an analysis is to estimate the reliability of the system in terms of probability of failure, based on historical failure data collected in the OE review.

A variety of reliability models are described by the Reliability Information Analysis Center (RIAC) [8]. The Weibull approach [8, 9] is used in this case because of its simplicity and ability to approximate failure rates and probabilities, based on limited information. The analysis was first performed on the entire population and then on individual EVR system types. The results are compared to identify areas and models of greater vulnerability to failure.

3.1.2 Reliability Modeling Using Weibull Analysis

The advantage of Weibull analysis is that it can approximate a solution even when the available failure data has some deficiencies, such as small sample size, multiple failure modes, external factors, and insufficient knowledge about the failure mechanisms.

Weibull analysis involves fitting the available historical failure data into a Weibull distribution function. In the two-parameter Weibull distribution, which is used in this analysis, the function is defined by the shape parameter, β, and the scale parameter, α. The Weibull cumulative distribution function is given by the following equation:

$$F(t) = 1 - e^{\left[-\left(\frac{t}{\propto}\right)^{\beta}\right]}$$

The following steps are involved in calculating the Weibull parameters:

1. The time to failure of all the failure events from the OE review were tabulated as data points in a single column, in ascending order. A second column was populated with the cumulative number of failures until each event, which is essentially the event's rank, in ascending order from 1 to 54.
2. The rank established for each event was adjusted for the presence of non-failed EVRs of age less than the time to failure of that particular event. The EVRs that have not failed are treated as "suspended data" in the Weibull analysis. This means that they are not included in the Weibull plot, but their influence on the overall distribution is estimated by adjusting the ranking of the failure events as follows [9]:

$$Rank\ Increment = \frac{(N+1)-(previous\ adjusted\ rank)}{1+(number\ of\ events\ beyond\ present\ suspended\ event)}$$

$$Adjusted\ Rank = Previous\ Adjusted\ Rank + Rank\ Increment$$

   The third column is populated with the adjusted ranks thus calculated. The EVR types used for each plant and their totals were taken from Appendix B of the EPRI report *Emergency Diesel Generator Voltage Regulator Maintenance Issues* (1011232) [1], and these numbers differ slightly from the numbers presented in Table 1-1, which is reproduced from a different section in the same EPRI report. This difference had negligible impact on the results of the Weibull analysis.

3. A fourth column is populated with the plotting position, *F*, which is the estimated percent fail of the population at the failure time, or the median rank. A common way to accomplish this is by using Bernard's formula, as follows:

$$F = \frac{i-0.3}{N+0.4}$$

where *i* is the adjusted rank and *N* is the total population of EVRs.

These data are shown in Table 3-1.

Table 3-1
Calculating Weibull curve plotting points from failure data

Time to failure, Years, t	Rank	Adjusted Rank, i	F (% Failed Until Event, or Median Rank)
1	1	1.0	0.29
3	2	2.0	0.69
5	3	3.0	1.10
9	4	4.0	1.51
9	5	5.0	1.92
10	6	6.0	2.32
11	7	7.0	2.73
12	8	9.0	3.55
12	9	8.0	3.14
13	10	10.0	3.95
13	11	11.0	4.36
14	12	12.0	4.77
15	13	13.0	5.18
16	14	14.0	5.58
16	15	15.0	5.99
16	16	16.0	6.40
17	17	17.0	6.81
18	18	18.0	7.22
19	19	19.0	7.64
20	20	20.1	8.05
20	21	21.1	8.47
21	22	22.1	8.89
21	23	23.1	9.30
21	24	24.2	9.72

Table 3-1 (Continued)
Calculating Weibull curve plotting points from failure data

Time to failure, Years, t	Rank	Adjusted Rank, i	F (% Failed Until Event, or Median Rank)
22	25	25.2	10.14
22	26	26.2	10.55
22	27	27.2	10.97
23	28	28.2	11.39
24	29	29.3	11.81
24	30	30.3	12.23
25	31	31.4	12.66
25	32	32.4	13.09
25	33	33.5	13.53
25	34	34.6	13.96
25	35	35.7	14.42
26	36	36.8	14.89
26	37	38.1	15.39
27	38	39.3	15.89
28	39	40.6	16.41
30	40	41.9	16.97
31	41	43.6	17.63
34	42	45.3	18.33
34	43	47.2	19.11
35	44	49.1	19.89
35	45	51.1	20.69
35	46	53.0	21.48
35	47	55.0	22.27
36	48	56.9	23.07
36	49	59.0	23.92
37	50	61.4	24.89
37	51	63.8	25.87
37	52	66.2	26.85
39	53	70.1	28.44
39	54	74.0	30.03

4. To calculate the Weibull parameters from Table 3-1, the equation for the Weibull cumulative distribution function is rearranged as follows:

$$\ln\left(\ln\left(\frac{1}{1-F(t)}\right)\right) = \beta\ln(t) - \beta\ln(\alpha)$$

This is in the form of the equation for a straight line Y = MX + C, where M is the slope and C is the intercept of the straight line.

Therefore, the data in Table 3-1 are used to plot ln(t) and $\ln\left(\ln\left(\frac{1}{1-F(t)}\right)\right)$, with a straight line fit, as shown in Figure 3-1.

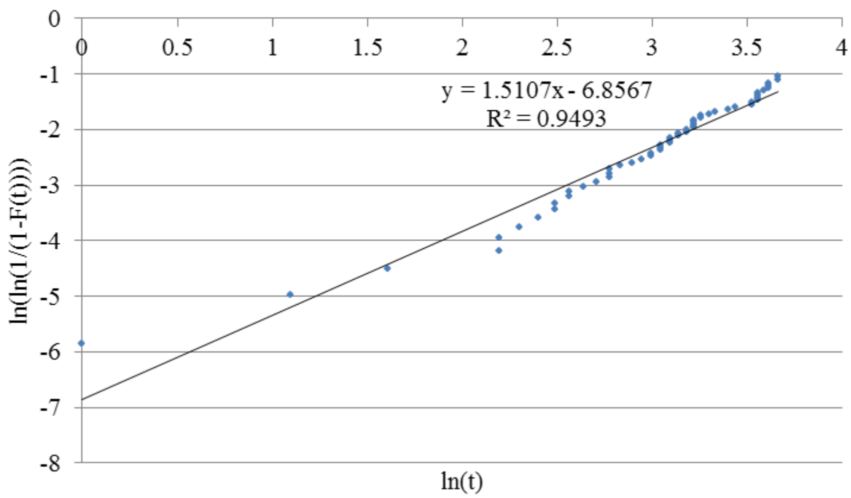

Figure 3-1
Weibull plot with failure data

5. The shape parameter, β, is the slope of the fitted line. The scale parameter, α, is calculated as follows:

$$\beta = 1.51$$

$$\propto = e^{\left(-c/\beta\right)} = 93.57$$

where c is the intercept of the line.

6. After calculating the Weibull parameters, the cumulative distribution functions are determined as follows:

$$F(t) = 1 - e^{\left[-\left(\frac{t}{\propto}\right)^{\beta}\right]}$$

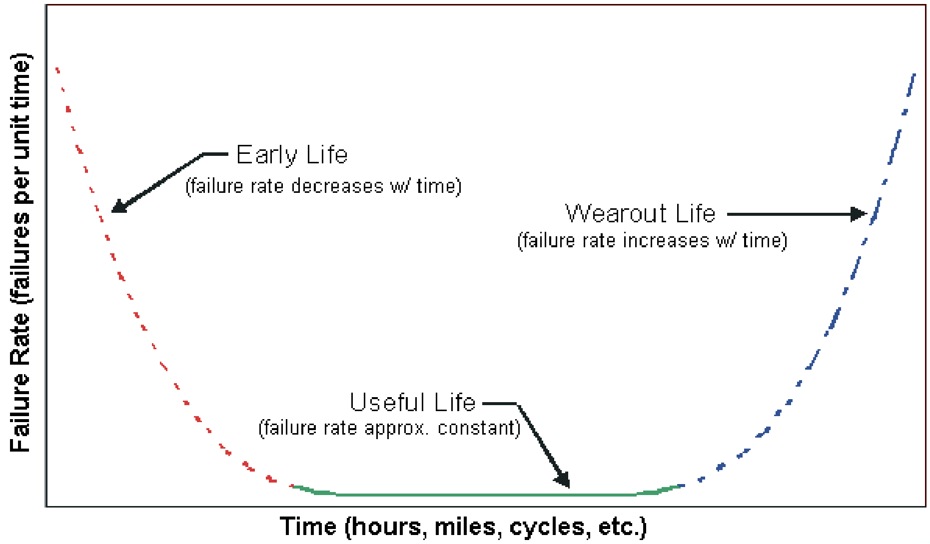

Figure 3-2
Bathtub curve showing component reliability

The shape parameter, β, gives an immediate insight into the way the failure rate trends with time of operation. The characteristics of various shape parameter values are summarized below:

- For a shape parameter < 1.0, the Weibull function takes the form of the gamma distribution with a decreasing failure rate (that is, infant mortality in the bathtub curve, Figure 3-2).
- For a shape parameter = 1.0, the failure rate is constant, so that the Weibull function takes the form of the simple exponential distribution (the flat part in the bathtub curve, Figure 3-2).
- A shape parameter > 1 indicates a failure rate that is linearly increasing with time (that is, the wearout period in the bathtub curve, Figure 3-2).

Therefore, a calculated Weibull shape parameter of 1.43 indicates an increasing failure rate representing a wearout period. The root causes identified in the OE review show that this wearout is accelerated by external factors such as PM deficiencies, operational errors, and so on. Figure 3-3 shows how the cumulative probability of failure changes with years after installation.

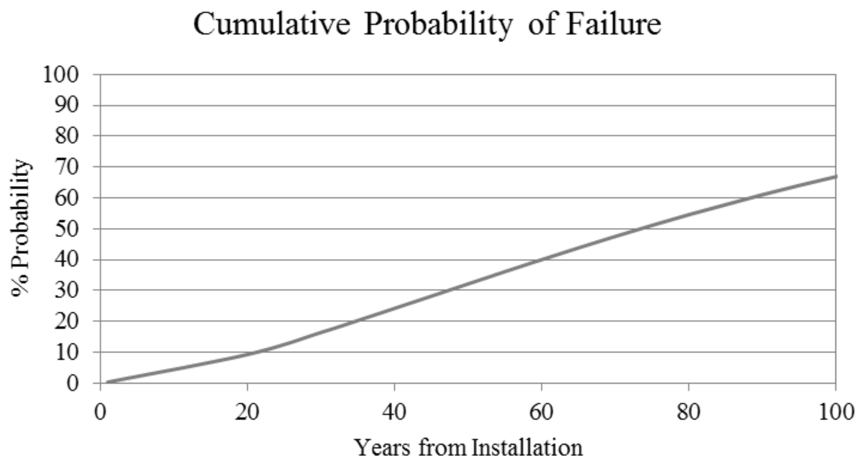

Figure 3-3
Holistic probability of failure of exciter-voltage regulator subcomponents

3.1.3 Manufacturer- and Type-Specific Weibull Analysis

The objective of the holistic analysis is to estimate the probability of failure of any subcomponent of any EVR system due to any failure mode. In other words, it takes into account all failure events and treats all subcomponents, system types, and failure modes equally.

However, it can be seen from the OE review that certain EVR types tend to experience more failures than others. This could be due to inherent design issues or other vulnerabilities. A similar Weibull probabilistic analysis was performed for seven of the nine EVR types—Portec, Basler SBSR, Basler SER-CB, Westinghouse (WH), Basler Vickers, Basler SR8A, GE Static—to compare their likelihood of failure progressions. EM and Jeaumont-Snyder EVRs were not included in this study due to very little or no failure data available. Table 3-2 shows the calculated Weibull parameters, and Figure 3-4 compares the probability of failure for these seven models.

Table 3-2
Weibull parameters for exciter-voltage regulator models

Weibull Parameter	Basler SBSR	Portec	Basler SER	WH	Basler SR8A	Basler Vickers	GE Static
Shape parameter, β	2.03	1.11	3.32	2.72	1.51	0.80	7.70
Scale parameter, α	99.44	109.01	35.24	20.16	93.57	289.90	42.80

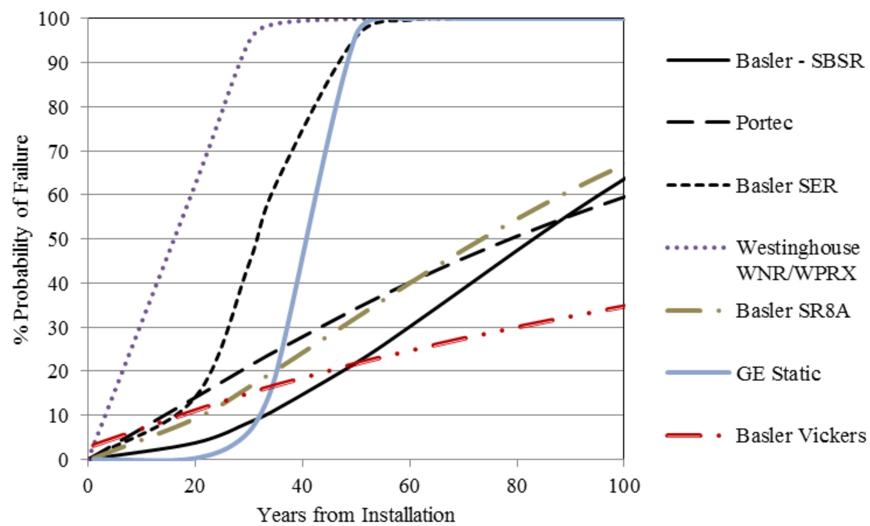

Figure 3-4
Probability of failure of exciter-voltage regulator subcomponents for different models

3.2 Common Issues and Failure Modes

From review of OE, it is evident that a number of failure modes affect a number of subcomponents in the EVR systems. To a large extent, these failure modes seem to be largely exacerbated by external operating factors such as lack of PM, manufacturing defects, operational errors, and so on. These external factors, in some cases, accelerated the aging degradation in the failed subcomponents, or acted alone. The subcomponents in the system are grouped together, and the factors leading to their failure are described in the following subsections.

3.2.1 Motor-Operated Potentiometer Failures

In most EVR models, the MOP (called motor-operated controller in Basler terminology) is used as a remote means to adjust the set point for automatic voltage regulators. These potentiometers have been identified as the weakest link in all analog voltage regulator units. "Dirty" potentiometers have been associated with erratic voltage swings at many plants, particularly the R2 potentiometer in the Portec units and the R60 potentiometer in Basler SBSR units. Dirty potentiometers are possibly caused by oxidation of the resistive element or fouling due to foreign material such as dust or dirt. In some cases, the erratic voltage spikes caused by dirty potentiometers can cause failure of a component downstream in the voltage regulator circuit.

In many cases, if the EDG exhibits erratic var/voltage swings, the problem can be rectified by wiping or cleaning the resistive element of the MOP. If the problem is not rectified, the potentiometer, and in some cases, the MOP assembly, may need to be replaced.

MOP-related failures can be minimized by ensuring that the potentiometers are clean before every test run. It is also advisable to check the condition of the potentiometers by measuring the resistance with an analog meter. Wiping the potentiometers would require their tuning to be adjusted afterwards.

3.2.2 Magnetics Failures

Several components in EVR systems fall under this category, including the linear reactors, saturable transformers, PPTs, PCTs, and operational amplifiers. Typically, the primary mechanism that drives these components to failure is degradation of the insulation on the winding. The stressors contributing to this are the electrical and thermal stresses resulting from operation.

However, generally, magnetics are manufactured to operate for at least 10,000 hours. A typical nuclear plant EDG system operates for not more than 60 hours a year. Keeping that in mind, it is safe to say that in this operating scenario, external factors play a large role in accelerating the degradation. These external factors could be undersized design, poor maintenance, lack of condition monitoring, operational errors, operating under higher temperature or humidity than allowable, and so on.

Portec voltage regulators, particularly, are vulnerable to failures in magnetics. This is due to the inherent design of their voltage regulator circuit. In the Portec models, the magnetics (PPTs and PCTs) are connected to the generator output and the control element (SCRs and so on) is in parallel to the magnetics, as opposed to being in series as in other models. The transformers are always fully energized, and the control is achieved by shunting the unneeded power around the field. This leads to the transformers experiencing a burn-out due to higher thermal and electrical stresses than in other models. This is supported by the number of Portec transformer failures, in that more than half of the reported failures attributed to transformers are Portec systems.

Also, in some Basler SBSR units, the cyclical contraction and expansion of the magnetic amplifier unit due to alternating cold (not operating) and hot (at operating temperature) cycles resulted in some units exhibiting failures of soldered joints. Over time, the solder develops cracks due to the continual flexing of the joint and eventually a loss of connection, although this tended to be intermittent.

3.2.3 Circuitry Failures

Components in the circuitry category make up the largest percentage of failure events found in the OE review. Like the magnetics, these components are manufactured for a long, continuous operating life. However, age-related degradation, acting along with other external factors, leads to failures in these components. The OE review has shown that these components are prone to failures that cannot always be predicted. Because they are in the power path of the voltage regulator circuit, often governed by the MOP, they are vulnerable to voltage spikes, which greatly accelerate the degradation in these components. There have been at least two failures of selenium rectifiers (installed as surge arrestors) in the industry, which were found to have been possibly caused by a combination of age-related degradation and one or more voltage spikes.

In the Basler SER-CB systems, one of the problems experienced is a breakdown on the flyback diode circuit, in which it did not trigger the SCRs off and the generator output went to a very high value until either the load was entirely removed (output breaker opened) or the exciter was shut down (tripping of the K1 contactor). This fault was traced to age-related corrosion over time of the connections of the SCRs and diodes, and particularly the flyback diode, to the heat sinks on which they were mounted, acting also as the electrical connections to the components. The diode bridge chassis were returned to Basler for correction of the fault, and Basler published an instruction for inspection, cleaning, torqueing, and renewing these components as may be required from time to time.

3.2.4 Relay and Contactor Failures

Failure of relays, especially the K1 relay, has been a persistent problem in the operation of EVRs. The K1 relay is used to turn the excitation on or off, while a second relay, K2, is used to manage flashing on the generator field when certain operating conditions are met, such as the engine achieving some minimum speed in the process of accelerating to rated speed on startup. A majority of failures have resulted from the mechanical degradation of the contacts due to wear and lack of maintenance. This has prevented the relay coils from becoming energized, leading to loss of excitation. In some cases, a burned-out coil has led the operator to use the manual latching mechanism, which resulted in the components being energized for much longer than required, leading to overheating and accelerated degradation. Mechanical degradation of the contacts occurs in the form of loss of contact spring stiffness, misalignment due to bending, and deposits and wear on contact surfaces. All these scenarios lead to inoperation or improper operation of the relays and then ultimately failure of the EVR.

3.2.5 Wiring and Connections

About 9% of EVR system failures were attributed to wiring and connections. In several cases, the failure was caused by mechanical wear and tear, occasionally resulting from rubbing against clamps, bolts, and so. Although this type of degradation is random and hard to prevent, proper maintenance and inspection can lead to early detection and prevent failures during EDG surveillance runs and increase reliability of the system.

3.3 Environmental Factors

In general, nuclear plant EDG systems are operated in a controlled environment with limits on temperature and humidity. However, because the environmental factors such as temperature, humidity, and airborne salinity can have a large impact on the degradation rates of EVR subcomponents, an attempt was made to identify any possible trends in geographical location of plants where EVR system failures have occurred. Figure 3-5 shows the geographical locations of the plants with EVR failures and all other U.S. plants, denoted with red and green markers, respectively.

Figure 3-5
Locations of U.S. plants with exciter-voltage regulator failures (red markers)

It can be seen that the failures in EVRs occurred in all geographical locations and climate types. Therefore, it does not appear that geographical location and local climate condition play a large role in EVR degradation. However, it is important to understand the significance that these environment stressors have in contributing to the EVR system degradation.

3.3.1 Temperature

The technical specifications for most nuclear power plants specify the EDG engine room environment not to exceed 122°F (50°C). Several EVR subcomponents require control of the room temperature to preclude exceeding the allowable temperature. These include magnetics (primarily transformers), devices with electrical coils (such as relays and contactors), and electrical/electronic equipment in general. Most EDG rooms have fans that either provide cool air to the room, or remove the hot air from the room, or both. The engine and the generator that is driven by the engine are the primary sources of heat to the room. Other pieces of equipment within the room, particularly those within control cabinets, are also a significant source of heat. A room not exceeding 122°F (50°C) would typically provide a sufficient heat sink to keep such equipment protected.

Typically, insulation systems on magnetics have an absolute temperature limit of 248°F (120°C). That is, a temperature above that point may begin to have a significant effect on the life of that insulation system. Temperatures above that point will begin to melt the insulation, making it weak and fragile, allowing it to soften to the point at which the insulation between adjacent layers of conductors begins to deteriorate. Organic compounds are most susceptible, rather than the metallic materials, which are typically more immune to temperature increases. It is difficult to predict how life is reduced because it is a factor of not only the temperature but also of the time at that temperature.

Because nuclear plant EDGs do not typically have many run hours, there should not be great concern about deterioration of components as a result of temperature effects. An occasional excursion in temperature, should the engine room cooling systems fail, would also not be considered to cause catastrophic failure unless extreme temperatures were encountered (temperatures near the melting point of insulating materials; the bottom of that temperature range is typically about 250°F [121°C]).

3.3.2 Other Environmental Stressors

Other than temperature, there are some other environmental and external factors that could contribute to degradation in EVR subcomponents. From the failures reported, there is little to no evidence of these factors playing a significant role, possibly because they are controlled effectively in the EDG environment. However, these stressors play a role in the degradation of electronic components in general; therefore, they should be monitored as much as possible to avoid any possible degradation. Specifically, the following factors are of concern:

- Moisture
- Vibration
- Mechanical shock

- Sand and dust
- Chemical exposure
- External grid disturbances

With respect to external grid disturbances, a plant identified that a potential damaging situation exists, in that an EDG operating in test mode, running in parallel with the offsite network, could exceed its field current ratings if prompt operator action is not taken when grid conditions change abruptly. Current technical specification surveillance requirements for the EDGs at this plant require a reactive load to simulate, as close as practicable, the accident design load conditions. An over-excitation event showed that EDGs are, in fact, vulnerable to inadvertent over-excitation of the field due to grid fluctuations. Under operating conditions with elevated network voltage and increased reactive load, there is a risk of the EDG responding automatically to increase its excitation output due to grid fluctuations.

As a corrective action, an effort was undertaken at this plant to revise operating procedures to ensure that large step voltage adjustments on the grid made at the local substation be coordinated with the plant's main control room during an EDG surveillance test. This would give advance notification to operators to adjust EDG kvar to keep excitation ratings and reactive loading within the recommended specifications for the surveillance specification. This was in line with the requirements that other utilities with similar situations have requested and received.

Section 4: Review and Recommendations

4.1 Obsolescence Issues

The EVR systems in U.S. nuclear power plants have shown a high overall reliability, demonstrated by the fact that more than 90% of the original installations are still in service and have not been replaced. This reliability meant fewer equipment and part orders from nuclear plants. Therefore, original equipment manufacturers did not see a business case for continuing support for these installations and maintaining a 10CFR50, Appendix B, Nuclear Utility Quality Assurance program.

However, as can be seen from the OE and the probability of failure curves, the equipment is facing increasing subcomponent failures, and the likelihood of such failures will only increase with time. Obsolescence is a significant problem for the utilities in finding replacement and spare parts and vendor support. The following EVR models are currently obsolete:

- Portec
- EMD Mag Amp (also known as Basler Vickers)
- GE Static
- Westinghouse WRN/PRX
- Electric Machinery

Only the Basler series models are supported, through an agreement with a third-party company, even though Basler does not maintain a nuclear quality assurance program. A third-party company offers retrofits for Portec units, but the original design and parts are not supported.

These models make up about 40% of the total EVRs currently in service. The plants in which they are installed are at a greater vulnerability than others, especially if their spare parts inventory is not sufficient. These plants should consider both short-term and long-term options to resolve this issue, as described in the following subsections.

4.1.1 Replacement Parts

It can be seen from the OE review that the parts most prone to failure are magnetics (transformers and so on), rectifiers, diodes, MOPs, relays, and contacts. For obsolete systems, a like-to-like replacement of these parts would be quite difficult. However, there are many equivalent commercial-grade parts available that would require a commercial-grade dedication for safety-related use.

For magnetics, sizing is typically customized for each installed EVR system, which could increase the time to acquire replacement parts. For the obsolete models, commercial-grade parts manufactured by third-party companies can be obtained, but having them qualified for safety-related use would add to the lead time. Therefore, a plant with a vulnerable system should acquire spare magnetics to reduce replacement time in the event of a failure.

Other parts such as relays, contactors, rectifiers and other circuitry can be obtained through third-party commercial suppliers and qualified, as well. The plants would benefit from working with the EDG owners' groups and/or other plants or group of plants, to collectively find solutions for recurring parts issues. This could also be an opportunity to fix the design issue with the replacement part, where possible. An example would be the now-obsolete ITE contactors used for K1 relays. These contactors were of the normally closed design, which caused problems in excitation shutdown. A replacement contactor of the normally open design was found that fixed the design issue.

In general, finding third-party replacement parts and qualifying them is a short-term and expensive solution because the EVR system would still be the vintage design that has shown problems. A more long-term solution for vulnerable systems would be a complete retrofit or upgrade to a new system as part of a life cycle management plan. Considering extended plant lifetimes, this would be a cost-effective solution.

4.1.2 Retrofit to an Analog System

At least two plants have chosen this option, and Basler SBSR has been the replacement system in both cases. This analog system has continued third-party support for parts and service, which makes it a good choice for this type of retrofit. Although it is also a vintage design from the 1960s, it has shown relatively fewer failures among the currently installed systems and has proven to be highly reliable.

4.1.3 Retrofit to a Digital System

One nuclear plant in the United States has chosen this option. In 2002, TXU Power started the effort to replace the Portec systems on the EDG at Comanche Peak with the only digital EVR system qualified for safety-related use in the United States, the Siemens THYRIPART system [10].

When Portec discontinued its 10CFR50, Appendix B, Nuclear Utility Quality Assurance program in 1994 and then ceased all product manufacturing, repairs, and engineering support in 1998, TXU Power purchased some spare components and a complete set of design documents from Portec.

The design documents had sufficient information to manufacture the majority of the components. Unfortunately, this approach was determined to be costly and time consuming. Additional modifications were also needed to add fault recording and diagnostic capabilities to the analog system. Because of the limited capabilities of the current system, troubleshooting efforts were time consuming due to the lack of data after a fault or disturbance had been identified.

Because of continuing operating issues with the EDG, TXU Power decided to replace the static EVR, PPTs, current transformers and linear reactors, generator control devices, and protective relays.

To solicit input from other utilities and to have a basis of support from within the industry, TXU Power invited other utilities and industry experts to a joint conference in 2002. The goal was to determine the advantages and disadvantages of various solutions and the design concepts associated with each solution. After this meeting, TXU Power proceeded with a digital excitation system at Comanche Peak.

TXU Power was seeking higher reliability, compatibility with other plant control systems that would eventually be upgraded to digital systems, and commitment by the alliance partner to support the delivered digital solution for the lifetime of the plant. After evaluating a number of available options, Comanche Peak selected the Siemens THYRIPART excitation system, a safety-related system that was qualified by Framatome ANP in the United States.

The excitation system is a load-dependent, static excitation system powered by the generator voltage and current. A major portion of the field current is provided through a passive analog power excitation circuit that maintains the generator output voltage to within ±2%. A digital voltage regulator, shunted to the field winding, fine-tunes the generator output to ±0.5%.

A key feature of the excitation system is its ability to continue operating even if the automatic voltage regulator has been shut down and automatically isolated after a failure. Additional key features of the system include the following:

- Visual fault analysis and alarm records to aid operator response
- Full trace recording and fault recording coupled with onboard diagnostics
- Simple structure of the passive power excitation circuit, which limits the possibility of system failure
- Expected reduction of maintenance and calibration efforts
- Clear text display on cabinet front door for system status and alarms
- Communication to remote locations made possible

When work started in October 2002, significant challenges existed, including design of the system, manufacture and testing of a prototype, testing of the production units, and writing of the modification package and procedures. All of this work, including INPO grade training and installation, was completed in 18 months. One of the expected challenges involved plant personnel working with digital systems for the first time. However, the challenge was met with extra training to familiarize plant engineers with the new digital technology.

4.2 Comparison with Exciter-Voltage Regulator Systems in Non-Nuclear Applications

The EVR systems in the nuclear industry are only a small fraction of those used throughout other commercial applications and industries such as marine propulsion, ship service power supply, locomotion, municipal power generation, and industrial power generation. There are many other diesel generators in a service similar to nuclear EDG applications, such as standby generators in hospitals, prisons, critical government facilities, and so forth. Because these industries do not report failures and experience as nuclear plants are required to, little information is available in the public domain regarding the experience in these industries regarding the operation of EVRs. Therefore, subject matter experts were consulted during the preparation of this guidance to identify any differences in operation, level of knowledge, and technology between nuclear and non-nuclear applications. This section summarizes the findings from these consultations.

EVR systems in commercial applications typically run daily and accumulate thousands of hours of service every year (typically 4000 to 7000 hours). The personnel involved in their operation generally act as operators, mechanics, and electricians. This increases the operators' familiarity with the system and their intuition in predicting problems and troubleshooting. EDGs at commercial plants are run continuously, with most maintaining a running log of important engine parameters (with hourly readings) that are used to spot changes and potential problems. The nuclear plants also do that, but they run for only an hour or two once a month and for 24 hours once a year in some plants. It is then necessary to compare one run to another over time to determine whether changes are taking place.

An area that experts found generally lacking in nuclear plant applications is training, due in part to the fact that the nuclear units are seldom operated. In lieu of actual experience with the equipment, training becomes imperative.

Spare parts management at nuclear power plants is generally quite good, with at least one spare in stock for all of the critical parts, such as a voltage regulator module, governor system components, relays, control parts, and so forth. Most nuclear spare parts have been through a qualification program. In commercial service, few parts are stocked; because there is no need for a safety-related qualification, parts are usually easily available as needed.

It is difficult to compare the two types of applications in terms of historical failures rates because most non-nuclear applications do not report failures the way nuclear plants do. However, it is the experts' opinion that the EVR systems in non-nuclear applications are becoming more reliable with time and experiencing fewer failures. This is largely because these applications are quick in upgrading to new technology when available, which reduces aging-related problems and also makes the system more reliable. This is in stark contrast with nuclear power EDG applications, in which most EVR systems still use aged technology from the 1960s, and there have been few upgrades to new technology. Because the problems related to aging and obsolescence are on the rise, it is advisable for nuclear power plants to make a concerted effort in finding options to qualify and upgrade to new technology. This becomes more cost-effective when done in coordination with EDG owners' groups, other plants, or group of plants.

4.3 Condition Monitoring and Preventive Maintenance

4.3.1 Thermography

Thermography is not performed widely on EVR systems currently, but it can be a useful tool in assessing the extent of degradation in EVR circuits, especially magnetics and rectifiers. Thermal compounds used on power diodes and power SCRs can degrade over time, resulting in adverse thermal effects (such hot spots). In addition, the misapplication (usually over-application) of thermal compound can result in hot spots and premature failure of power diodes and power SCRs. Thermography would effectively detect these hot spots, and the results would be a useful data point in determining a replacement interval for aged components.

In the OE review, an event was noted in which a plant performed thermography before a monthly performance test, identified overheating in a connection leading to one of the rectifiers, and performed preventive replacement of the connections, after which the test was performed normally. This is an example of how performing thermography can help in proactively identifying weak areas in the circuits, so that they can be replaced before they fail and/or spare part availability can be ensured.

4.3.2 Good Preventive Maintenance Practices

In the OE review, more failures were attributed to insufficient PM than to any other root cause. Failures caused by dirty MOPs and degrading connections can be reduced by cleaning and inspecting the system periodically. Model-specific PM guidance is available for EVR systems in the following EPRI reports:

- *Portec (NEI Peebles) Voltage Regulators for Emergency Diesel Generators* (1011108) [2]
- *Basler SBSR Voltage Regulators for Emergency Diesel Generators* (1011110) [3]
- *Basler SER-CB Voltage Regulators for Emergency Diesel Generators* (1011218) [4]

- *Basler SR8A Voltage Regulators for Emergency Diesel Generators* (1011109) [5]
- *EMD Mag Amp Voltage Regulators for Emergency Diesel Generators* (1011111) [6]

It is recommended that system engineers and operators familiarize themselves with these reports and adopt their recommendations. This would help mitigate the number of failures that the systems encounter in the future.

Section 5: Conclusions

The OE review summarized in Table 2-1 has shown that EVR systems still show considerable reliability—a majority of EVR systems originally installed are still in service, and only 54 subcomponent failure events in approximately 40 years were found in the OE search. However, with the design and manufacture of these systems aging, it is becoming increasingly likely that a subcomponent will fail during EDG testing and operation. This is evident from Figure 3-3, which shows that the probability of failure is on the rise. Figure 3-4 shows that some EVR models are at higher risk than others.

EDG engineers and system managers can use the OE review and probabilistic analyses presented in this report to assess their system's level of vulnerability by comparing it to the OE. If an EVR system is considered to be at risk of aging and obsolescence, short-term and long-term solutions must be considered. This could include procuring third-party engineered spare parts or retrofitting the whole system to a new analog or digital system. The life of the current system can also be extended by ensuring that proper PM is performed and that the condition of the crucial subcomponents is assessed periodically.

Section 6: References

1. *Emergency Diesel Generator Voltage Regulator Maintenance Issues.* EPRI, Palo Alto, CA: 2004. 1011232.

2. *Portec (NEI Peebles) Voltage Regulators for Emergency Diesel Generators.* EPRI, Palo Alto, CA: 2004. 1011108.

3. *Basler SBSR Voltage Regulators for Emergency Diesel Generators.* EPRI, Palo Alto, CA: 2004. 1011110.

4. *Basler SER-CB Voltage Regulators for Emergency Diesel Generators.* EPRI, Palo Alto, CA: 2005. 1011218.

5. *Basler SR8A Voltage Regulators for Emergency Diesel Generators.* EPRI, Palo Alto, CA: 2004. 1011109.

6. *EMD Mag Amp Voltage Regulators for Emergency Diesel Generators.* EPRI, Palo Alto, CA: 2004. 1011111.

7. INPO Database of Operating Experience. Institute of Nuclear Power Operations (INPO), Atlanta, GA.

8. *Reliability Modeling—The RIAC Guide to Reliability Prediction, Assessment and Estimation.* Reliability Information Assessment Center (RIAC), Utica, NY: 2010.

9. R. B. Abernathy, J. E. Breneman, C. H. Medlin, and G. L. Reinman. *Weibull Analysis Handbook,* Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, OH: 1983. AFWAL-TR-83-2079.

10. "The Battle for Obsolescence," *Power Engineering*, Vol. 108, No. 9, 2004. http://www.power-eng.com/articles/print/volume-108/issue-9/features/the-battle-of-obsolescence.html.

Appendix A: Questions to Consider

The following questions can be used to determine the need for developing a long-term or contingency plan for an exciter-voltage regulator (EVR) system that is at or is approaching its expected end of life.

Expected Life

1. Has an evaluation of the expected life of the system been conducted?

2. Have industry- and site-specific operating and maintenance experiences related to the EVR system been compared and assessed?

3. Has the EVR system been experiencing an increasing number of failures with time?

4. Has the EVR system been increasingly related to emergency diesel generator inoperability in recent years?

Aging and Obsolescence

1. Have the subcomponents been inspected for any signs of aging?

2. Has the EVR system's vulnerability to obsolescence been assessed?

3. Is the plant's EVR system of a type that is obsolete?

4. If the EVR system is obsolete, are sufficient spares available for all the crucial subcomponents, such as transformers, diodes, bridge rectifiers, silicon-controlled rectifiers, relays, contactors, and so on?

5. If spares exist, are they known to be ready for service?

6. If a spare is not manufactured by the original equipment manufacturer, has all consideration been given with regard to sizing, interface with the rest of the system, dimensions, and so on?

7. Has a long-term resolution been considered for the obsolescence issue?

Preventive Maintenance and Condition Monitoring:

1. Has care been taken to ensure that the circuits, printed circuit board, and subcomponents are clean?

2. Has the motor-operated potentiometer been periodically checked for cleanliness?

3. Has thermography been considered to assess the condition of the system?

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

Program:

Plant Engineering

3002000568

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com