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Plant Engineering: Relay Failure Analysis

Understanding the Causes of Relay Failures

2017 TECHNICAL REPORT

Plant Engineering: Relay Failure Analysis

Understanding the Causes of Relay Failures

3002010689

Final Report, December 2017

EPRI Project Manager
D. Knapp

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YES [✓ NO]

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

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ACKNOWLEDGMENTS

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

Engineered Solutions Group
4820 Rupp Farm Drive
West Chester, Ohio 45069

Principal Investigators
R. Minadeo
E. Hurley

This report describes research sponsored by EPRI.

EPRI would like to acknowledge the support of the U.S. Nuclear Regulatory Commission for providing access to the NRC ADAMS records database and the support of the Technical Advisory Group (TAG) for this project consisting of the following personnel:

Luke Donney	APS
Ben Sun	Bruce Power
Randy Fulp	Duke Energy
Michael Jenkins	Duke Energy
Sudhir Thakur	Exelon Corp
Brian Young	First Energy
Ed Tahlman	PG&E
Michael Yackoski	Talen Energy
Andrew Blattel	Wolf Creek
Andrew Dehn	Xcel Energy
Sinnathurai Gajanetharan	Xcel Energy

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

Plant Engineering: Relay Failure Analysis—Understanding the Causes of Relay Failures. EPRI, Palo Alto, CA: 2017. 3002010689.

ABSTRACT

Relay malfunctions are one of the leading contributors to nuclear reactor scrams. Operating experience has documented these failures over many years. Evaluation of the failure reports for common causes may help develop mitigating actions to prevent some failures.

This project investigated failure modes of control, timing, auxiliary, and protective relay models in service in U.S. nuclear power plants. To do this, the project team conducted queries of industry operating experience (OE) databases. Although the data utilized is from U.S. plants, the results of this study are applicable to all plant designs and origin.

The project team compared the failure modes identified in the OE databases to relay failure modes in the EPRI Preventive Maintenance Basis Database (PMBD) and found that the two sets of failure modes were consistent. In addition, where appropriate, the team identified relay models with common design features that are susceptible to the various failure modes.

The team also identified time-dependent or partially time-dependent relay aging mechanisms. For each of these conditions, the report describes possible approaches for the development of aging models. Some degradation modes were not time dependent, but could be better analyzed statistically. Appendix B contains a template for reporting relay failure information.

Keywords

Condition monitoring
Failure analysis
Operating experience
PMBD
Preventive maintenance
Relays

Deliverable Number: 3002010689

Product Type: Technical Report

Product Title: Plant Engineering: Relay Failure Analysis: Understanding the Causes of Relay Failures

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PRIMARY AUDIENCE: Relay component engineers and system engineers

SECONDARY AUDIENCE: Maintenance planners, and those responsible for generating relay operating experience reports

KEY RESEARCH QUESTION

Identification of the common causes of relay failures can help formulate strategies to mitigate identified failures, as well as determine degradation precursors leading to failure. This could aid in the development of condition-based monitoring for relays. Condition monitoring should help realize cost reductions compared to time-based preventive maintenance (PM) and replacement strategies, while maintaining or even improving reliability.

RESEARCH OVERVIEW

The project team searched existing industry and regulatory operating experience (OE) databases for relay failures. The team then analyzed the relay failure reports for data in two areas: factors leading to relay degradation, including service condition and duty cycle; and the failure modes and causes identified for those failures. The team then compiled and analyzed this data to determine correlations between failure modes and their causes and the factors leading to degradation.

KEY FINDINGS

- Existing OE databases are well designed to record relay failures and the consequences of those failures on plant licensing and operability, and can be used to compile statistics on those failures.
- Analysis of these OE databases shows a significant decline in the number of relay failures reported from 2010 to 2017.
- Relay failure modes identified are consistent with the EPRI Preventive Maintenance Basis Database (PMBD)
- Existing OE databases do not typically provide data on the key factors leading to component degradation that could be used to determine failure causes.
- Better failure data reporting is needed, and a form is provided in Appendix B that members can use to facilitate reporting.

WHY THIS MATTERS

Relay failures continue to be a major constituent of reactor scrams and forced loss rate, as well as incur significant operating and maintenance (O&M) costs. Understanding the degradation and failure modes, as well as developing mitigation strategies, will improve reactor safety and reliability while also reducing O&M costs.

HOW TO APPLY RESULTS

Engineers can review the mitigation strategies identified in this report, in addition to the maintenance activities identified in the EPRI PMBD, to ensure their preventive maintenance (PM) program incorporates them. Engineers can use the trends that the PM program identified to locate the relevant precursor identified in the table in Section 8 to predict potential failure modes. Utilities can use Attachment B when reporting operating experience involving a relay failure to help other members learn from identified failure causes.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI will provide an email to members of the EPRI Nuclear Utility Relay Users Group (NURUG) when this product is available for download.
- EPRI conducts annual NURUG meetings, in which relay engineers and technicians share their operating experience and learn from other members and vendors through presentations and workshops.
- The NURUG website is at: https://msites.epri.com/ms/research/117997/relay-users-group
- The NURUG collaboration website is at: https://msites.epri.com/ms/research/117997/relay-users-group

EPRI CONTACTS: David Knapp, Technical Leader, dknapp@epri.com, 704.595.2960

PROGRAM: Plant Engineering, P41.05.02

IMPLEMENTATION CATEGORY: Category 2, Plant Optimization

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

ACRONYMS AND GLOSSARY OF TERMS

The following terms are applicable to this scope of work and are used within this document:

- Agencywide Documents Access and Management System (ADAMS) database (NRC)
- Arrhenius model – A standard method for addressing time-temperature aging effects relating rate of reaction to temperature through a simple exponential function, which is used to determine the estimated thermal life of a component.
- Auxiliary relay – A relay with the function of assisting another relay or control device in performing a general function by supplying supplementary actions.
- Coil resistance or winding resistance (WR) – Electrical resistance (ohms) to current flow through a coil.
- Condition monitoring (CM)
- Contact resistance (CR) – *T*he *resistance* to current flow *(in milliohms or ohms)* due to surface conditions and other causes, when contacts are touching one another (closed).
- Contactor – An electrically-controlled switch used for switching an electrical power circuit, which is similar to a relay except with higher contact current ratings. This report does not address contactors.
- Control relay – A relay with the function of initiating or permitting the next desired operation in a control sequence; a remotely controlled switch.
- Critical component – A component which is functionally important (e.g., significant risk, required for power production, safety related, or other regulatory requirements).
- Drop-out – Contact operation (opening or closing) as a relay departs from pickup. This also identifies the maximum value of an input quantity that allows the relay to depart from pickup.
- Electromagnetic compatibility (EMC) – The branch of engineering that studies the emission or generation of unwanted electromagnetic energy and the susceptibility or immunity of electrical equipment to that energy. The term is often used almost interchangeably with EMI and is referred to as EMI in this report.
- Electromagnetic interference (EMI) – The disruption of (or interference with) the operation of an electrical device due to the radiated or conducted electromagnetic emissions from another electrical device.

- Electric Power Research Institute (EPRI)
- Environmental qualification (EQ) – A process for ensuring that equipment is capable of withstanding the ambient conditions that could exist when the specific function to be performed by the equipment is actually called upon to be performed under accident conditions.
- EPRI Preventive Maintenance Basis Database (PMBD)
- Heat rise – Temperature increase above ambient resulting from electrical (ohmic) heating. This includes heat generated within the component of interest as well as heat that adjacent components generate and heat dissipation limitations of the equipment enclosure.
- Inspection and enforcement notice (IEN)
- Inspection and enforcement bulletin (IEB)
- Institute of Electrical and Electronics Engineers (IEEE)
- Institute of Nuclear Power Operations (INPO)
- Insulation resistance (IR) – The resistance (ohms) between two conductors, or between a conductor and earth, when they are separated only by insulating material. For contacts, a measurement of resistance between open contacts or between separate contact poles. Also, electrical resistance between a conductor and earth ground.
- Motor control center (MCC)
- Normally closed (NC) contact – A relay contact that is NC when the relay coil is not energized.
- Normally open (NO) Contact – A relay contact that is NO when the relay coil is not energized.
- Nuclear Utility Relay Users Group (NURUG, also called the Relay Users Group)
- Nuclear Regulatory Commission (NRC)
- Operating Experience (OE) – Refers to historical performance records of the nuclear industry.
- Operating and maintenance (O&M)
- Preventive maintenance (PM)
- Protective relay – A relay with the function of detecting a fault or abnormal operating condition and initiating appropriate control circuit action.
- Pull-in – The relay change of state that normally occurs when the relay coil is energized. For timing relays, this occurs after the set timing has elapsed. Pull-in voltage is the minimum voltage required to be applied to a *relay* coil to pick-up the relay.

- Polyvinylchloride (PVC) – A polymer consisting of chains of – $(CCl_2\text{-}CCl_2)_n$-
- Safety related – Classification of systems, structures, components, procedures, and controls (of a facility or process) that are relied upon to remain functional during and following design-basis events.
- Solid-state (SS) relay
- Timing relay – A relay with the function of introducing one or more time delays in the completion of an associated function.

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1

INTRODUCTION AND BACKGROUND

Control, timing, and protective relays at most nuclear power plants have accumulated many years of service life. Continued reliable functioning of relays is essential to support plant operation and life extension. Control and timing relays are primary elements of the control system for electrical equipment in the plant. Protective relays are tasked with:

- Safeguarding the plant electrical components and systems to ensure they are operating within their design limits
- Taking appropriate actions as required to ensure both normal and transient operation, including safe shutdown as required by the plant technical specifications

The purpose of this project was to analyze relay failure modes for reported relay failures that have occurred over the life of commercial nuclear plants and to develop that data into a set of failure modes common to the various types of relays. The project team then used the most predominant failure modes to identify appropriate condition monitoring and/or preventive maintenance action recommendations to minimize in-service relay failures.

Site evaluations have identified issues related to relay preventive maintenance programs, including adherence to scheduled relay replacement intervals, failure to follow manufacturer replacement recommendations, and inadequate justifications for deviations from vendor component life recommendations. While plants have made progress in reducing relay failures, relay issues continue to surface, and interest in relay failures remains high [1]. Many relays are not within the control of engineering programs such as environmental qualification (EQ) or other regulatory programs, but are essential for power production – protective relays are a prime example. Lost power production may result from a single relay failure.

One consideration that can significantly impact relay reliability is the service environment in which the relay operates. For normal service, the environmental conditions (e.g., temperature, humidity, vibration, and radiation) tend to be benign for most relays. This is especially true for protective relays, which are usually not located in an application that diverges significantly from a control room environment. Some relays are installed in enclosures inside the plant power block, such as in relay cabinets, motor control centers (MCCs), switchgear enclosures, or other panels.

In-cabinet applications can also create more extreme local environments, especially where relay installation includes a tight packing density with a considerable number of relays in close physical proximity to each other. In this configuration, heat dissipation becomes critical. When coupled with coil ohmic heat rise, the tight packing may create an unexpectedly high relay operating temperature, especially for relays in the center of the pack. Other relays may be located in areas vented to the outdoors, which can create issues with humidity and salt spray. Occasionally, a relay may be installed adjacent to equipment that adds a significant vibration factor to its service conditions.

However, most relays are installed in environments ranging from 20 to 50°C (68 to 122°F), with humidity at 20 to 90%, and relatively low radiation (typically below 1E4 rads over 60 years), which is fairly uniform for most relay applications in nuclear plants. Evaluation of the data is not biased toward a particular plant or application. Therefore, the conclusions of this report are considered applicable to many relays.

The relay’s duty cycle is another aging stressor. Normally energized relays are subject to more rapid aging than normally de-energized relays, especially for electromechanical (EM) relays. This is largely due to the increased thermal exposure the coils experience in energized relays. Extreme cycling of the relays can also contribute to wear aging of internal parts, but some level of cycling is also beneficial. Limited cycling can result in parts seizing due to loss of lubrication, increased friction/wear, or other internal degradation factors. This report considers the contribution of these factors.

This project investigates failures that have occurred over time and offers mitigating measures to address not only the classical Arrhenius time-temperature aging mechanism of failure, but also to highlight real-life failures with causes that do not readily lend themselves to classical life estimation methods. For all relays, the Arrhenius aging model that relies on material property degradation versus time and temperature must be considered [2], but other failure modes are also considered and may be even more prevalent than aging failures caused by time and temperature. For this reason, the recommendations and maintenance practices contained in this report also address the failure modes that are not caused by time and temperature aging for control, timing, and protective relays. Many of these failures may not be identified until critical functions are not performed as intended.

For the failure mechanisms identified that do not follow Arrhenius life models, the ability to predict relay end of life becomes the mission of condition monitoring. Various service conditions and electrical parameters associated with relay service must be carefully evaluated. For example, the report considers failures associated with the formation of tin whiskers that can bridge open contacts on relay designs that feature tin-plated contact faces [3, 4, 5, 6]. Such failure modes are not directly linked to aging, as failures have been noted as early as two years after installation, while others of the same model are still functioning properly after more than 30 years. Other relay types exhibit failure modes associated with corrosion of the coil magnet wire due to chemical attack. The corrosion may be related to off gassing from vinyl (i.e., polyvinylchloride or PVC) components inside the relay or solder flux that contain halogens, creating a corrosive condition for the copper coil wiring.

2

PROJECT SCOPE

Relays are an industry issue that warrants attention [1]. The importance of control, timing, protective, and other relays to plant operation is paramount. Relays are the devices assigned to the control and protection of plant electrical equipment, including the safety-related plant systems, to support the safe operation of the plant in compliance with license technical specifications. Relays also support the plant systems that are critical for power production. Additionally, a relay failure may be recognized during plant operation (causing loss of equipment operability or impacting system function) or during surveillance testing when the failure is more easily corrected. Failure of a safety-related relay initiates the determination of investigations on the cause of failure, extent of condition, and bounding of other affected components that could be susceptible to that failure mode.

The scope of this project was to investigate the actual failure modes that have occurred historically, determine the set of failure modes common to the various types of relays, identify the mechanisms that cause those failures, and provide recommendations for mitigating them. To accomplish these objectives, this report compiles data from research performed on the Nuclear Regulatory Commission (NRC) Agencywide Documents Access and Management System (ADAMS) database [7], industry OE databases [8], and the EPRI work order database. The team compiled data for electromechanical, solid state, and digital relay designs, which perform control, timing, auxiliary, and protective functions. This report does not address contactors.

Not all relay failures encountered during this project were caused by aging effects or normal wear. Some failures were due to improper application/design, improper maintenance practices, personnel errors, or events external to the relay. If these failures are recognized as constituting a potential common mode failure initiator, they are addressed herein, but otherwise these errors are assumed to be atypical and outside the scope of this project. Such failures are considered a part of operating experience, and separate measures should address these failures commensurate with their importance.

For other relay failures that are aging- or duty-cycle related, periodic testing via surveillance and condition monitoring may be effective in identifying some failures. These types of failures were the focus of this project.

3
CATEGORIES OF RELAYS

Relay classifications for this report encompass both the function of the relay (what it does) and the design of the relay (how it does it). This report classifies relay designs according to their operating mechanism type, which may be electromechanical (coil operated), solid-state, or digital, although some switching designs include mechanical contacts or solid-state output.

This section presents the general characteristics of each of the above considerations, which become major factors in creating the relay failure modes, as noted in the analysis sections of this report.

Potential failure modes are specific for each of the relay designs and may be used as a starting point in determining the appropriate condition monitoring activities required to detect degrading performance pointing to relay failure. The following categories follow IEEE 649-2006 [9].

Design Categories

Relays, as mentioned in Section 3, are remotely-controlled electrical switches. There are three predominate categories of relay designs used in the nuclear power industry. The categories are based on the operating mechanism that controls the switching function of the contacts and the type of contacts used. For the scope of this report, the relays evaluated are those that have their own plant identification number and not those that are basically subcomponents of electrical components and therefore maintained as a part of an assembly, such as those mounted on printed circuit boards. This report does not address contactors, as they are power relays and are more properly addressed under equipment topics such as MCCs, switchgear, etc.

Electromechanical (EM) Relays

Electromechanical relays are the earliest relay designs, consisting of a coil of magnet wire wound on a bobbin that produces a force of attraction by magnetically attracting a movable member (also called an *armature*) that moves against a spring force when the coil is energized. The movement of the attracted piece is translated into movement that opens or closes one or more sets of electrical contacts. The contacts are simply a pair of conductive surfaces that can be separated or brought together to open or complete an electrical circuit. The operating mechanism is based on magnetic forces generated by current flowing through the coil windings. Contacts are separate electrical circuits from the coil. EM relays are typically tolerant with regard to transient and short-term spikes in both the coil and contacts. EM relays are usually unaffected by the polarity of the power applied to the coil. EM relays are not as susceptible to electromagnetic interference as other relay types.

However, this design tends to develop significant heat rise when used in applications that require continuous coil energization. This heat rise is a major source of aging effects for organic materials. Coil heat rise within the relay affects all parts of the relay to some degree, depending on proximity to, and conductivity of, the coil. Heat rise within the coil may be 50 to 90°C (120 to 190°F) or more above ambient temperature.

EM relays generally do not generate significant heat through their contacts, but rather at the coil. Contacts are frequently exposed to the air, and arcing during switching can lead to high contact resistance due to oxidation or contaminant buildup. In limited instances, with high currents, contacts can actually weld together, resulting in a permanently closed circuit. Some relays feature contacts that are self-cleaning by virtue of a small amount of shear motion between the two mating surfaces of the contacts when the contacts close.

Solid-State (SS) Relays

A solid-state relay uses a semiconductor switching mechanism to operate the relay switching function. The contacts change state without any physical movement, which makes the SS relay extremely resistant to seismic and plant induced vibration. The SS relay is built with semiconductor junctions that can be used to switch electrical current when the relay is properly energized. Most SS relays are provided with normally open (NO) and/or normally closed (NC) contacts.

As the electronics industry has advanced over the last 50 or so years, semiconductor junction designs have been miniaturized to permit smaller and lighter assemblies. However, while smaller devices may be desirable for general industry, the miniaturized components have evolved to feature miniaturized semiconductor junctions with a design that is tightly controlled to meet the electrical demand of the component with very little margin for overvoltage and overcurrent conditions. In an SS relay design, the contacts generate most of the heat rise via resistance associated within the switched junction (ohmic heating), even though this heat rise is usually lower than for EM relays.

Both the input (coil analog) and output (contacts analog) are designed as semiconductor junctions. This means they inherit the intolerance for electrical overenergization voltage or current. The SS relay also has some amount of current feedthrough, even when the input conditions demand the relay to be in the de-energized state. This is a small current value, but designs incorporating SS relays need to allow for this characteristic. Load power factor is a significant concern for SS relays, especially if the loads are inductive, as switching creates both voltage and current spikes that can easily damage the relay. External electromagnetic effects do not generally affect SS relay operation.

Due to their limited heat rise and compact size, SS relays are ideal for low power control circuits where significant electrical surges do not occur. SS relays can tolerate the small amount of open state current leakage and are insensitive to vibration issues.

Digital Relays

Digital relays are relays with switching functions (including protective relays, multi-function relays and some time-delay relays) that microprocessor circuits control. These circuits are usually programmable devices that contain some degree of internal software. This software within the microprocessor is subject to validation and verification when used for safety-related applications. This requirement is imposed to ensure that there are no credible modes of mis-operation, regardless of the input/output conditions.

While the microprocessor controls the switching function, the output/contacts may be either electromechanical or solid state. In addition to the potential for vibration-induced contact chatter, external electromagnetic inputs can potentially impact the operation of the microprocessor if the electronics pick up the electronic noise at a sensitive frequency. The clock function in the microprocessor is the most vulnerable subcomponent in such digital relays.

As in EM relays, digital relays with mechanical contacts are tolerant to some level of electrical load current and voltage surges, but are potentially sensitive to plant-induced and seismically induced vibration that can, at the natural frequency of the contact assembly, cause intermittent open/closed contact chatter. Digital relays with solid-state contacts are subject to the same vulnerabilities as the SS relay contacts, such as voltage and current spike intolerance.

Newer protective relay designs feature digital components. Digital protective relays are much more complicated items than EM or SS protective relays due to the electronic processing functions, and may have more failure modes. Unlike protective EM relays, digital protective relays require separate inputs for power and signal. This complexity poses added failure modes associated with the aging of electronic components, such as electrolytic capacitors. Digital relays are the most environmentally-sensitive and electromagnetic emissions-sensitive type of relay. They also generate some level of heat rise, as they are generally energized continuously.

Function Categories

Relay function categories reflect the applications in which the relays are installed to service plant equipment. In this sense, timing and auxiliary relays are a subset of control relays. These relay applications provide controls for the plant electrical system equipment. Protective relays are tasked with more complicated functions, as they are tasked with monitoring electrical parameters and changing state when a preset value for that parameter is reached. Therefore, protective relays are both sensors and switches, whereas control relays are simple switches controlled by an on/off signal to the coil.

This report follows the practice introduced in a previous EPRI report [1] at the request of the TAG to follow the Institute of Electrical and Electronics Engineers (IEEE) designations, which separate relays into either the *control and timing relay group* or the protective *relay group,* according to the tables in Appendix A.

Control/Auxiliary/Timing Relays

A control relay is a device that acts as a switch that controls electrical current. This type of relay opens and/or closes contacts in order to allow current to flow through a separate independent circuit. An *auxiliary relay* assists another *relay* or device in performing an action. A *timing relay* is a combination of a control *relay* and a timing circuit that controls the operation of the *relay* and *timing* range.

As described above, there are several designs for the control mechanism and also for the switching function. As defined for this report, control, auxiliary, and timing relays are actuated via a binary (on/off) input that results in contact status change.

Timing relays typically have pneumatic timers or solid-state timing modules installed in series with the relay coil to add a timing delay function (on delay, off delay, or interval). Other time delay mechanisms include pneumatic mechanisms consisting of a captive air volume that requires controlled pressure bleed-off to allow the relay contact controls to change state following the bleed-off time period. The accuracy of the time delay may be as important as the ability to switch the output circuits.

Protective Relays

A protective relay is a device designed to trip a circuit breaker or actuate another device when it detects a fault or abnormal operating condition. Protective relays are used to detect electrical or equipment performance parameters that are outside a set range of normal operations and take appropriate actions via switching contact status. The protective relay’s detection of out-of-range parameters supports the correct energization of electrical buses, proper loading of emergency buses, and proper operation of large electrical power equipment. Protective relays receive input from sensing devices (such as current and potential transformers) to detect changes in the monitored parameter. Most modern protective relays are digital designs that feature a significantly enhanced capacity for programmability.

The sensing portion of the protective relay may be electromagnetic, solid-state, or digital. The output of the relay is usually a set of contacts that controls the output or acts as input to an auxiliary relay that provides output control.

For protective relays, the selection between digital and electromechanical designs is a trade-off. Digital relays may have higher vulnerability to electromagnetic interference (EMI) and electrical power spikes, but low set point drift. Electromechanical relays have higher vulnerability to vibration and set point drift, but simpler operation and lower vulnerability to EMI effects.

4

SERVICE CONDITIONS, DUTY CYCLE, AND OTHER FACTORS

Relay failure modes are based on the relay design, including materials, layout, and packaging. However, the failure of relays also involves the duty cycle and service conditions. Most equipment failures are a response to the degrading conditions under which they must operate in order to perform their required function. This report addresses relay failure modes that result from factors present in normal service conditions and does not consider the impact of transients.

Service Condition Factors

The EPRI Preventive Maintenance Basis Database (PMBD) categorizes service conditions for relays as either severe or mild [10, 11]. The severe conditions include:

- High or excessive humidity
- Excessive temperatures (high/low) or temperature variations
- High radiation
- Excessive environmental contaminant conditions (e.g., salt, corrosive, humidity dust, dirt)
- High vibration
- Higher than rated voltage
- Proximity to other relays or heat sources with inadequate ventilation

Mild conditions are identified as clean conditions, with normal operating temperatures, though not necessarily air conditioned environments.

For the severe conditions, the factors most relevant to the identified failures were humidity, temperature, and over/under voltage conditions. These are discussed more fully in this section.

Humidity can promote two mechanisms: moisture can pick up decomposition products that then tarnish copper surfaces, or a corrosive effect at the exposed end of the coil winding magnet wire. This can result in an open coil as corrosion consumes the wire conductor.

Most relays are installed in fairly benign ambient conditions ranging from 20 to 50°C (68 to 122°F), with most relays installed in 25 to 35°C (77 to 95°F), nominal noncondensing relative humidity, insignificant radiation, and insignificant vibration. Relays may be normally energized or de-energized. This determines whether the relay internal components are subjected to the significant, sustained heat rise levels associated with the electromagnetic coil. This coil heat rise may be on the order of 40 to 80°C (104 to 176°F) above the ambient temperature. In addition, relays located in relay cabinets that feature numerous relays in close proximity are subject to additional heat rise due to the lack of a radiative heat path, which can add 10 to 30°C (18 to 54°F) in heat rise.

In a worst-case scenario, the approximate total temperatures for relay coils may be 35°C (95°F) (room ambient) + 75°C (135°F) (coil heat rise) + 30°C (54°F) (cabinet/proximity heat rise) = 140°C (284°F), with the other parts of the relay outside the coil affected as well at somewhat lower temperatures. This effect can be significant and can rapidly accelerate relay aging because the actual material temperature is the driving factor in Arrhenius aging of materials [2].

Duty Cycle Factors

The relay duty cycle can also contribute to or mitigate aging and is categorized in the EPRI PMBD as high or low. Normally energized relays are subject to increased thermal aging as discussed previously and categorized as a “high” duty cycle. Frequent cycling of relays is another duty factor that is categorized as “high” and can contribute to internal wear aging. Internal wear aging includes wear on contact surfaces, contact control mechanisms, and even plunger to coil vibration, which can cause “notching” of the plunger core and resultant impediment to full motion. The potential for such wear aging is more typical when relays are frequently cycled.

Infrequent cycling can also contribute to mis-operation of relays. In some cases, the reverse of wear aging can lead to earlier degradation of relay function. Specifically, lack of contact exercise can result in contact surface oxidation. Additionally, thermal conditions can contribute to internal aging of organics and off-gas deposits that create high contact resistance. These changes can interfere with relay output acceptability and proper recognition of relay change of state. For this reason, the EPRI PMBD recommends that normally de-energized relays that are not operated for the majority of their design life should be treated as a “high” duty cycle.

Other Factors

However, there are failure modes that do not seem to be directly correlated with normal aging effects, either from service condition or duty cycle, in that their frequency does not seem to be correlated with time (age). An example is the phenomenon of the growth of metallic (tin or zinc) “whiskers” extending from conductive surfaces to other conductive surfaces or ground [3, 4, 5, 6]. These thin metallic crystals act as simulated contacts that are stuck closed. This occurrence is less likely in circuits that carry significant current, as the current tends to burn off the whiskers and restore normal operation. The impact of whiskers is more likely in low current conditions. Another example is silver migration, which consists of movement of material from one contact face to the other due to high current.

5
DATABASES SEARCHED

In order to develop a comprehensive analysis of the various modes of failure, the project team searched the industry operating experience (OE) and NRC ADAMS database [7] to identify all reported failures of protective, control, timing, and auxiliary relays back to the earliest limits of these databases. In addition to these databases, the team evaluated the EPRI work order database to determine if it could be analyzed for additional insights into relay failures.

Industry Operating Experience (OE) Databases

Various organizations in the industry maintain databases of nuclear plant events that include those resulting from equipment failures. While the databases were created to capture these events, they only contain reports for those events that meet the threshold of industry reporting requirements. Furthermore, many reports are written primarily from the perspective of the event's impact to plant operation, safety, and licensing bases. Many of the report entries contain relay manufacturer and model numbers, but only a small subset contain actual detailed cause analyses.

Searching the industry OE database on the term "relay failure" produced over 1350 resulting reports. To reduce this to a manageable number, the team searched the database using the term "relay failure" together with additional terms related to:

- Relay models or series (e.g., "CR120")
- Specific plants (for correlation to the EPRI work order database)
- Subcomponents (e.g., "contact," "coil," etc.)
- Relay function, specifically "protective relay"
- Relay failure type (e.g., "tin," "contact welding," etc.)
- Year of reported event

The team downloaded and analyzed the reports matching these search parameters and then compiled the relevant information into spreadsheets.

The industry OE database does not provide information on the number of relays of a given model or series in industry use. Therefore, to identify the most common relay series, this project leveraged a previous EPRI report: *Plant Engineering: Control Relay Aging Management Guideline* [1]. Table 5-1 taken from that report) shows the most common relay series as determined by a survey of the industry on the left. Each series is ranked according to the percentage it contributes to the total relay population. Note that only 24 plants responded to the survey, so the results are approximate. On the right is shown the relay series that contributed the most failures according to industry OE. The team searched the leading relay series in the manner described, except for the Agastat 7000 and E7000 series, because the same previous report specifically evaluated those relay series in significant detail.

Table 5-1
Relay population and failures by series [1]

Plant Sites That Submitted Control Relay Data

Relay Series	Norm %
EGP Series	14.23
CR120 Series	13.97
HFA Series	4.81
7000 Series	4.40
AR Series	3.60
156 Series	3.59
MDR Series	3.44
E7000 Series	3.35
2384 Series	2.94
ETR Series	1.97
HGA Series	1.96
219 Series	1.95
IC Series	1.75
BF Series	1.68
GP Series	1.47
DIL Series	1.47
2383 Series	1.19
700 Series	1.11
KRP Series	1.09
71C620005411401 Series	0.90

Industry OE Failure Data: All Relay Types

Relay Series	Norm %
HFA Series	7.1
EGP Series	5.5
E7000 Series	5.5
CR120 Series	3.6
2837 Series	3.3
MDR Series	2.8
HEA Series	2.5
7000 Series	2.4
ETR Series	2.3
BF Series	2.0
AR Series	1.9
156 Series	1.8
HGA Series	1.5
ADM Series	1.4
D26 Series	1.4
BFD Series	1.3
700 Series	1.2
ARD Series	1.2
J13 Series	1.1
NGV Series	1.0

The team also consulted a list of relay series identified as being of interest to the Relay Failures Working Group of the Nuclear Utility Relay Users Group (NURUG). This list, shown in Table 5-2, is consistent with the series shown in Table 5-1.

Table 5-2
Relay series that the NURUG Relay Failures Working Group identified

Relay Series		
Agastat EGP	Cutler Hammer D26	Potter Brumfield MDR
Agastat ETR	General Electric HFA	Potter Brumfield KRP
Agastat E7000	General Electric HEA	Struthers Dunn 219X
Agastat SSC	General Electric CR120	Westinghouse AR/ARD
Agastat SCB/SCC		

NRC ADAMS Database

The NRC maintains a publicly accessible database (document collections) that contains the various events reported from the nuclear fleet, as well as NRC response documents to these events. The team conducted a search using the search term “relay failure,” which yielded a set of documents, including 10CFR21 reports, inspection and enforcement notices (IEN), inspection and enforcement bulletins (IEB), license event reports (including event reports), generic letters, NRC circulars, and other miscellaneous documents.

The team sorted the search results chronologically and reviewed them to gather specifics on relays addressed, failure descriptions, and extent of condition. The NRC database reflects the failures based on their impact to plant safety and licensing bases and are often compilations of reported failures that indicate a common mode failure mechanism.

The 10CFR21 notices include both failures of installed equipment and manufacturing defects on equipment that has not yet been installed. For several of the entries in the NRC database, additional supporting supplementary documents are included that add detail and information regarding the nature of the failure.

IEBs and IENs are frequently issued based on a compilation of information from other reports that are determined to have some type of commonality, including the manufacturer and model numbers, relay types, or unique applications that involve an unusual stressor, etc.

There is some correspondence between the content of the industry operating experience and NRC databases. For example, many of the NRC IEB and IEN documents are compilations of individual event reports that share a common aspect. Additional details for these event reports are frequently captured in corresponding industry event reports. Therefore, the NRC data was quite complementary to the industry operating experience data, and contributes significantly to the analysis provided in later sections of this report.

The team compiled a summary of all NRC documents related to relay failures and then sorted them in a spreadsheet. They are part of the supporting documentation for this project. Appendix D provides the main content of this summary.

EPRI Work Order (WO) Database

EPRI is developing a database of industry work orders that can be mined for insights into the reliability benefits gained from maintenance versus the cost of performing that maintenance. This will lead to insights that optimize the value of maintenance programs by optimizing maintenance frequency and type.

This project evaluated the applicability of the work order database to the analysis of relay failures, their mechanisms, and precursors. For this purpose, a spreadsheet containing a portion of the initial version of the work order database information was provided for analysis. The work order summaries were reviewed to identify if the work order information provided would be of sufficient detail for evaluation of failures. Finally, this project offered suggestions that would make future versions of the work order database more effective or valuable in this regard. After review of the information, the team identified more fields that could be provided to enhance future reviews. In addition to the suggestions offered to the database team, the relay failure report template offered in Appendix B requests the component ID so that the work order history associated with that relay can be cross referenced in the work order database. As the work order database matures, it may be used to provide more specific insights for relay maintenance and failures since it covers all work orders (corrective, deficient, and preventive) completed in the last ten years.

6

ANALYSIS OF DATA

The project team then analyzed the reports collected as the result of the searches described in the previous section to identify data relevant to the understanding of failure modes and mechanisms. The team used spreadsheets to sort and compile this data. Columns were created to record the following:

- Relay manufacturer, model number, and series
- Relay service age (and total age if reported and significantly different)
- Service condition and duty cycle data described in Section 5 as factors contributing to relay degradation
- The subcomponent that failed, its failure mode, and its failure cause
- The report number, plant, date of event, contact information, and any comments or notes

This project used this data, sorted and compiled as described, to determine the most prevalent types of relay failures, where failure type was defined as the combination of the specific subcomponent that failed (e.g., contact, coil, etc.), along with the failure mode. The objective was to also compile root, or at least apparent, causes for reported failures along with the factors contributing to relay degradation discussed in Section 5, to correlate them to the failure modes and mechanisms.

Analysis of Industry Operating Experience (OE) Data

The industry OE database search on “relay failure” resulted in a total of 1355 reports, ranging from May 1985 to September 2017. The team evaluated the sorted data in blocks to develop a conclusion regarding the type of equipment malfunction or failure being reported, the circumstances of the failure, and as much actual cause data as it was possible to gather. The team then tabulated the failure incidents as described above. The team noticed significant variance in the quality, clarity, and detail of reports analyzed. The team also noted that earlier reports were submitted with somewhat less rigor and detail than the later reports.

In general, existing OE reports document the plant impact of the equipment issue, but frequently provide few details on the actual or root cause of the initiating equipment failure. Many reports simply note that a relay “failed to operate” or give a similar description without further information. Other reports give the failure mode, but not the cause of that failure, most likely because there was no cause investigation performed. Only a minority of the reports detail the failure mode and cause. For this reason, existing OE reports are well designed to track trends in industry issues and derive statistics on component failures (as in Figure 6-1), but less well designed to determine common failure causes.

In addition to a scarcity of information on the causes of relay failures, information on duty cycle and service conditions was often incomplete or absent, making it difficult to correlate those factors to relay failures. In those cases, the team could occasionally interpret the event description to derive additional information that was not explicitly stated. Finally, since the reporting criteria are based on the significance of the event with plant operation, many reports describe a relay failure within the context of a system or major equipment failure and therefore required careful reading to avoid confusion over which component actually failed.

Once the team determined the predominant failure modes for the relays in the reported events, the team associated a relative frequency of occurrence with each failure type. The team did not normalize the results against the entire nuclear fleet population of each relay type. The failure modes were evaluated to focus on the predominant modes of failure and specifically on the main failure mode (or the main 2 or 3 modes, as applicable). The team examined the NRC database search results to verify that the industry OE search results were appropriately representative of the historical performance and failure history of each relay group.

Overall, the analysis of this data demonstrates a significant decline in the number of relay failures reported since 2010 (see Figure 6-1). The year 2010 was chosen in order to tie the analysis of this report back to reference [1], which was published in 2011. Note that the team extrapolated the number of failures for 2017, based on the failures reported to date at the writing of this report, to provide a projected, or estimated, total.

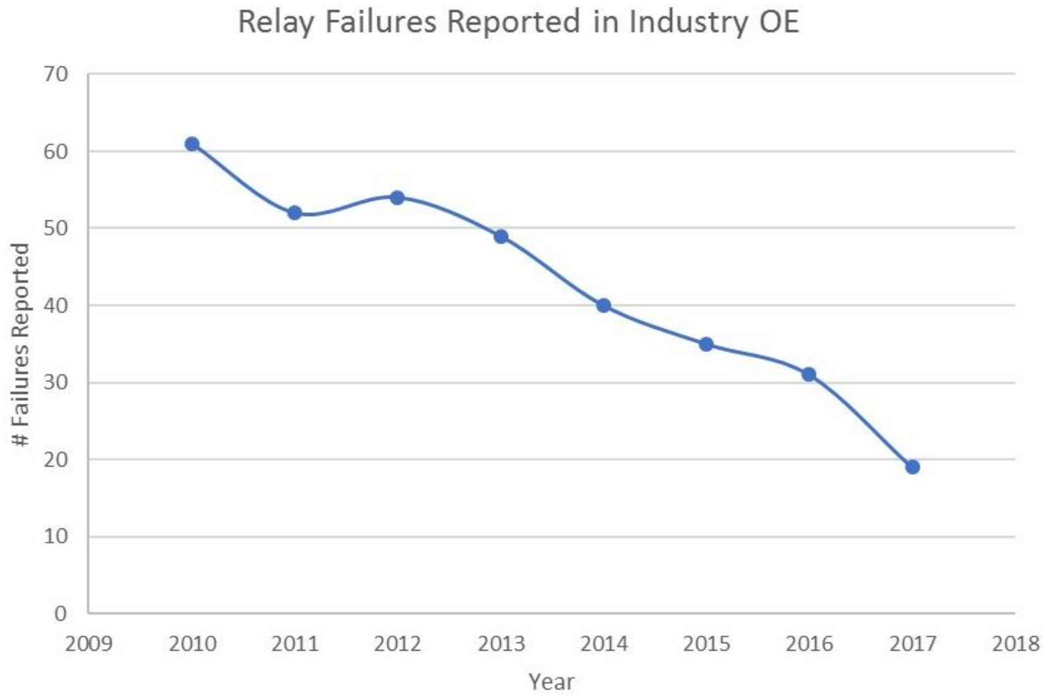

Figure 6-1
Relay failures by year

Protective Relays

The project team searched the protective relays based on the search term “protective relay” because of the wide variety of relay manufacturers and models included within that classification. Certain relay manufacturers and model numbers, such as GE HEA and HEA relays, were included in the industry OE database under both “control/auxiliary relays” and “protective relays.” The relay classification depends on the application. In many cases, a “protective relay” may have an output to an HEA relay to initiate a trip coil actuation to accomplish the required safety function. Therefore, since the HEA relay is involved in a protective function, it is addressed as a protective relay, even though it is perhaps more appropriately classified as an auxiliary relay. (See the definitions of protective relay and auxiliary relay in Section 3 and Appendix A of this report.). (See Figure 6-2).

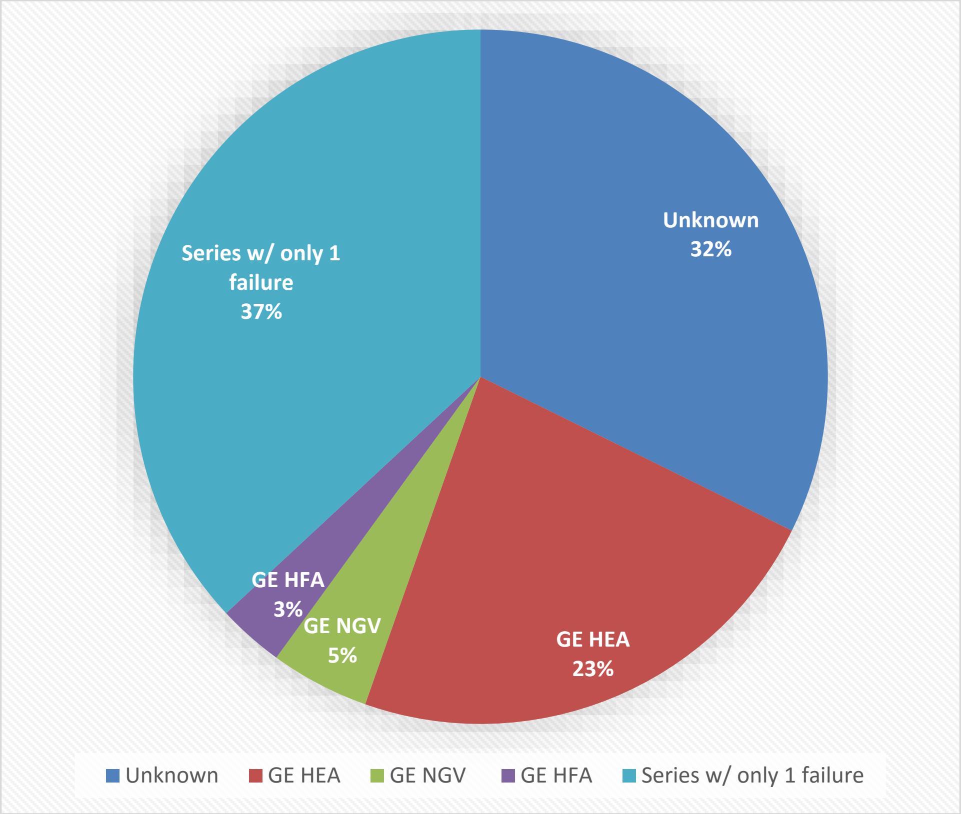

Figure 6-2
Protective relay failures by series

As seen in Figure 6-3, the number of reported failures of protective relays constitutes only a small percentage of all 1355 relay failure reports. This is a reasonable result for the following reasons:

- Protective relays have an isolated power feed that is separate from the sensing inputs, power output, and contacts. This power feed is always on, so there is no power cycling, and is well controlled because it is from an essential power supply.
- The sensing circuit operates on a small amount of voltage or current, so there are no significant electrical stresses coming from that circuit.

- The contacts tend to power only components that are low power, such as alarms, indicators, and other relay coils, so they do not have high power switching requirements.
- They are always located in environments, such as a relay rooms or control rooms, which are under rigorous climate control.
- They are not subject to significant vibration because these environments do not have power equipment.

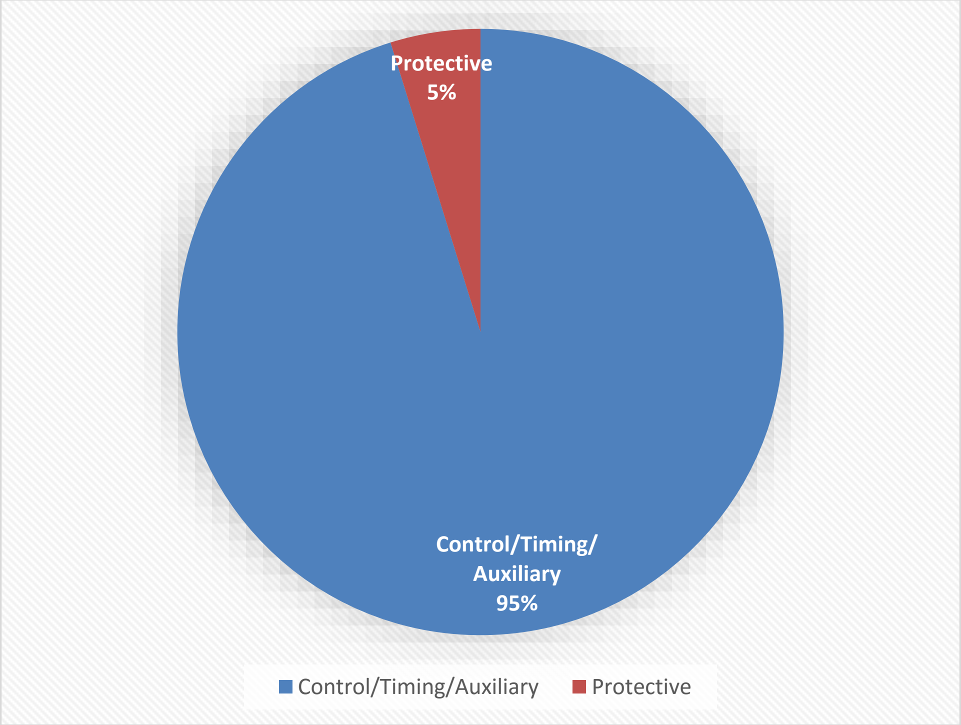

Figure 6-3
Percentage of reported failures by relay function

The team also analyzed the protective failure data for patterns related to relay series, because protective relays had not been analyzed previously [1]. As anticipated, relay series identified in the OE reports were distributed over a wide range. Also, with only a few exceptions, the number of failures reported were evenly distributed over the relay series. In fact, 37% of the failures were associated with a relay series that had only 1 reported failure. However, one-third of the OE reports for protective relays did not identify the relay series. That data, if available, could change the distribution.

Analysis of NRC ADAMS Data

The NRC search returned approximately 85 relevant relay failure documents, many of which were part 21 reports, LERs, and IEN/IEB documents. Many of these documents were compilations of individual event reports and LERs. In some instances, multiple documents referred to the same issue. Appendix D provides a summary of these.

The team plotted the number of these documents versus time to determine if this data shows a decline like that found in the OE data (see Figure 6-1). The team excluded part 21 reports that were not also associated with IENs, IEBs, or event reports, because they pertain exclusively to manufacturing issues. The team combined the data into two-year intervals because the data was somewhat sparse, and because NRC documents are sometimes in response to multiple industry events. As shown in Figure 6-4, there is no statistically significant increase or decrease in NRC documents related to relays. However, this does not contradict the decline of relay failure reports shown in Figure 6-1 because the NRC documents are concerned with relay issues of a different kind and degree than the industry OE reports.

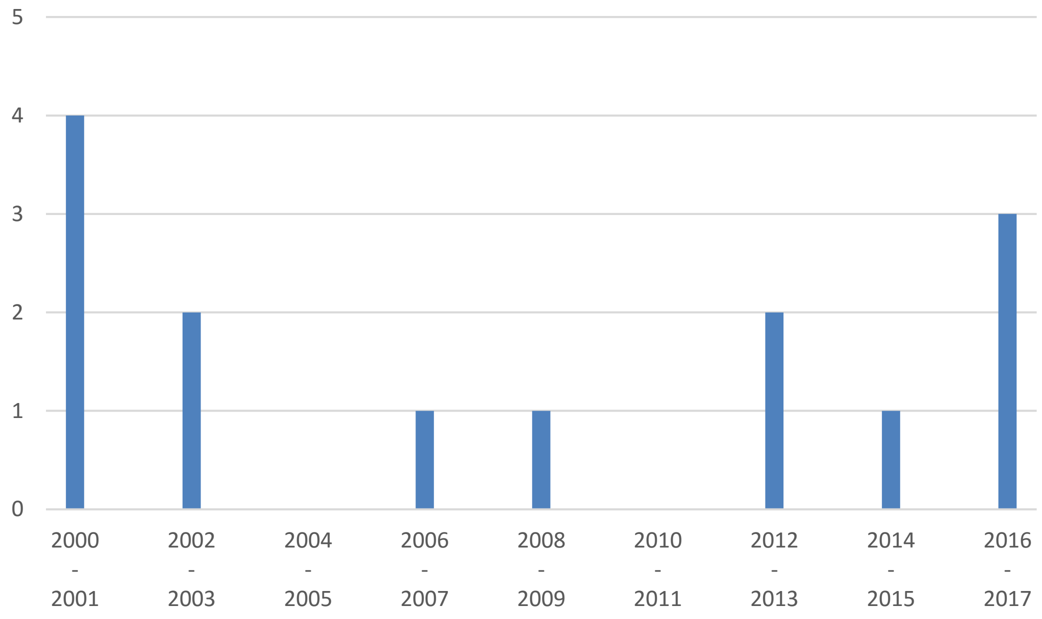

Figure 6-4
Number of NRC relay reports by year

Analysis of Overall Data

The results of the sorted research data provide the basis of the predominant modes of failure of the groups of relays reported in Section 8 of this document. These results consider all significant factors that were involved in the failures such that a true cause of failure is presented. The team then used this conclusive result to generate the recommendations for relay condition monitoring in order to identify the presence and degree of degradation of each type of relay.

Identifying the relay failure modes and condition monitoring requirements enables utilities to prescribe appropriate activities to minimize the occurrence of many failures. Section 9 explains the proper application of the failure modes and frequency data to drive the performance of condition monitoring (CM) and preventive maintenance (PM) activities to minimize in-service failures. Some failure modes are difficult to detect because they do not present trends of degradation, but the reported history of failures may provide an opportunity for the implementation or adjustment of periodic maintenance/replacement activities to minimize the chances of in-service failures.

7

FAILURE MECHANISMS AND PRECURSORS TO IDENTIFIED CAUSES

The project team sorted relay failures reported in the industry OE and NRC ADAMS database by manufacturer and model. The team then analyzed failures from the most prevalent models to determine the failure mode. The approaches applied to these relays can be considered for other less common relays that share the same or similar design characteristics. It is likely that such other relays share these same failure modes.

The evaluation of the database information on relay failures revealed several failure mechanisms that are characterized by gradual degradation trends in material parameters and/or relay functionality. These failure modes can be addressed with condition monitoring (CM) techniques to track the level of degradation so that corrective actions (i.e., repair, refurbishment, or replacement) can be implemented prior to actual relay failure. In addition to these failure mechanisms that exhibit trends, the team found other failure mechanisms that were neither age-dependent nor failures with detectable degradation in materials or relay function. For failure mechanisms that do not lend themselves to CM techniques, other approaches could be “run-to-failure” or “replace with different design.”

Table 7-1, Table 7-2, and Table 7-3 show common relay failures as reported in the industry OE and NRC ADAMS databases for electromechanical relays, solid-state relays, and digital relays, respectively. The team derived the precursors from an understanding of the physics of the failure mechanism. (Note that Appendix C of this report contains a table of failure mechanisms identified in the EPRI PMBD for comparison.)

Table 7-1
Commonly reported relay failures for electromechanical relays

Function or Application	Relay Failed Subcomponent*	Failure Mechanism*	Precursor	Models with Failure
Control/Timing/Aux	**Contact mechanism**	**sticking from off-gassing, foreign materials**	0	P&B MDR, WEC BFD, Agastat E7000, A-B 7000, C-H ARD
	contact	**Oxidized, high resistance**	1	GE HEA & GE CR120A/B, Agastat EGP
	contact/latch	sticking from warpage	0	GE CR120A/B/HFA151/HFA51
	contacts	Shorting across open	2	GE CR120A/B
	coil	**burned**	3, 4	GE HEA/HFA151/HFA51, Gould J10/J12/J13, GE CR120A&B, WEC NBFD, Agastat EGP, A-B 700
	coil	shorted	3, 4, 5	GE HFA/ CR120A&B
	coil	**Open, mag wire corrosion issue**	3	GE HEA/HFA, A-B 700RTC, NBFD, GE HMA, S-D 255X, MidTex 156, Agastat FGP, GE CR120A, WEC CO-7 & CO-9 & KC-4 & COM-5 & CV-2 & CVE,
	Coil exterior	Cracked covering	3	WEC BFD/NBFD,
	timer	SS timer attachment shorted, opened, drifted, failed	6	GE CR120A/B
	plunger/core	notched from vibration	3	Sylvania GTE 12U, CR120A/B
	plunger/core/linkage	sticking	0	WEC ARD, S-D 219,
	terminals/pins	broken/bent/bad connection	3	S-D 255XC, Theta 0FA, GE CR120A/B
	internal shorting	tin/zinc whiskers	0	MidTex 156, Agastat EGP

Table 7-1 (continued)
Commonly reported relay failures for electromechanical relays

Function or Application	Relay Failed Subcomponent*	Failure Mechanism*	Precursor	Models with Failure
Protective	setpoint	drift	6	
	control	**Zener, cap, or transistor shorted/open**	0	WEC SA-1, GE 12SLV/12NGV/12CEH, ASCO 214B
	trip	spurious	0	WEC SA-1
	coil	**burnt**	3, 4	GE HEA/HFA/IJS
	contact	**high resistance**	1	GE HEA/HFA/NGV/12IFC
	contact	Shorted to GND	2	ITE Gould 27N
	Contact, linkage	**sticking**	0	WEC 666D/CV-7, GE 12SFC

* Bold items are the predominant relay failure modes based on the number of relay failures reported in the industry OE and NRC ADAMS databases and the number of relay models affected.

1. None known
2. Increasing closed contact resistance
3. Decreasing open contact resistance or resistance to ground
4. Visible degradation
5. Decreasing coil winding resistance
6. Increasing temperature or thermographic indication
7. Increasing set point drift

Table 7-2
Commonly reported relay failures for solid state relays

Function or Application	Relay Failed Subcomponent*	Failure Mechanism*	Precursor	Models with Failure
Control/Timing/ Aux	Input	Capacitor fail	0	Agastat ETR/E7102
	electronics	Timing drift	6	WECEC SBF, ABB 211T
Protective	Input	blown cap or Zener diode	0	GE GEMAC/12SGC
	output	Contact mis-operation	1, 2	NONE FOUND

* Bold items are the predominant relay failure modes based on the number of relay failures reported in the industry OE and NRC ADAMS databases and the number of relay models affected.

1. None known
2. Increasing closed contact resistance
3. Decreasing open contact resistance or resistance to ground
4. Visible degradation
5. Decreasing coil winding resistance
6. Increasing temperature or thermographic indication
7. Increasing set point drift

Table 7-3
Commonly reported relay failures for digital relays

Function or Application	Relay Failed Subcomponent*	Failure Mechanism*	Precursor	Models with failure
Timing	Input	EMI functional disruption	0	ATC 365
		board short	0	C-H 423T
	output	Contact mis-operation	1, 2	NONE FOUND
Protective	Input	drift	6	NONE FOUND
	control	**chip or cap failed**	0	ABB 59N, Basler BE4,
	output	Contact mis-operation	1, 2	NONE FOUND

* Bold items are the predominant relay failure modes based on the number of relay failures reported in the industry OE and NRC ADAMS databases and the number of relay models affected.

1. None known
2. Increasing closed contact resistance
3. Decreasing open contact resistance or resistance to ground
4. Visible degradation
5. Decreasing coil winding resistance
6. Increasing temperature or thermographic indication
7. Increasing set point drift

Description of Failure Modes

Contact Failure Modes

Relay contacts are required to open and close to create or interrupt circuit current flow. Contact failure modes are based on whether the contacts can open or close as required, and whether the current flows or interrupts when the contacts change state. The following modes were identified:

- **High contact resistance:** Contacts may close, but still not effectively create an acceptable current path due to the high resistance of the film, usually due to non-conductive films (oxidation or polymer off-gassing materials). This is a common failure mode.
- **Contacts inadequately change state:** Contacts may be directed to open and interrupt the circuit by the coil, but are unable to do so because of electrical shorting across open contacts or by contact surfaces that have become welded together. Contacts that stick closed or short across open contacts are uncommon failure modes.
- **Contacts fail to change state:** Contacts may not change state as demanded by the coil due to mechanical sticking of the contact linkages or by the plunger interfering with the coil core inner diameter due to warpage lubricant degradation, misalignment, or foreign materials. This is a common failure mode.

Coil Failure Modes

Relay coils, especially on electromagnetic coil models, usually operate at the highest temperature of any relay subcomponent, and this elevated temperature accelerates aging of the organic material insulation. When a coil is intended for momentary energization but is subjected to continuous energization, the coil may overheat. The coils are wound with magnet wire (enamel over copper), which must be interfaced to the relay terminals or pins using a connection scheme that may involve crimps or soldering. The coil failure modes identified are as follows:

- **Coil overheating/burning:** Coil overheating and burning may occur when a momentary duty coil is continuously energized (improperly) or when elevated temperature over extended time degrades the coil insulation. This can also occur due to relay installation configurations in which the relays in an enclosure are clustered together such that there is insufficient means for coil heat dissipation. Degradation of the coil winding insulation may result in turn-to-turn shorts, which lower the winding resistance of the coil and increase the current flow through the coil at the given applied voltage. These shorts can lead to catastrophic failure of a coil. This is the most common failure mode of relays identified in the industry databases.
- **Coil opening:** Coil opening may occur because of heat buildup damaging the insulation and causing a hot spot that damages the copper of the magnet wire. It can also occur when the coil wire connections corrode or suffer mechanical damage. Corrosion at the connection between the relay coil magnet wire and internal solder is common among certain models of relays, as shown in Table 7-1, due to dissimilar metal contact or corrosive solder flux.

Electronics Failure Modes

Electronic components, such as capacitors, transistors, Zener diodes, varistors, and integrated circuits (ICs), are used in SS relays, digital relays, and time delay modules for EM relays. These components support relay status and timing controls and are susceptible to elevated temperature and voltage/current spikes. Digital relays are also susceptible to EMI effects. Identified failure modes for electronic components in relays were:

- **Subcomponent failures:** Electronic subcomponent failures are somewhat uncommon and tend to occur on a random basis, with the exception of electrolytic capacitors that have a failure mode related to aging. The team noted EMI-induced failures on a few isolated digital relays as a part of this project.

Miscellaneous Failure Mechanisms

Certain relay models have unusual failure modes, such as internal electrical shorts resulting from the development of metallic whiskers (tin or zinc) that form between conductive surfaces and create a potential short circuit current path. Another miscellaneous failure mode is vibration sensitivity, which normally induces mechanical wear. Each of these is discussed further below.

- **Tin whiskers:** Whisker growth causes internal electrical shorts inside certain relays. While more prevalent in relays that feature tin-plated contacts or high-tin solders, other factors such as temperature, humidity, applied voltage, etc., may also contribute to whisker growth. The exact mechanism for this occurrence is not well understood and is not limited to tin, but can include zinc, gold, and silver. This failure mechanism is common for the MidTex 156 relay model, but rare in others. In fact, the team identified only two such failures in the industry OE in the last ten years.
- **Vibration/wear related:** Certain relay designs are susceptible to specialized wear mechanisms that are associated with relay operation in environments with significant vibration during relay service life. The wear mechanism involves the wear of the coil plunger that translates within the coil core inside diameter, fretting against the edge of the coil core. This creates a notch in the plunger surface, which can then act as a sticking point for the plunger, especially as the notch grows with additional vibration. The notch can interfere or even prohibit the contact movement. A contributing factor is that the specific susceptible relay designs feature gravity return contacts/plunger, and so do not have a spring force to create a stabilizing factor. Applications for relays in which there is significant vibration are uncommon and mainly relegated to skid-mounted equipment applications. This is not a common failure mode.

8

RECOMMENDED STRATEGIES TO MITIGATE FAILURES

Strategies for managing relay health first involve identifying the failure modes that threaten the target relay population. Once that task has been completed, the failure modes that have the highest significance with respect to plant safety and power production should be identified. To provide an objective approach, it is assumed that no specific make or model of relay is more significant than another. This can be adjusted as appropriate for each individual plant or application [12, 13].

The next consideration is to determine which of the identified failure modes are predictable based on the factors that initiate and contribute to their occurrence. For example, elevated service temperature conditions, configurations involving tight spacing between relays causing excessive heat rise, continuously energized relay coils (especially in relays designed for limited energization), coil and contact loadings that may have voltage or current spikes, and relays subject to continuous high vibration levels are all known factors. Some of these failure modes are predictable and produce trends, but some are not.

Predictable vs. Unpredictable Failure Modes

Time-temperature degradation of organic materials is a well-known mechanism that degrades organic materials at various rates based on temperature. This phenomenon is well understood and modeled via Arrhenius theory. Degradation of the material corresponds to degradation of the material’s ability to perform its required function in supporting relay operation. Application of the Arrhenius theory for a coil wire/insulation is an example of a predictable failure mode, especially if operating history is used as a source of data on failures.

Organic material degradation is the cause of most coil failures involving burnout and shorting. Other material aging failure modes include coil encapsulant cracking, relay internal subcomponents warping and embrittlement, and to some degree, contact oxidation/contamination, which can foul contact surfaces. Such contact fouling is a normal expected occurrence in many relay designs, is highly dependent on the contact surface materials and the electrical loading conditions, and does not typically signal end of relay life if the contacts are accessible. It does however require the performance of a preventive maintenance activity such as contact burnishing, where feasible.

Mechanical wear is also potentially predictable, as cycling a relay containing EM contacts can often be used to predict cycle life at any given electrical loading. However, cycling is not a significant failure mechanism for EM relays, as they are normally designed for significantly more cycles than would typically be seen in many years of relay service. An additional stressor is normally required to experience cycle aging for EM relays, such as electrical conditions outside the rated relay specifications or misapplication of the relay.

An example of an unpredictable failure mode is the growth of tin whiskers. Tin whisker growth is not a predictable failure mode, at least using present methods, and a definitive list of causal factors has not yet been fully derived. Similarly, failure of electronics due to voltage/current spikes is not age related.

Set point drift can be an age-related phenomenon but is difficult to predict and the mechanisms differ between relay designs. Change in the pneumatic performance of pneumatic relays is a common mechanism, whereas drift due to electronic component changes is usually of a smaller magnitude.

The project did not include in this analysis relay failure modes that have resulted from human errors such as incorrect wiring, applications that are outside relay specifications or ratings, handling damage, inappropriate storage, and similar errors. This analysis assumes that relays are properly specified, installed, and maintained.

Mitigating Strategies: Managing Failure Modes

For relays with failure mechanisms that are amenable to predictive assessment of their condition via material degradation analysis, condition monitoring (CM), and/or industry operating experience, the key is to determine if the relay models are being used in a way representative of the rest of the industry. If so, industry experience can be a primary input. If the relay has calculable (Arrhenius) data including critical organic material activation energies, ambient service temperature, component and cabinet heat rises, duty cycle, and material critical characteristics for supporting relay function, then predicting relay failure may be possible. However, if the Arrhenius calculations yield a prediction in excess of that indicated by the industry OE, then the industry OE value should be used.

The relay condition may exhibit trends via monitoring and trending relay functional performance plus vigilant monitoring of the key relay materials for any signs of degradation. An example of functional testing would include: contact resistance, pull-in/drop-out voltage, and coil winding resistance. In general, the most useful relay failure predictors are the industry operating experience databases, and should include the specific failure history of other plant relays of the same make and model.

Relay failure modes are more challenging when they are time-dependent and comingled with time-independent failure mechanisms, such as contact oxidation, tin whisker growth, or electronic component failure due to electrical spikes or EMI exposure. In such cases, the presence of any age-related contribution involved in the failure must be determined. For example, electrolytic capacitors, including board level capacitors, age, and their aging is time-dependent. However, this is not the case for many other board-level electronic components. ICs have an unknown expected life because most IC designs do not yet have a well- documented failure history in nuclear applications and are not considered age-sensitive. For the most part, ICs are not documented as age-sensitive.

Table 8-1 evaluates the failure modes identified as a part of this project and shows which specific ones are judged to be age-related or potentially age-related. The table shows mitigation strategies for these failure modes, along with some models that could be vulnerable to the identified failure mode and possibly amenable to one of the mitigation strategies.

Table 8-1
Failure mode type vs. mitigation strategies

Failure Mode	Predictable?	Mitigation Strategies[1]	Some Applicable Relay Models[2]
Coil Burnt, Open, Shorted	Yes	Trend coil, winding and insulation resistance for given model	GE HEA, GE CR120A/B
Coil Encapsulant Damage	Yes	Evaluate installed configuration to ensure proper heat dissipation Visually inspect relays periodically	WEC AR & ARD
Setting Drift	Yes	Trend drift on each relay	Agastat E7000
Contact Sticking	Possibly	If sticking is aging related, use OE or OEM recommended service life to establish replacement interval	WEC ARD, GE CR120A/B
Contacts High Resistance	Possibly	Determine if application is appropriate for relay model Clean contacts electrically or mechanically	WEC ARD, GE CR120A/B, GE HEA/HFA
Vibration Damage	Possibly	Inspect for visible signs of vibration damage	Sylvania Clark 5U12
Open Contacts Shorting	No	Check contact adjustment	ITE Gould 27N, GE HFA
Mechanism Sticking	No	Visual inspection for foreign material, warpage, adhesion	GE HEA & HFA, WEC ARD
IC, Zener, Varistor, Transistor, Resistor, Capacitor Failure	Possibly	None known	Various Protective Relays, C-H D26, CR120 w/timer
EMI Induced Failure	No	Determine EMI environment at relay application Corrective design required if possibility of repeat EMI event	ATC 365TC
Tin Whiskers Shorting	No	Replace with a different relay design if failure rate unacceptable	MidTex 156

Notes:
1. Not all mitigation strategies are applicable to all relay models, and may not be applicable to the example relay models shown in the right-most column.
2. The relay models shown in the right-most column are not intended to be an exhaustive list but only some example models

In order to develop a strategy to minimize the occurrence and impact of relay failures, relay failure modes should be a main driving factor. Relay failures include both age-related (time-dependent) mechanisms and also failures that are unpredictable due to subtle variations in relay tolerances and manufacturing differences between members of a manufacturer/model number.

For age-related or time-based predictable failure mechanisms, the strategy is simply to determine which parameter is driving the failure mechanism (e.g., thermal aging, radiation aging, cycling, electrical loading, vibration, radiation, etc.) and provide a reasonably conservative estimate of the capacity of that relay model with respect to that mechanism. For relays that are limited by thermal aging (following the Arrhenius aging model), material expected life analyses may provide a good estimate of the relay life. For relays with other aging mechanisms, such as wear aging, the analysis may be a bit more complicated, as combined effects may be responsible for aging. Number of cycles, contact loading, duty cycle, etc., are all factors. In this case, trending contact and coil resistance or pull-in and drop-out voltage are examples of CM methods that can be used to predict relay failure.

Performing an Arrhenius relay life calculation can be time consuming and involves a number of environmental inputs:

- The room ambient temperature plus contributions from the cabinet heat rise and the local self-generated heat rise from the relay coil itself
- Electrical service factors (e.g., contact loading, actual coil applied voltage especially in dc applications, and relay coil energization fraction)
- Material identification (e.g., type of polymer and its application, metallic, and ceramics are largely not age sensitive)
- Assignment of activation for that material application

Calculation of material expected life using Arrhenius methodology is typically considered to be a conservative means of calculating end of life, and may actually result in a determination that the relay is at its end of life when it may have considerable service life remaining.

For relays with age/time-related failures, CM measures are useful if they are able to measure the performance of relay in a manner that exhibits trends. The applicability of CM to demonstrate acceptable relay condition is based on the assumption that any CM activities can accurately model the prevalent relay failure modes in a quantifiable manner that enables the plant engineer to identify a decline in the relay performance using that parameter. Pass/fail tests are not particularly because no input provides trends up to the point of failure (constituting a “failure” result), which is too late to prevent the in-service relay failure. However, pass/fail tests remain useful in making a return-to-service determination. Timing relay drift measurement trending is an example. Contact and coil resistance are also potentially useful, but tend to vary with various external effects, such as the measurement equipment used, the temperature at which the test is conducted, how recently the relay was cycled, etc. For this reason, the availability of a large sample size of similar relays can provide a good basis for estimating the end of lifetime for relays that are subject to aging-related failure modes.

For relays with prevalent failure modes that are not directly attributable to a known aging/time-based failure mechanism, the parameter(s) that establish relay life capacity are more difficult to isolate. Expected relay service life may also be based on demonstrated service history both at the specific plant and throughout the industry. This is one way of approaching the relay expected life issue via integration of numerous failure modes and parameters. While not a perfect means of eliminating in-service failures, the statistical base of a large number of nuclear industry relays can be a good basis for predicting when a relay is approaching the end of its life. Relay failure due to electronic component failure is an example of this mechanism. For this example, a decision must be made based on a set of factors that include:

- Frequency of failures of that relay in that specific application in the plant, as well as in the industry
- Impact of a random failure of that relay in a design basis event scenario
- Design modifications to replace the relays subject to random failure with a more predictable design if the above factors warrant this change

9

SUMMARY AND CONCLUSIONS

This project leveraged the results of an industry survey detailed in a previous EPRI report [1] that established the contribution of various relay series to the population of control, timing, auxiliary, and protective relays in the industry (see Table 5-1). The most common relay series identified in that survey determined the focus of this project's search of industry OE. The results of that search demonstrate a significant decline in the number of relay failures reported since 2010 (see Figure 6-1).

The team also searched the NRC ADAMS database for relay failures. Appendix D summarizes the results of that search. The NRC documents show neither a significant increase nor decline since 2000 (see Figure 6-4). This does not contradict the decline exhibited in the industry OE data because the NRC documents address relays issues of a different degree and nature than the OE data.

The project team then analyzed the results of both searches to identify common relay failures and identify their mechanisms and the precursors of those mechanisms. Tables 7-1, 7-2, and 7-3 summarize these common failure mechanisms and their precursors.

The team addressed protective relays as a specific subset of the OE data, because previous reports had focused primarily on control, timing, and auxiliary relays. The analysis demonstrates that protective relay failures represent a small subset of reported failures (see Figure 6-3). However, due to the critical role of protective relays, this finding does not justify reductions in their PM. The analysis also demonstrates that protective relay failures are distributed over a large number of relay series (see Figure 6-2).

The team also sorted failure modes according to whether they are predictable (i.e., age-related and exhibit trends) or not (i.e., are influenced by external factors and/or that are not time-dependent). Those modes that are not age-dependent are more difficult to predict, as external factors are typically unpredictable, or the failure mechanism is not currently well understood. Table 8-1 summarizes the failure modes identified during the OE review, their ability to be trended, and possible mitigation strategies.

This project identified no "new" failure modes. The failure modes identified were consistent with those identified in the EPRI PM Basis Database (PMBD) for relays. Appendix C summarizes the PMBD for electromechanical and solid state relays. This report provides additional information about the chemical and physical mechanisms that affect specific subcomponents, as well as some model susceptibility. The model susceptibility factors (see Table 8-1) are based on design features, not necessarily that the particular relay model is more or less subject to failure.

Industry OE databases contain a wealth of information on plant events and do an excellent job of documenting the impact of the equipment issue on the plant. For this reason, existing OE reports are well designed to track trends in industry issues and derive statistics on component failures (as shown in Figure 6-1). Furthermore, due to the large number of the reports contained in the databases, a good and comprehensive representation of the relay failures that have occurred in the U.S. nuclear industry was available and compiled.

However, the reports reviewed in this project typically did not contain a root or apparent cause of failure. The reports typically stated that a relay failed, and sometimes indicated how it failed, but seldom indicated why it failed. Furthermore, key data related to service conditions and duty cycle were usually lacking. The correlation of failure mode, failure cause, and the service conditions and duty cycle that potentially contribute to degradation, is essential to developing a deeper understanding of relay failures and how to predict or prevent them.

Based on the reports reviewed, better reporting of relay failures is needed. Appendix B provides a short form for reporting relay failures. Use of this form would provide the necessary data to better predict or mitigate those failures.

The relay failures reports in the OE databases that did provide failure information were varied in modes and causes, so that no one mitigation strategy or strategies would result in a significant reduction of failures. Since the identified failure mechanisms and modes were consistent with those found in the EPRI PMBD, addressing a relay PM program with the strategies in that database – particularly when using the vulnerability tool included in the PMBD – would provide the best PM strategy to mitigate failures when combined with operating experience within an individual plant.

10

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A

RELAY SCOPE BREAKDOWN IEEE DESIGNATIONS

Table A-1
Control and timing relay group

Device Codes	Control and Timing Relay	Protective
3.1.2 Device number 2—time-delay starting or closing relay	**X**	
3.1.3 Device number 3—checking or interlocking relay	**X**	
3.1.5 Device number 5—stopping device	**X**	
3.1.7 Device number 7—rate-of-change relay	**X**	
3.1.30 Device number 30—annunciator relay	**X**	
3.1.42 Device number 42—running circuit breaker	**X**	
3.1.44 Device number 44—unit sequence starting relay	**X**	
3.1.48 Device number 48—incomplete sequence relay	**X**	
3.1.49 Device number 49—machine or transformer thermal relay	**X**	
3.1.53 Device number 53—exciter or dc generator relay	**X**	
3.1.56 Device number 56—field application relay	**X**	
3.1.58 Device number 58—rectification failure relay	**X**	
3.1.62 Device number 62—time-delay stopping or opening relay	**X**	
3.1.69 Device number 69—permissive control device	**X**	
3.1.74 Device number 74—alarm relay	**X**	
3.1.77 Device number 77—telemetering device	**X**	
3.1.79 Device number 79—reclosing relay	**X**	
3.1.82 Device number 82—dc load-measuring reclosing relay	**X**	
3.1.83 Device number 83—automatic selective control or transfer relay	**X**	
3.1.85 Device number 85—carrier or pilot-wire relay	**X**	
3.1.93 Device number 93—field-changing contactor	**X**	
3.1.94 Device number 94—tripping or trip-free relay	**X**	

Table A-2
Protective relay group

Device Codes	Control and Timing Relay	Protective
3.1.21 Device number 21—distance relay		**X**
3.1.24 Device number 24—volts per hertz relay		**X**
3.1.25 Device number 25—synchronizing or synchronism-check relay		**X**
3.1.27 Device number 27—undervoltage relay		**X**
3.1.32 Device number 32—directional power relay		**X**
3.1.37 Device number 37—undercurrent or underpower relay		**X**
3.1.40 Device number 40—field relay		**X**
3.1.46 Device number 46—reverse-phase or phase-balance current relay		**X**
3.1.47 Device number 47—phase-sequence or phase-balance voltage relay		**X**
3.1.50 Device number 50—instantaneous overcurrent relay		**X**
3.1.51 Device number 51—ac time overcurrent relay		**X**
3.1.55 Device number 55—power factor relay		**X**
3.1.59 Device number 59—overvoltage relay		**X**
3.1.60 Device number 60—voltage or current balance relay		**X**
3.1.63 Device number 63—pressure switch		**X**
3.1.64 Device number 64—ground detector relay		**X**
3.1.67 Device number 67—ac directional overcurrent relay		**X**
3.1.68 Device number 68—blocking or “out-of-step” relay		**X**
3.1.76 Device number 76—dc overcurrent relay		**X**
3.1.78 Device number 78—phase-angle measuring relay		**X**
3.1.81 Device number 81—frequency relay		**X**
3.1.86 Device number 86—lockout relay		**X**
3.1.87 Device number 87—differential protective relay		**X**
3.1.91 Device number 91—voltage directional relay		**X**
3.1.92 Device number 92—voltage and power directional relay		**X**

B

RELAY FAILURE REPORT TEMPLATE

Utility, Plant, and Unit:	
Date of Failure or Misoperation:	
Relay Manufacturer:	
Relay Model:	
Relay Serial #:	
Equipment ID:	
Relay Function (Control/Protective/etc.):	
Component Class (critical/non-critical):	
Quality Class (safety, non-safety):	
Location within Plant:	
Service Conditions1 (Severe or Mild):	
Duty Cycle2 (High or Low):	
Time in Service / Actual Age:	
Subcomponent which Failed:	
Description or Mode of Failure:	
Work Order #:	
Root/Apparent/Direct Cause Report #:	
OE Report #:	
Corrective Action:	
Contact Name:	
Contact Email/Phone:	
Additional Comments:	

Notes:

1. Service conditions include: temperature, humidity, radiation, vibration, environmental contaminants, energized/de-energized, etc. Describe service conditions in Additional Comments.
2. Normally de-energized relays not operated for majority of their design life should be categorized as “high.”

C

EPRI PREVENTIVE MAINTENANCE BASIS DATABASE (PMBD)

Table C-1
EPRI PMBD for electromechanical relays

	Subcomponent	Description	Calibration	Functional Testing	Scheduled Replacement	Thermography
Control	coil	insulation degradation/shorted turns	yes	yes	yes	yes
	contact	contamination	yes	yes	yes	yes
	contact	loose fasteners	yes	yes	yes	yes
	contact	misalignment	yes	yes	yes	yes
	contact	oxidation	yes	yes	yes	yes
	contact	oxidation or corrosion	yes	yes	yes	yes
	contact	pitted, stuck, bound, or welded	yes	yes	yes	yes
	mechanical assembly	bound	yes	yes	yes	
	mechanical assembly	failed	yes	yes	yes	
	mechanical assembly	spring relaxation	yes	yes	yes	yes
	relay base	contamination	yes	yes	yes	yes
	relay base	cracked, damaged, degraded	yes	yes	yes	
	relay base	misaligned, loose	yes	yes	yes	
	wiring and terminations	loose	yes	yes	yes	yes
	wiring and terminations	stripped or cracked	yes	yes	yes	

Table C-1 (continued)
EPRI PMBD for electromechanical relays

	Subcomponent	Description	Calibration	Functional Testing	Scheduled Replacement	Thermography
Protective	coil	insulation degradation	yes			
	contact	contamination	yes		yes	
	contact	loose fasteners	yes		yes	
	contact	misalignment	yes		yes	
	contact	oxidation or corrosion	yes		yes	
	contact	pitted, stuck, bound, or welded	yes		yes	
	cup type assembly	drift from binding	yes			
	cup type assembly	drift from cup slippage	yes			
	electrolytic capacitors	drift from dielectric breakdown	yes		yes	
	electrolytic capacitors	leakage, short circuit or open circuit	yes		yes	
	hinge type assembly	binding	yes		yes	
	induction disk assembly	binding	yes		yes	
	induction disk assembly	distorted spring	yes		yes	
	induction disk assembly	drift	yes		yes	
	plunger type assembly	binding	yes		yes	
	wiring	insulation degradation	yes		yes	
	wiring	wiring errors	yes		yes	

Table C-2
EPRI PMBD for solid state relays

	Subcomponent	Description	Calibration	Functional Testing	Scheduled Replacement
Control	SS components and PCB	corroded edge connectors		yes	yes
	SS components and PCB	drift		yes	yes
	SS components and PCB	failed electronic components esp. diodes			yes
	wiring and terminations	loose			yes
	wiring and terminations	stripped or cracked			yes
	Sub-component	**Description**	**Test and Calibration**	**Functional Testing**	**Scheduled Replacement**
Protective	coils	insulation degradation	yes		yes
	contacts	contamination	yes		yes
	contacts	loose fasteners	yes		yes
	contacts	misalignment	yes		yes
	contacts	oxidation or corrosion	yes		yes
	contacts	pitted, stuck, bound or welded	yes		yes
	electrolytic capacitors	drift from dielectric breakdown	yes		yes
	electrolytic capacitors	leakage, short or open circuit	yes		yes
	SS components and PCB	corroded edge connectors	yes		yes
	SS components and PCB	drift	yes		yes
	SS components and PCB	failed electronic component	yes		
	SS components and PCB	failed electronic component, esp. trim pots and electrolytic capacitors	yes		
	wiring	insulation degradation	yes		yes
	wiring	wiring errors	yes		yes

D

NRC ADAMS DATABASE

Table D-1
NRC ADAMS Database on relay failures

Report or Document	Incident/Failure Date	Manufacturer	Model/Part #	Subcomponent (coil, contact, socket, etc.)	Failure or Degradation Mode	Notes
50.55 report NCXXR 700 and 714	1979	Crydon	A1202-1 SSR	Test method	SS dielectric short	Failure of 10% of relays due to test voltage applied
Part 21	2010	Westinghouse C-H	ARD660UR	Coil core	Binding	Mfr defect due to process change
IEB 76-02	1973 and 1976	GE	HFA HGA HKA HMA	Coil bobbin and wire	Corrosion of mag wire	Coil design changed to "Centru" series coils, Temp fix: Lexan bobbin replaced Nylon
IEN 84-02	1984	GE	HFA	Coil bobbin and wire	Corrosion of mag wire	Lexan replacement bobbin also causes coil shorting on "several" relays
Part 21	2014	Allen Bradley	700RTC	Coil winding	Corrosion of mag wire	"Several" relays failed
IEZB 80-19	1980	Clare	HG2X-1011	Contacts	Contacts not opening on demand	No data on actual failure cause is available for 31 failures
GEL 2341	1970	GE	Multiple	Contact carrier	Sticking due to paint and lube adhesion	General condition, no specifics, "numerous" failures
Part 21 NRC Event48223	2012	Westinghouse C-H	ARD660UR	Coil bobbin	Sticking due to paint and lube adhesion	Change in MFR process caused issue on 1 relay

Table D-1 (continued)
NRC ADAMS Database on relay failures

Report or Document	Incident/Failure Date	Manufacturer	Model/Part #	Subcomponent (coil, contact, socket, etc.)	Failure or Degradation Mode	Notes
LER2000-15	2000	Struthers-Dunn	219BBBX222NE	Contact armature bearing capsule	PVC bearing degraded	No OPEX at Monticello or Hope Creek incident (below) would have been noted. 10 failures.
LER 97-01	1997	Struthers-Dunn	219BBBX222NE	Contact armature bearing capsule	PVC bearing degraded	"Several" relays showed some notching.
IEN 94-20	1994	ATC	365A	Electronics	EMC induced failure	1 failure
IE Circular79-20	1979	GTE Sylvania	5U12-11-AC	Armature core	Binds doe to vibration notching	1 failure
IEN 94-02	1994	Potter Brumfield	MDR	Rotary mechanism	Binding due to corrosion and outgassing	Over 60 failures
Part 21	2011	GE	CR120B	Armature core	Failed to drop out	6 failures of NEW relays
NCV 2006-003-01	2016	GE	HEA 86	Set point drift	Set point drift	WCNS extended PM to 6 years, resulting in too much drift.
IEN 92-27	1992	ITE-Gould	J10 & J12	All, heat rise	Internals	7 failures due to high heat rise and possibly to shoulder-shoulder mounting

Table D-1 (continued)
NRC ADAMS Database on relay failures

Report or Document	Incident/Failure Date	Manufacturer	Model/Part #	Subcomponent (coil, contact, socket, etc.)	Failure or Degradation Mode	Notes
IEN 91-45	1991	Westinghouse	NBFD	coil	open winding	72 failures, possibly to shoulder-shoulder mounting
Event 49911 Part 21	2014	Allen Bradley	700RTC	coil	Chlorine corrosion of mag wire	1 failure
IEB 79-25	1979	Westinghouse	BFD	Armature	Sticking due to softened epoxy adhesive	2 failures
ML053130070	UNK	Westinghouse	AR	contacts	Failed to close	No root cause given, 1 failure
Part 21	1993	GE-Hitachi	SS Relays on RM cards	SS mech	Set point drift	Attributed to over aging past 10-year life
LER 95-02-00	1995	UNK	Protective relay	Capacitor	Capacitor aging	1 failure
1982 Event Report	1982	UNK	Protective relay	Blown Fuse in relay circuit	Not Relay issue	1 failure
Part 21	2015	ABB	50H 58 Overload Protective relay	Could not bench calibrate	Unknown	1 failure
Part 21	2016	Struthers-Dunn	255XCXPFHSC 125V	coil to lead attach	connection failed	2 failures
Part 21	1978	GE	CR120A	coil	coil overheat	1 failure
Part 21	2004	GE	HMA	coil	mag wire corrosion	4 failures

Table D-1 (continued)
NRC ADAMS Database on relay failures

Report or Document	Incident/Failure Date	Manufacturer	Model/Part #	Subcomponent (coil, contact, socket, etc.)	Failure or Degradation Mode	Notes
Part 21	2015	Struthers-Dunn	219BBX200	contacts	glass fibers embedded in contact	1 failure
Event 40364	2003	MidTex	156-14D200	coil	mag wire corrosion	1 failure
LER 2009-03-01	2009	Agastat	E7024PN	Various	Poor mfg, foreign materials	8 failures
n/a	2000	Westinghouse	NBFD	Dimensions	Fit	New relays are wider which eliminates required cooling path causing overheating
LER-00-012	2000	GE	CR120A	coil	Open coil	1 failure, attributed to aging
IEN 92-04	1992	Potter Brumfield	MDR	Rotary mechanism	Binding due to corrosion and outgassing	Due to off gassing and PVC degradation corrosion
LER 13-01-00	2013	Agastat	FGPDC750	coil	mag wire corrosion	1 failure, attributed to aging
LER 50-21	2000	Theta	0FA2405-2	PC board pins	Pin broke	1 relay, no root cause
IEN 94-78	1994	ABB/ Westinghouse	CO-7, CO-9, KC-4, COM-5, CV-2 and CVE	coil wire	coil wire corrosion due to PVC breakdown	"several" failures

Table D-1 (continued)
NRC ADAMS Database on relay failures

Report or Document	Incident/Failure Date	Manufacturer	Model/Part #	Subcomponent (coil, contact, socket, etc.)	Failure or Degradation Mode	Notes
IEN 84-20	1984	Agastat and GTE Sylvania	GP/EGP and Sylvania AC	coil	coil open due to high Heat rise	Under proposed redesign (Agastat)
Event 52913	2017	GE	HMA124A2	Mfr issue	Misassembled	2 relays found misassembled
IEB 77-02	1977	Westinghouse	AR w/latch	Latch	Bad tolerances	several relays found bad due to tolerance stack up
IEB 78-06	1978	C-H	D23 MRD	contacts	Incorrect gap	Gap too small, adjustment or manufacture issue
LER 03-05-00	2003	MidTex	156-14D200	coil	mag wire corrosion	several failures
NCV 2003-2007	2003-2007	Allen Bradley	700DC	coil & contacts	Coils overheated, contacts welded	4 failures
Spec Rept 85-02	1985	UNK	UNK timing relay	coil	Open	1 relay, no root cause
LER 2016-01-01	2016	Agastat	ETR	coil	Open	1 relay, no root cause, but attributed to "normal aging"
Part 21	2016	Struthers-Dunn	B255XCXPFHS C125V	coil	Open	1 relay, potential defect could cause coil shorting
Part 21	2016	GE	HEA	contacts	Design issue	Qualified with Ag contacts, supplied with Sn plated contacts with higher CR

Table D-1 (continued)
NRC ADAMS Database on relay failures

Report or Document	Incident/Failure Date	Manufacturer	Model/Part #	Subcomponent (coil, contact, socket, etc.)	Failure or Degradation Mode	Notes
IEN 88-98	1988	Various	Various	contacts	Hi CR from oxide film	No specifics, could have been low power measurements.
Part 21	2016	Tyco Agastat	ETR	Electronics	Capacitor on PC board	Capacitor installed backwards on PC board of 4 relays
IEN 91-81	1991	Westinghouse	SA-1 protective relay	Electronics	Zener diode on PC board	Zener diode failed (volt spike?) on 1 relay
LER 88-017-00	1988	GE	CR120A	contact carrier	Melted/burnt plastic	1 failure, relay replaced with same model but different plastic contact carrier and is OK
LER 88-02-00	1988	Unknown	Unknown	Coil housing	bent/damaged	1 failure of lockout function due to relay coil housing being bent

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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