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Final Report

Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE)

Volume 1:

Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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NOTE

ABSTRACT

Volume 1 of this report documents the results of a Phenomena Identification and Ranking Table (PIRT) exercise that was undertaken on fire-induced electrical circuit failures that may occur in nuclear power plants when cables are damaged by fires. Volume 2 documents the PRA expert elicitation results and will include the best estimate conditional probabilities of hot short-induced spurious operations of control circuits, given fire damage to associated cables. This program was sponsored by the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) under the NRC-RES/EPRI Memorandum of Understanding (MOU) collaborative research agreement. The electrical expert PIRT panel (herein referred to as the PIRT panel) was comprised of a group of experts sponsored equally by NRC and EPRI. Staff from Brookhaven National Laboratory (BNL) facilitated the efforts of the PIRT panel.

The objective of this PIRT was to identify phenomena that can affect the fire-induced failure modes of electrical circuits after cables are damaged by fire. The PIRT panel used the results from recent fire tests performed by the Nuclear Energy Institute (NEI), EPRI and NRC, identifying and ranking the parameters that can influence the hot short induced failure modes of electrical control circuits. Using these influencing parameters, the results of cable-fire tests, expert judgment, and operating experience, the PIRT panel developed circuit configurations vulnerable to hot short induced circuit failure modes that can cause the spurious operation of certain end devices. In addition to completing the PIRT exercise on control circuits, the PIRT panel reached technical consensus on the majority of issues in analyzing fire protection circuits such as power-cabling consequential hot shorts, open circuits on the secondary of current transformers, and multiple high-impedance faults. The PIRT panel noted the lack of data on instrument circuits, including process monitoring indication, needed to support a structured evaluation of the influencing phenomena. The panel identified key areas for future research to advance the current knowledge base.

CONTENTS

FIGURES

TABLES

REPORT SUMMARY

Volume 1 of this report documents the results of a Phenomena Identification and Ranking Table (PIRT) exercise that was performed on fire-induced electrical circuit failures that may occur in nuclear power plants (NPPs) as a result of fire damage to cables. Volume 2 documents the findings from the elicitations of a risk assessment expert panel, and will include the best estimated conditional probabilities of hot short-induced spurious operations of control circuits, given that a fire has damaged the associated cables. This program was sponsored by the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) and by the Electric Power Research Institute (EPRI) under the NRC-RES/EPRI Memorandum of Understanding (MOU) collaborative research agreement. The electrical expert PIRT panel (herein referred to as the PIRT panel) was comprised of a group of electrical and fire protection experts half sponsored by the NRC and half by the EPRI. Staff from Brookhaven National Laboratory (BNL) facilitated the work of the PIRT panel.

The PIRT process affords a systematic method of obtaining information from experts in a technical area by generating lists of phenomena ranked systematically in tables. Under the PIRT process, "phenomena" can refer to a particular reactor condition, a physical- or engineering-approximation, a safety-related component or parameter, the importance of parameters on the likelihood of spurious operation of equipment, or anything else that might influence the chosen criteria. Usually, these phenomena are ranked using scoring criteria, consensus, or a combination of both to help determine the importance of an individual phenomenon. The ranking process supports identifying and prioritizing future research needs for a safety issue, or substantiates the regulatory decision-making process. Thus, the PIRT methodology, including the PIRT panel, brings into focus those phenomena that dominate an issue, while identifying all plausible effects so to demonstrate its completeness.

The objective of this PIRT exercise was to identify the phenomena (electrical circuit configurations) that can affect the circuit failure modes from fire-induced cable damage. Using the results from recent fire tests performed by the Nuclear Energy Institute (NEI)/EPRI in 2002 and the NRC/Sandia National Laboratories (SNL) (CAROLFIRE in 2008 and DESIREE-Fire in 2010), the electrical expert PIRT panel identified and ranked the parameters that could influence the hot short-induced spurious operations in electrical circuits. Utilizing these parameters, the findings from cable fire tests, expert judgment, and operating experience, the PIRT panel indentified and developed circuit configurations that would be vulnerable to hot short circuit failure modes of concern that can cause certain end devices to operate spuriously.

This PIRT investigated such fire-induced spurious operations of plant components, evaluating both alternating current (ac) and direct current (dc) types of circuits. The PIRT panel's focus encompassed three specific types of electrical circuits, i.e., power, control, and instrument circuits. Their primary emphasis was upon the control circuits (e.g., 120 VAC and 125 Vdc) because fire-induced damage of these types is considered to pose a higher risk to plant safety than does the other types of circuit. Accordingly, the majority of test data from industry, along with the NRC's tests, were related to low-voltage control circuits. Due to the limited test data available for instrument circuits, the PIRT could not undertake a complete parametric treatment of this type. Available failure modes for power circuits are well understood, except for a few unique cases. For certain types of power circuits (for example, three-phase power cables),

there were no available findings from specific testing by industry; therefore, the PIRT panel's technical recommendations rested upon their expert judgment involving engineering principles and physical configurations for power cables and power-cable installations. In other instances, such as the PIRT panel's considerations of open circuits in the secondary of current transformers (CTs), their recommendations were based upon available open-circuit test data, manufacturers' input, operating experience (nuclear and non-nuclear), and expert judgment.

A key, fundamental assumption made by the PIRT panel during their consideration of all of the phenomena was that the assessments of electrical circuit failure-modes *assumed that fire had damaged the cable(s) of concern*. In other words, the panel did not focus on parameters that influence the likelihood of cable damage from fire effects, such as ignition, fire growth, and fire intensity, nor on the likelihood of a fire occurring, but rather on the effects of circuit failure once cable damage from fire had occurred. The panel assumed the cables of interest are damaged to the point of insulation failure.

The PIRT panel ranked the following parameters "as having a" HIGH impact on the likelihood of hot short-induced spurious operations, and the duration of a spurious operation:

- <u>Spurious Operation</u>
    - Wiring Configuration (number of sources, target, ground/neutral and their locations)
    - Conductor Insulation Material Type [for inter-cable hot shorts (thermoset (TS) versus thermoplastic (TP))]
    - Grounding Configurations
        - Cable grounding configuration (e.g., ground or drain wire, shield wrap)
        - Armor Grounded versus Ungrounded Circuit (for grounded AC circuits) and Armored versus Unarmored (for ungrounded DC circuits)
        - Grounded versus Ungrounded Circuits (for inter-cable hot shorts)
    - Cable Routing/Raceway – Panel Wiring (ranked as important due to a lack of available test data and the belief that testing of this parameter is important)
    - Cable Raceway Fill – Bundles (The PIRT panel considered this important even though the panel ranked this medium).

- <u>Duration</u>
    - Fire Exposure Conditions
    - Time-Current Characteristics – fuses/breaker size
    - Wiring Configuration (number of sources, targets, ground/neutrals and their locations)
    - Cable Routing/Raceway – Panel Wiring
    - Cable Raceway Fill – Bundles (The PIRT panel considered important even though the PIRT panel ranked this medium)
    - Latching Circuit Design (e.g., motor operated valves) - This parameter is related to the specific circuit design, and not to any particular aspect of fire-induced circuit failure.

Taking all the above factors into consideration and using their expert judgment and experience, the PIRT panel identified thirteen different cases that represent control circuit cable configurations vulnerable to hot short-induced spurious operations. Based on this assessment, the PIRT panel presented several examples of cases that are currently used in NPPs and are considered in the post-fire safe-shutdown[1] and fire probabilistic risk assessment (Fire PRA) circuit analyses. As examples, this report offers an assessment of the types of failure modes possible for the 120 VAC and 125 VDC control circuit including both grounded and ungrounded circuit configurations, and the likelihood of such failures, given the various parameters considered to be of importance.

In addition to reviewing and evaluating the spurious operation of the control circuits and its duration, the PIRT panel provided their technical recommendations[2] on other aspects of fire-induced circuit failures associated with control and power circuits in the post-fire safe-shutdown circuit analyses. Specifically, the PIRT panel concluded the following:

- The spurious operation of a three-phase AC motor due to proper polarity hot shorts on three-phase power cabling is incredible.[3]
- The spurious operation of DC compound-wound motor due to proper polarity hot shorts in the motive/power cabling is incredible.
- The ignition of a secondary fire from an open circuited CT secondary circuit with a turns-ratio of 1200:5 or less is incredible.
- The guidance given in Nuclear Energy Institute, NEI 00-01, Rev. 2 (Ref. 13), Appendix B.1, can be applied safely to fire safe-shutdown methodologies throughout the plant in resolving concerns associated with Multiple High-Impedance Faults (MHIFs). (Note: Appendix B.1 of NEI 00-01, Rev. 2 offers a basis for concluding that MHIFs need not be considered provided there exists breaker coordination for any circuits damaged by the fire that should previously have been assessed for the effects of MHIFs and appropriate testing and maintenance is performed).
- The spurious operation likelihood reduction factor of “two” provided in the Fire Probabilistic Risk Assessment (Fire PRA) methods when a control power transformer (CPT) is the derived energy source for a circuit, does not accurately reflect the entirety of the test data; no credit should be taken in the Fire PRA for their use in a CPT-powered control AC circuit. (Note: The revised probability in Volume 2 of this NUREG/CR will be based on a composite of all testing undertaken, and, hence, the probability offered for using with both CPT and non-CPT circuits may be increased by a factor less than 2).
- Kapton® cable, a polyamide stable from -271 to +400 ^{o}C, should be treated as a thermoplastic (TP) material for assessment of circuit failures, including risk-informed applications, unless (1) the cable has been fully qualified against the requirements of the IEEE Std. 383 severe accident equipment qualification standard, in which case it may be treated as a thermoset (TS) cable, or (2) an alternate product/case specific basis can be established for the cable’s thermal damage limits (e.g., manufacturer or utility testing).

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[1] The term “safe-shutdown” is synonymous with “nuclear-safety capability assessment” for NFPA 805 plants.

[2] The PIRT panel recommendations do not represent NRC-accepted guidance or methods, unless specifically endorsed by the NRC via generic communication, regulatory guide(s) or some other means.

[3] Incredible as defined in Section 2.1.3 is, “The term “incredible” used in conjunction with the phenomenon of a fire-induced circuit failure, signifies the PIRT panel’s conclusion that the event cannot occur. In these cases, the PIRT panel could find no evidence of the phenomenon ever occurring, and there were no credible engineering principles or technical argument to support its happening during a fire. Any likelihood value assigned to these types of phenomena would have little meaning.”

- Spurious operation caused by shorting conductors through a surrogate ground path in ungrounded circuits as a result of fire induced damage, is a failure mode which occurred during the DESIREE-Fire testing and is referred to as “Ground Fault Equivalent Hot Short.” The probability of this failure mechanism with respect to cable-to-cable hot shorts is such that it warrants consideration for including in future testing programs and, subsequently, in analyzing post-fire safe-shutdown conditions.

Additionally, the PIRT panel recommended future research in several areas. The recommendations were based upon a lack of knowledge (and available test data) therein, and the importance of the configurations to plant operations during a fire and the potential consequences of faulty operation of or fire damage to certain electrical devices. The PIRT panel recommended considering the following areas in future research:

1. Instrumentation and Control Circuits (Discussed in Section 5) [highest priority]
2. Panel Wiring (Discussed in Section 6.6)
3. Surrogate Ground Path Hot Short (Discussed in Section 7.3)
4. Control Circuit Cable Testing (Influencing Parameters given in Section 7.1)
5. Current Transformers (Discussed in Section 6.2 & 7.4)
6. High Conductor Count Trunk Cables (Discussed in Section 6.7) [lowest priority]

Finally, based upon the findings of the PIRT panel, BNL will conduct a follow-on expert elicitation via a PRA panel to determine the best-estimate conditional probability (or likelihood) of failure, given fire-induced cable damage. Their findings are documented in Volume 2 of this NUREG/CR report. These probability estimates represent an advancement of the state-of-art for the likelihood of circuit failure and could be used for revising, directly replacing, or creating new probabilities for Table 10-1 through Table 10-5, entitled “Failure Mode Probability Estimates Given Cable Damage,” of NUREG/CR-6850 for conducting Fire PRAs.

Keywords

Circuit Analysis
Fire Protection
Phenomena Identification and Ranking Table (PIRT)
Nuclear Power Plant (NPP)
Risk-Informed Regulation
Fire Hazard Analysis (FHA)
Fire Safety or Fire Safe-shutdown
Hot Short
Performance Based
Probabilistic Risk Assessment (PRA)
Spurious Operation (or Actuation)

EPRI PERSPECTIVE

Under a joint Memorandum of Understanding (MOU), NRC-RES and EPRI initiated a collaborative, results-oriented research program with the primary objective to develop improved methods for conducting Fire PRA at nuclear power plants. This report was developed using that process and represents a comprehensive assessment of fire-induced circuit failures. The Electrical Phenomena Identification and Ranking Table (PIRT) Panel was made up of electrical experts sponsored equally by EPRI and the NRC. All panel members have backgrounds in nuclear fire protection and circuit failures and also represent a broad range of functional disciplines, including research, regulation, program implementation, and technical application. This unique mix of individuals was independent and objective and reached conclusions based on technically substantiated observations. While the conclusions are objective, the Panel members did not agree on all points, which is not surprising given the technical challenges and sometimes limited data sets. Nonetheless, the expertise and qualifications of the Panel in combination with effective implementation of the PIRT process provides confidence that this report represents the most current state of knowledge for fire-induced circuit failures at the time of publication.

The PIRT Panel charter was to investigate and rank the phenomena applicable to fire-induced circuit failures based on available test data and other relevant information. The experimental data reviewed by the PIRT Panel represented the latest and most comprehensive set of cable fire damage data available. Additionally, as part of the process the Panel agreed to address several ancillary circuit failure modes not specifically covered by fire test data, the rationale being that the test data provided sufficient insights into the other failure modes to afford better characterization and application. As noted, the PIRT process was effectively applied by the Panel and included significant deliberations, which, due to the diverse background of team members, resulted in a critical vetting of consensus positions documented in this report. In general, deliberations performed by the PIRT Panel were data-driven. When data were sparse or not available, the Panel acknowledged the limitations and provided the appropriate caveats to their conclusions.

Results and conclusions of the Electrical PIRT Panel, as documented in this report, are intended as the primary input to a follow-on PRA Expert Panel, which is tasked with establishing appropriate application guidelines within a Fire PRA based on the PIRT Panel findings, including updated circuit failure likelihood estimates for hot-short induced spurious operations.

PREFACE

This report supplements previous work related to the effects of fire on cable failure modes and circuit response.

In December 2002, EPRI published EPRI 1003326, *Characterization of Fire-Induced Circuit Faults.* This report documented the results of a comprehensive research and test effort undertaken jointly by EPRI and NEI to investigate, characterize, and quantify fire-induced circuit failures. This testing series also included monitoring cable electrical performance with a patented system developed and fielded by Sandia National Laboratories. The results of which are presented in NUREG/CR-6776, *Cable Insulation Resistance Measurements Made During Cable Fire Tests,* June 2002.

In September 2003, NRC published NUREG/CR-6834, *Circuit Analysis – Failure Mode and Likelihood Analysis*, to address weaknesses in existing fire PRA circuit analysis methods. This report reviewed the existing data available on fire-induced cable failure and characterized that state of knowledge by conducting a formal failure modes and effects analysis (FMEA).

In 2008, the NRC published NUREG/CR-6931, Volumes 1-3, *Cable Response to Live Fire (CAROLFIRE)*, documenting the results of fire-induced failure cable test results to support resolution of Regulatory Issue Summary 2004-03, *Risk-Informed Approach for Post-Fire Safe-Shutdown Circuit Inspections*, and to provide improvements to fire modeling in the area of cable response to fires.

In 2012, the NRC published NUREG/CR-7100, *Direct Current Electrical Shorting in Response to Exposure fire (DESIREE-Fire): Test results*, documenting the results of fire-induced circuit damage to control cables and circuits powered from a direct current power source.

In 2012, the NRC also published Draft NUREG-2128, *Electrical Cable Test Results and Analysis during Fire Exposure (ELECTRA-FIRE).* This report systematically evaluated the test data from the three major fire-induced circuit damage testing programs and provided graphical interpretations of various parametric effects on the likelihood of circuit failure modes and the associated hot short durations.

This document does not constitute regulatory requirements. NRC-RES participation in this study does not constitute or imply regulatory approval of applications based upon this methodology.

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The authors thank the members of the expert panel, Harold Barrett, David Crane, Robert Daley, Daniel Funk, Thomas Gorman, Steven Nowlen, Andy Ratchford, and Gabriel Taylor for their dedication to this PIRT process. We are grateful for the support of panel members' organizations who cooperatively shared some or all of the cost and time for their participation in this study. We thank the panel members for devoting much time to developing the technical discussions reported in this document.

Additionally, we gratefully acknowledge the technical contributions of Steve Nowlen of SNL, a panel member, to various sections of this report. Last but not the least; we sincerely thank Robert Daley of NRC, also a panel member, for his support in transcribing the consensus opinions reached by the PIRT panel during the meetings into this report. Without his ability and electrical knowledge, the excellent quality of this report would not have been achieved.

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LIST OF ACRONYMS

A or Amp	Ampere
ac	Alternating Current
AOV	Air-Operated Valve
ARM	Armature
AWG	American Wire Gauge
BNL	Brookhaven National Laboratory
CAROLFIRE	Cable Response to Live Fire
CFR	Code of Federal Regulations
CPE	Chlorinated Polyethylene
CPT	Control Power Transformer
CSPE	Chloro-Sulfonated Polyethylene
CT	Current Transformer
DESIREE-Fire	Direct Current (dc) Electrical Shorting in Response to Exposure Fire
DID	Defense-in-depth
dc	Direct Current
EPR	Ethylene-Propylene Rubber
EPRI	Electric Power Research Institute
EQ	Equipment (or Environmental) Qualification
Fire PRA	Fire Probabilistic Risk Assessment
FMEA	Failure Mode and Effects Analysis
FP	Fire Protection
FPP	Fire Protection Program
FR	Fire-Rated
GDC	General Design Criteria
GL	Generic Letter
HGL	Hot Gas Layer
HIF	High Impedance Fault
HS	Hot Short
I&C	Instrumentation and Control
IEEE	Institute of Electrical and Electronics Engineers
IR	Insulation Resistance
IRMS	Insulation Resistance Measurement System
kV	Kilovolt
LER	Licensee Event Report
LLC	Limited Liability Company
mA	milli-Ampere
MCC	Motor Control Center
MHIF	Multiple High Impedance Fault
MIL STD	Military Standard
MOU	Memorandum of Understanding
MOV	Motor Operated Valve
n/C	‘n’ Number of Conductor
NC	Normally Closed
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Association
NO	Normally Open

NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation, NRC
NSCA	Nuclear Safety Capability Assessment
PE	Polyethylene
PIRT	Phenomena Identification and Ranking Table
PORV	Power-Operated Relief Valve
PPL	Pennsylvania Power and Light Corporation
PRA	Probabilistic Risk Assessment
PT	Pressure Transmitter
PVC	Poly-Vinyl Chloride
R	Resistive Impedance
RDS	Ratchford Diversified Services
RES	Office of Nuclear Regulatory Research, NRC
RG	Regulatory Guide
SA	Spurious Actuation
SCDU	Surrogate Circuit Diagnostic Unit
SME	Subject Matter Expert
SNL	Sandia National Laboratories
SO	Spurious Operation
SOV	Solenoid Operated Valve
SR	Silicone-Rubber
SSCs	Structures, Systems and Components
SSD	Safe-shutdown
STD	Standard
SWGR	Switchgear
TCP	Transmission Control Protocol
TEF	Tefzel
TP	Thermoplastic
TR	Technical Report
TS	Thermoset
US	United States
V	Volt
Vac	Voltage in AC
Vdc	Voltage in DC
VA	Voltage-Ampere
EXCEL	MICROSOFT® EXCEL
X	Reactive Impedance
XLPE	Cross-Linked Polyethylene
XLPO	Cross-Linked Polyolefin

1 INTRODUCTION

1.1 Background

The primary objectives of fire protection programs (FPPs) at U.S. nuclear power plants (NPPs) are to minimize the probability of the occurrence of fire, and its consequences. In meeting these objectives, the FPPs for operating NPPs are designed to provide reasonable assurance, through defense-in-depth (DID), that a fire will not prevent the operation of the necessary reactor safe-shutdown functions, and that should there be a fire, radioactive releases to the environment will be minimized. The goals of the DID concept for fire protection are to assure a high degree of fire safety in an NPP by preventing fires from starting, timely detecting those that do start, and promptly suppressing them. In addition, the DID concept affords protection for the structures, systems, and components (SSCs) important to safety, so that if a fire is not promptly extinguished, it will not prevent the safe-shutdown of the reactor.

To achieve DID, each operating reactor has a Nuclear Regulatory Commission (NRC) - approved fire protection program that, when properly designed, implemented, and maintained, will satisfy Section 50.48, “Fire Protection,” of Title 10 of the *Code of Federal Regulations*, Part 50 (10 CFR 50.48) (Ref. 1). This regulation requires that each holder of an operating license issued under 10 CFR 50, “Domestic Licensing of Production and Utilization Facilities” (Ref. 2) or 10 CFR 52, “Licenses, Certifications, and Approval for Nuclear Power Plants” (Ref. 3), has a fire protection plan that satisfies General Design Criterion (GDC) 3, “Fire Protection,” of Appendix A to 10 CFR 50, (Ref. 4). The GDC 3 requires that SSCs important to safety are designed and strategically located to minimize the probability and the effect of fires and explosions. GDC 3 also establishes the criteria for detecting fires, for firefighting systems, and for using noncombustible and heat-resistant materials throughout the plant.

In recent years, the NRC encouraged utilities operating NPPs to use risk-informed, performance-based approaches as an alternative to the existing deterministic fire protection requirements (e.g., Appendix R to 10 CFR 50, “Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979” (Ref. 5)). The NRC amended its fire protection requirements in 10 CFR 50.48 to permit existing reactor licensees to voluntarily adopt the fire-protection requirements detailed in the National Fire Protection Association’s (NFPA’s) Standard 805, “Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition” (Ref. 6).

The Browns Ferry Fire of 1975 and confirmatory testing of representative circuits revealed that fire-induced failures of electrical circuit, leading to spurious equipment operations, can occur in the event of a fire. The type of circuit failure that may result from fire-induced cable damage, depends on many factors including the type of circuits (i.e., power, control, or instrument), the cable’s failure modes (i.e., open circuit, short to ground, or hot short), the specific circuit design and construction, and the location of the cable with respect to the site of the fire (e.g., cable’s orientation, raceway routing and fill, circuit grounding). Once a cable is damaged by a fire, faults in a circuit can result in the malfunction of a component or system, including hot short-induced spurious operation of safety components, or false indication of instrumentation and control (I&C) circuits.

To better understand these phenomena, both the NRC's Office of Nuclear Regulatory Research (RES) through Sandia National Laboratories (SNL), and the Electric Power Research Institute (EPRI), in collaboration with the Nuclear Energy Institute (NEI), conducted fire testing of various cables in controlled environments. These tests helped in determining the likelihood of such failures, and in understanding the effects of those parameters affecting the hot short phenomenon in electrical circuits during a fire. More specifically, in 2002, EPRI/NEI reported a cable-test program addressing the nature and characteristics of such fire-induced failures of alternating current (ac) control circuits, particularly the potential of hot shorts to initiate the spurious operation of equipment (Ref. 7). Subsequently, NRC sponsored the CAROLFIRE (CAble Response tO Live FIRE) test program to (1) offer an experimental basis for resolving the issues identified as "Bin 2 Items" in Regulatory Issue Summary 2004-03, "Risk-Informed Approach for Post-Fire Safe-Shutdown Circuit Inspections" (Ref. 8); (2) improve fire-modeling tools to aid in predicting cable damage under fire conditions; and, (3) complement the EPRI/NEI test results for AC control circuits. In 2008, NRC/SNL published the results of this CAROLFIRE test program on electrical performance and fire-induced cable failure (Ref. 9). NRC also sponsored tests under the DESIREE-Fire (Direct Current Electrical Shorting In REsponse to Exposure Fire) effort to assess cable failure modes and effects on the behavior of direct current (dc) control circuits. In 2010, a draft form of the findings from this program became available, and in 2012, NRC/SNL detailed the outcomes of the electrical performance and fire-induced cable-failure tests (Ref. 10). This project was sponsored by the NRC-RES with support from EPRI under a collaborative research agreement termed in the NRC-RES/EPRI Memorandum of Understanding (MOU).

In May 2002, EPRI also published a technical report (EPRI Technical Report 1006961, "Spurious Operation of Electrical Circuits Due to Cable Fires – Results of an Expert Elicitation") detailing the results of an expert elicitation process on the EPRI/NEI cable-fire test results to develop best-estimate conditional probabilities for spurious operation of devices in electrical circuits due to fire-induced damage to electrical cables (Ref. 11). These results were incorporated into the current state-of-the-art method for conducting Fire Probabilistic Risk Assessments (Fire PRAs) documented in NUREG/CR-6850, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities" (Ref. 12). In addition, findings from the EPRI/NEI and CAROLFIRE tests were included in the industry's deterministic guidance document NEI 00-01, Rev. 2, "Guidance for Post Fire Safe-shutdown Circuit Analysis," (Ref. 13) for evaluating fire-induced circuit failures.

1.2 Objective

In 2010, under the auspices of the NRC-RES and supported by EPRI through an NRC-RES/EPRI MOU, Brookhaven National Laboratory (BNL) conducted a Phenomena Identification and Ranking Table (PIRT) study of fire-induced electrical-circuit failures. This effort used all the cable test findings from EPRI/NEI and NRC/SNL, along with eliciting expert judgment as a basis for ranking various influencing parameters on hot short-induced spurious operational phenomena caused by a fire. Therefore, factors leading to influencing cable damage by a fire were outside the scope of this PIRT panel. This PIRT identified the influencing parameters, assuming that the fire damaged a cable that can affect the failure modes of induced electrical circuit faults. Thereafter, they ranked the current knowledge relative to each identified phenomena. Using these PIRT results, BNL will assemble a PRA panel to conduct a separate follow-on expert elicitation of these occurrences to assess their conditional probability (or likelihood) of failure after fire-induced damage to the cable This second PRA effort will revisit and complement the expert elicitation work undertaken by EPRI in 2002 (Ref. 11), but with the addition of the data from the CAROLFIRE and DESIREE-Fire testing. The electrical expert PIRT panel and the Expert Elicitation PRA Panel[4] will deliver both qualitative and quantitatively important data for use in Fire PRAs in applying NFPA 805 (Ref. 6), and possibly also for incorporating into deterministic post-fire safe-shutdown circuit analyses.

Volume 1 of this NUREG/CR report discusses the PIRT process and the results obtained from the PIRT panel in identifying the influencing factors and ranking their importance to the hot short phenomenon in the failure of electrical circuits leading to spurious operation of devices after the cable is damaged by fire. It also identifies the PIRT panel's prioritization of the future research needed to resolve technical challenges considered important in characterizing the fire-induced hot short phenomenon and establishing the risk significance associated with certain equipment, conditions or configurations. Volume 2 of this NUREG/CR details the findings from the PRA panel; they will give the conditional probabilities for use in Fire PRAs, particularly on the spurious operation of devices due to hot short mode of failure of control circuits following fire damage to the associated cables.

1.3 The Approach

The expert elicitation process conducted in this PIRT study is based on methods employed by other PIRT panels that the NRC used in many areas (Refs. 14 & 15), where no tests or analyses could address the technical issues with the desired level of certainty. The PIRT process systematically obtains information from experts about the concerns that involve generating lists (tables) of phenomena, where "phenomena" also can refer to a particular reactor condition, a physical- or engineering-approximation, a safety-related component or parameter, the importance of parameters on the likelihood of spurious operation of equipment, or anything else that might influence the chosen figures-of-merit or criteria. The process often entails ranking of these observable events using scoring criteria, consensus, or a combination of them to determine what is the most important. That ranking, as well as the information explaining and justifying it, allows the NRC to prioritize research needs for a safety issue, or to support some decision-making process. Thus, the PIRT methodology, including the expert panel, highlights the phenomena that dominate an issue, while identifying all plausible effects to demonstrate completeness.

Each PIRT application is unique in some respect; the electrical expert PIRT is no exception. This PIRT investigates the fire-induced spurious operation of plant components, encompassing AC and DC circuit types. The PIRT focus falls into three specific electrical circuit types, namely, power, control, and instrument, with the primary focus on control circuits (e.g., 120 VAC and 125 Vdc), because fire-induced mal-operation of these types of circuits is considered to pose a higher risk to plant safety in comparison to the other circuit types. Accordingly, the majority of available industry and NRC test data was related to low-voltage control circuits. Due to the limited amount of test data available for instrument circuits, a complete parametric treatment of this circuit type was not possible. Available failure modes for power circuits are well understood, with the exception of a few unique cases. For certain types of power circuits (for example, three-phase power cables), specific industry testing was not available; therefore, the PIRT panel developed technical recommendations based on their expert judgment involving engineering principles and physical configurations for power cables and power-cable

[4] In this report, hereafter the "PIRT panel" refers to the "Electrical Expert PIRT Panel" and the "PRA panel" refers to the "Expert Elicitation PRA Panel."

installations. In other instances, such as open circuits in current transformer (CT) secondary circuits, the PIRT panel developed recommendations based upon available open circuit test data, manufacturers' input, operating experience (nuclear and non-nuclear), and expert judgment.

The evaluation of circuit impacts for each electrical circuit type assumed that the cable(s) of concern was damaged by fire and fire damage has resulted in loss of cable functionality. In other words, the panel did not focus on parameters that influence the likelihood of cable damage from fire effects, such as ignition, fire growth, fire intensity, nor the likelihood of a fire occurring. The fire-induced hot short mode of failure entailing the spurious operation of equipment of interest is influenced by the following three elements:

1. <u>Fire-induced hot shorts:</u> Individual conductors of the same or different cables that come in contact with each other and that may result in an impressed voltage or current on the circuit being analyzed (definition per Regulatory Guide 1.189, "Fire Protection for Nuclear Power Plants" (Ref. 16)).

2. <u>Hot short-induced spurious operations:</u> A circuit-fault mode wherein an operational mode of the circuit is initiated (in full or in part) due to failure(s) in one or more components (including the cables) of the circuit[5]; examples are a pump spuriously starting, or the spurious repositioning of a valve.

3. <u>Duration of the spurious operation:</u> Length of time that a hot short-induced spurious operation condition exists.

The following are the two figures-of-merit associated with these elements:

1. <u>FIGURE-OF-MERIT 1:</u> **Spurious Operation[6]:** After fire-induced cable damage has occurred to an appropriate conductor in an electrical circuit resulting in a hot short(s), a spurious operation(s) of the component occurs driven by the same electrical circuit. Note that an appropriate conductor in an electrical circuit is one with the potential to cause an inadvertent change of state of the component or device.

2. <u>FIGURE-OF-MERIT 2:</u> **Duration of Spurious Operation:** Duration is the amount of time during which the fire-induced hot short transfers voltage or current to an appropriate conductor of a specific component or device that then can cause the component to move or travel in the undesired direction.

   The duration evaluated in this report is the length of time that the impressed voltage or current on the circuit can cause a spurious operation. It can be affected by the grounding of the conductor or the opening of a fuse. In practice, the length of the spurious operation would take into account the specific circuit-design of the component and whether this design resulted in a "sealed-in" or "latched" condition once the circuit was energized to move in the undesired direction. For both conditions, clearing or removing the hot short (i.e., de-

[5] The PIRT panel defined this based on the definition of spurious actuation in RG 1.189 (Ref. 16), "The undesired operation of equipment, considering all possible functional states, resulting from a fire that could affect the capability to achieve and maintain safe-shutdown."
[6] The PIRT panel used the term "spurious actuation" during their early deliberations and later changed to the term "spurious operation". Both terms were used interchangeably.

energizing the circuit) does not reverse the position of the component to the pre-hot short condition.

In addition to reviewing and evaluating spurious operations and their duration for control circuits, the PIRT panel considered other fire-induced circuit failures that are included in this report, some of which are listed below.

- Power cabling consequential hot shorts (AC and DC)
- Open circuit secondary of current transformers (CTs)
- Multiple high impedance faults – MHIFs (AC and DC)
- Common enclosure and common power supply concerns

Although not all these topics are directly associated with spurious operations of a device or component they are postulated failure modes with which both industry and regulators have historically struggled, and that the PIRT panel believed could be resolved during the PIRT process. Sources of information for the PIRT panel primarily included, but were not limited to, the findings from the EPRI/NEI and the NRC/SNL tests of both AC- and DC-circuits. In addition, the overall conclusions of this PIRT befitted from expert knowledge about the plant-specific cable and circuit configurations, publically accessible utility test information on armored cables (e.g., Refs. 17 & 18), the findings from fire protection inspections and Fire PRAs.

1.4 The PIRT Panel

The staff at NRC/RES and the EPRI identified members of the electrical expert PIRT panel. Those selected possess extensive expertise in electrical circuits, post-fire safe-shutdown circuit analysis, and overall knowledge of post-fire safe-shutdown SSCs. The panel representation was balanced evenly among the regulator (i.e., four members from the NRC) and the nuclear power industry (i.e., four members from EPRI).

Brief resumes of the panel members listed below, along with their affiliations, are given in Appendix A.

Harold Barrett, U.S. Nuclear Regulatory Commission (NRC)
David Crane, Pyrolico Corporation
Robert Daley, U.S. Nuclear Regulatory Commission (NRC)
Daniel Funk, Kleinsorg Group Risk Services (KGRS)
Thomas Gorman, PPL Susquehanna, LLC
Steven Nowlen, Sandia National Laboratories (SNL)
Andy Ratchford, Ratchford Diversified Services (RDS), LLC
Gabriel Taylor, U.S. Nuclear Regulatory Commission (NRC)

BNL staff provided technical support to the PIRT panel. Mark Henry Salley of NRC and Rick Wachowiak of EPRI also attended and offered general assistance at the panel meetings and oversight. Finally, Mano Subudhi or Jim Higgins of BNL served as the moderator of panel meetings held at the NRC/RES Church Street Office in Rockville, Maryland.

1.5 Report Organization

Section 2 gives an overview of the deliberations of the electrical expert PIRT panel on electrical circuits. This section also presents the definitions and process used by the panel in developing the scenarios and the influencing parameters for the control circuits. The panel's scoring process and technical challenges also are discussed. Section 3 provides the findings of the PIRT panel's evaluation findings for control circuits and discusses their conclusions. Section 4 summarizes the panel's technical positions about several issues in analyzing circuits associated with control and power circuits. Section 5 describes their recommendations for future testing to better understand the hot short-induced spurious operations in instrumentation and control (I&C) circuits. Section 6 details the panel's technical positions on various problems related to safe-shutdown circuit analysis. The research priorities identified via the findings from this PIRT process are summarized in Section 7. Finally, Section 8 gives the summary discussions and conclusions by the PIRT panel.

Appendix A includes the resumes of PIRT panel members and the moderators. Appendix B presents the MICROSOFT® EXCEL scoring sheets on ranking the influencing parameters on the hot short-induced spurious operation of control circuit devices. Appendix C describes the electrical control circuit scenarios selected by the PIRT panel for their deliberations and for the PRA panel's consideration in calculating the best-estimate conditional failure probabilities. Finally, Appendix D includes a number of viewgraphs that were shown to the panel at the first PIRT meeting.

2 OVERVIEW OF ELECTRICAL EXPERT PIRT PANEL ACTIVITIES

The electrical expert PIRT panel convened six separate times, in 2½-day meetings at the NRC's RES Office in Rockville, Maryland. These meetings were held from November 2010 through December 2011.

In the first meeting, the results of the EPRI/NEI (Ref. 7) and NRC/SNL (Refs. 9 &10) cable-fire test programs were presented to the panel members (Appendix D), along with the findings from other publically available results from industry tests (Refs. 17 and 18). They identified that hot short-induced spurious operations of control circuit device(s) or associated components could be induced by fires damaging the cables in nuclear power plants. One of the primary objectives of these test programs was to better understand these phenomena of induced spurious operation so that this knowledge could be used to improve both deterministic fire-safety protection and fire probabilistic safety assessments (Fire PRAs). Using these test results, the following were the specific objectives of this overall project:

- to identify the parameters of the phenomena that lead to fire-induced hot shorts causing the spurious operation of equipment important to safety;
- to rank the influencing parameters affecting fire-induced hot shorts, and subsequently, to determine the duration of such induced operations, and to assess the current level of knowledge for each of the identified phenomena; and,
- to develop best-estimates for the conditional probability (or likelihood) of these phenomena representing the current NPP design and cable configurations, and for the durations of those phenomena where the length of its persistence could affect the circuit function of the component or device being considered.

To achieve these objectives, two independent panels of experts were formed: an "Electrical Expert PIRT Panel" and an "Expert Elicitation PRA Panel." Using the PIRT process, the former identified and ranked various influencing parameters that could affect the hot short-induced circuit failures. Their findings will be used by the latter, the "Expert Elicitation PRA Panel" to develop the best-estimate conditional probabilities for using in Fire PRA applications; their findings are not documented in this report, but are the subject of Volume 2 of this NUREG/CR report.

The first question posed to the electrical expert PIRT panel was "Under what circuit and cable configurations could a fire resulting in cable damage cause hot short-induced spurious operations of electrical or electronic circuits?" The second question, posed to the Expert Elicitation PRA Panel, was "What is the probability of such spurious operations, given that fire-induced cable damage has occurred?" Volume 1 of this NUREG/CR report addresses the electrical expert PIRT panel's conclusions on the first question covering the first two objectives above. The second question that deals with the third objective above will be addressed by the Expert Elicitation PRA Panel who will take into account these results and conclusions of the electrical expert PIRT panel to accomplish the third objective. The PRA panel will calculate the best-estimate conditional probabilities of the likelihood of hot short-induced spurious operation given cable damage due to a fire, and their results are documented in Volume 2 of this NUREG/CR report. These probability estimates could be used to revise, directly replace, or create new probabilities for Table 10-1 through Table 10-5, entitled “Failure Mode Probability Estimates Given Cable Damage,” of NUREG/CR-6850 (Ref. 12).

The electrical PIRT process can be described in terms of the nine steps as depicted in Figure 2-1. The general meaning and application of these steps are detailed below[7].

Step 1: Selecting The Electrical Expert PIRT Panel: As discussed in Section 1.4 of this report, eight members comprised the electrical expert PIRT panel. They represented a range of areas of expertise and background, i.e., researchers, consultants, regulators, and plant inspectors, along with fire protection and electrical engineers currently working in practical field applications. Factors considered in selecting the panel members included their expertise, availability and willingness to serve, absence of financial conflicts of interest, impartiality, and prior experience working as subject matter experts (SMEs) in related committees, subcommittees, and advisory panels.

Step 2: Defining the Impact and Terminology of Cable Failure: The PIRT panel initially established three primary terms and associated definitions for evaluating fire-induced circuit failures, i.e., fire-induced hot shorts, spurious operations, and duration of the hot short and spurious operation. However, later in the process, the PIRT panel determined that it would be difficult to characterize the first two separately from the kind of fire-test results available to them. Additionally, the PIRT panel concluded that identifying hot shorts independently from spurious operation was unnecessary; since hot short-induced spurious operations better define the failure event that must be evaluated. Also, combining the terms would better translate into Fire PRA applications that utilize the estimates, “…probability of spurious actuation given cable damage” in Tables 10-1 through 10-5 of NUREG/CR-6850. Therefore, the PIRT panel ultimately combined the first two terms (fire-induced hot short and spurious operation) to one (hot short-induced spurious operation). Thereafter, the panel established two figures-of-merit: 1) Spurious Operation; and, 2) Duration of Spurious Operation, defined in Section 1.3 of this report.

We note that the PIRT panel ultimately limited the term “spurious operation” to the operation of a component as presented in Section 1.3 of this report. Therefore, a spurious operation was defined by a change in the operating state or the repositioning of a piece of equipment due to a hot short; this definition thereby excluded control circuit activations, such as false light indications of equipment status.

[7] The parameter identification and ranking process used by the PIRT panel was performed for grounded AC and ungrounded DC control circuits, since these control circuit types were believed to be the most common types used in US Nuclear Power Plants. Later on in the process, however, ungrounded AC control circuits powered from a control power transformer (CPT) and ungrounded AC control circuits from an AC distribution system were included in this report addressing control circuit configurations. The inclusion of these latter two types of control circuits was done for completeness, since some Nuclear Power Plants may use these types of control circuits. Although these latter two types of control circuit configurations were included in this report, the ranking tables (in Section 3 and Appendix B) were never updated to include these control circuit types.

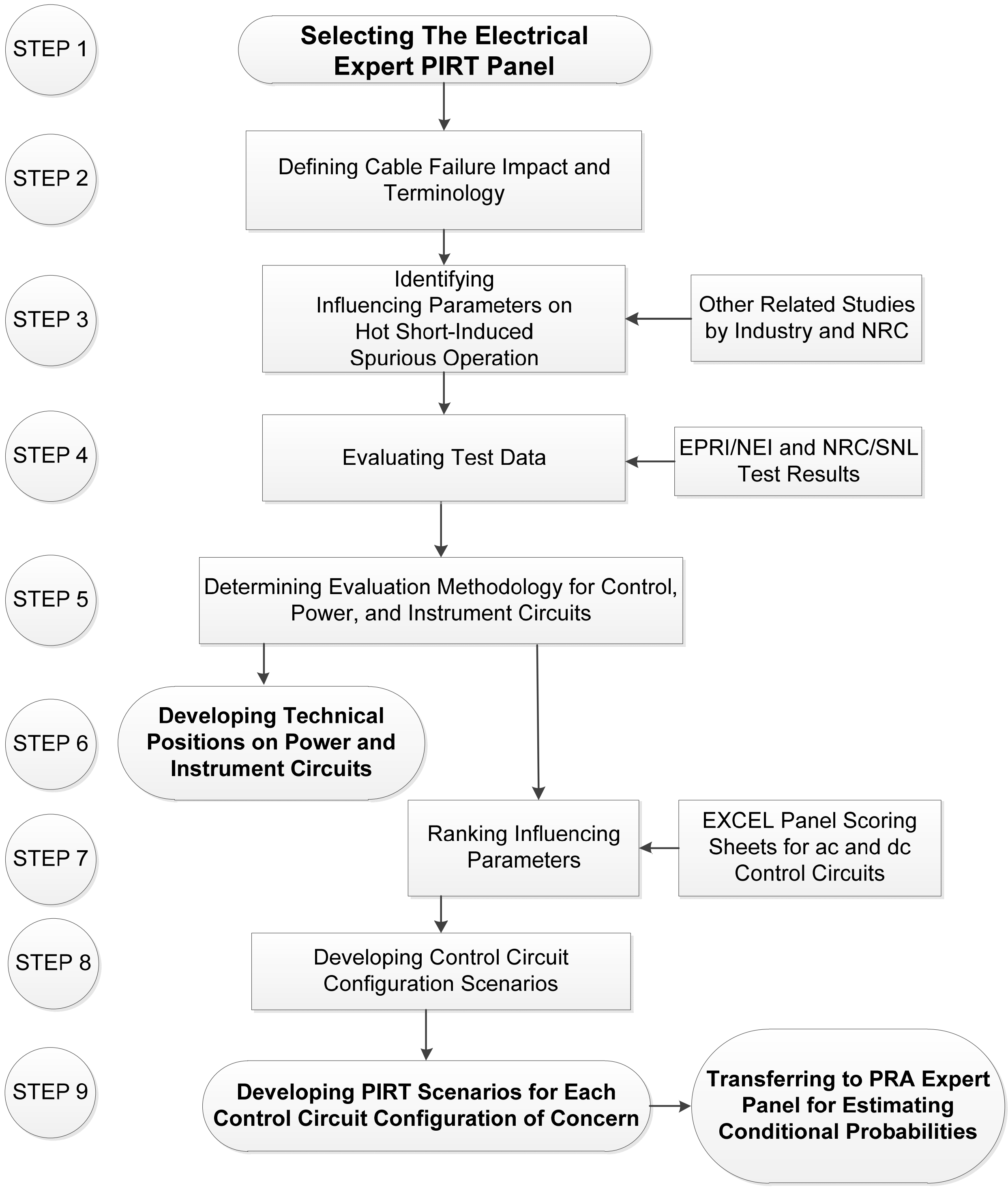


Figure 2-1. Flowchart for Electrical PIRT Expert Panel Activities

This omission of indicating lights was based on two primary functional differences between an indicating light and an electro-mechanical device. The first is that, even when fully energized, indicating lights will draw a lower total energy (e.g., watts) than most electro-mechanical components. Indicating lights generally are designed to draw current of about 0.1 Ampere (A) or less; electro-mechanical devices may draw a wide range of amperages, usually greater than 0.1A. The second difference is that indicating lamps generally have no true lower pickup threshold as do most electro-mechanical devices; that is, before an electro-mechanical device will operate, the minimum pickup voltage and current must be exceeded. In contrast, an indicating lamp may “glow” even when partially energized, for example, by a relatively low quality (high impedance) electrical short. By comparison, an electro-mechanical component requires a higher quality (lower impedance) short to transmit sufficient power to operate the component.

During Step 2 of the PIRT activities, several additional terms were defined. These frequently used terms during the PIRT panel discussions are defined in Section 2.1.

Step 3: Identifying Influencing Parameters on Hot short-Induced Spurious Operation: The PIRT panel identified parameters that could affect the hot short-induced spurious operation of safe-shutdown equipment from the following four broad groups: physical properties and configuration of cables; routing of cables in raceways; electrical function of the circuit; and, fire-exposure conditions (Ref. 19). These items are detailed in Section 2.3.1 of this report. Based on these parameters, the PIRT panel developed MICROSOFT® EXCEL worksheets for scoring by individual panel members for all three circuit types, namely, power, control, and instrument. However, later the PIRT panel found that there was insufficient test data for power and instrument circuits. Accordingly, the PIRT panel limited the PIRT evaluation process to control circuits.

Step 4: Evaluating Test Data: While evaluating the available data from the EPRI/NEI and NRC/SNL tests, the PIRT panel found that the form of the test data was not in a form suitable to assure their reaching a sound technical judgment about the influence of certain parameters on hot short-induced spurious operations of control circuits. Consequently, under the oversight of the PIRT panel, all test data was analyzed, parsed, and summarized in a more useful format. The results of this work are documented in draft NUREG-2128 (Ref. 20), as discussed in Section 2.2 of this report.

Step 5: Determining Evaluation Methodology for Control, Power, and Instrument Circuits: As discussed in Step 3, because of the dearth of test data for instrument circuits, a complete parametric treatment of this circuit type was not possible. Available failure modes for power circuits are well understood, with the exception of a few unique cases. For certain types of power circuits (for example, three-phase power cables), specific industry testing was not available; therefore, the PIRT panel developed technical recommendations based on their expert judgment involving engineering principles and physical configurations for power cables and power cable installations.

Step 6: Developing Technical Positions on Power and Instrument Circuits: For power circuits, the PIRT panel produced a consensus technical position about the credibility of certain fire-induced failure modes. For instrument circuits, the PIRT panel again proffered technical positions on credible failure modes and issues of concern. Additionally, since certain modes of instrument circuit failure could impact plant safety in a fire event, the PIRT panel recommended undertaking testing for certain instrumentation and control circuit-configurations as discussed in

Section 2.3.2. The resulting technical positions for power circuits are detailed in Section 4, and for instrumentation and control (I&C) circuits, in Section 5 of this report.

Step 7: Ranking Influence Parameter: Steps 7 through 9 specifically pertain to control circuits. Based upon the information obtained in Step 4, "Evaluating Test Data," the PIRT panel used the MICROSOFT® EXCEL worksheets for AC and DC control circuits, and scored the effect of each influencing parameter on hot short-induced spurious operations, as defined in the figures-of-merit. Thus, the PIRT panel scored the hot shorts for intra- and inter-cable shorting, including multiple ground-plane interactions for ungrounded DC circuits. The PIRT panel also included in the scoring sheets the effect on the duration of hot short. Section 2.4 discusses how the panel scored the impact of an influencing parameter on the intra- and inter-cable hot short-induced spurious operation and its duration. At first, the PIRT panel ranked these sheets independently and discussed their differences in subsequent PIRT meetings or in teleconferences. However, toward the end of the process, the panel members had reconciled most differences in individual rankings; hence, they decided to finalize the rankings based upon consensus among the panel members rather than relying on individual rankings. The final ranking of all influencing parameters are based on test data statistics given in draft NUREG-2128 (Ref. 20), the PIRT panel's operating experience, and their cumulative knowledge of phenomenological behavior under high thermal conditions, as is discussed in Sections 3.1 and 3.2.

Step 8: Developing Control Circuit Configuration Scenarios: Based upon the scoring, the PIRT panel identified high importance parameters and included them when defining the control circuits that should be considered in analyzing the circuits. Parameters whose influences on the figures-of-merit ranked low to medium were, for the most part, not considered in defining the control circuits requiring circuit analysis for spurious operations. The panel employed those parameters with a significant influence ranking to identify and develop various circuit configuration scenarios, as described in Section 3.3.

Step 9: Developing PIRT Scenarios for Each Control Circuit Configuration of Concern and Transferring to PRA Expert Panel for Estimating Conditional Probabilities: The PIRT panel based the final PIRT ranking tables upon different scenarios of control circuit configurations. These tables were provided to the expert elicitation PRA Panel to use in estimating the conditional probabilities of cable spurious operations after cable damage. Principally, using mostly the high importance influencing parameters, each case includes a base case and additional special cases representing the actual plant's circuit design and configuration. This is fully described in Section 3.4. Appendix C gives the electrical control circuits representing these special cases for use by the expert elicitation PRA panel.

2.1 Terminology Used by PIRT Panel

2.1.1 Hot Short-Induced Spurious Operation

Based on reviewing the results of the EPRI/NEI's and NRC/SNL's cable tests on control cables, and applying their technical expertise, the electrical expert PIRT panel considered that taking two steps would address the likelihood of the spurious operation of electrical equipment arising from a fire-induced hot short failure-mode : 1) Determine the likelihood of a hot short between the target and source conductors located in the same or different cable(s); and, 2) Assess the likelihood of a spurious operation of a device or equipment after the hot short has occurred. Not all hot shorts potentially can cause spurious operations; hence, the PIRT panel originally believed that splitting the hot shorts and the hot short-induced spurious operations into two phases would be the best approach to qualitatively assessing the parameters that influence either one of the failure modes. However, later they considered that this approach was not feasible, and so they reduced the figures-of-merit to the two presented in Section 1.3, i.e., spurious operation, and its duration.

The PIRT panel determined a hot short to be a subset of conductor-to-conductor shorts (i.e., a low-impedance electrical contact not involving an external ground) with one conductor being initially energized, and at least the other conductor being neither energized nor grounded. Thereupon, the PIRT panel categorized the spurious operations resulting from intra-cable hot short(s) (within a multiconductor cable) between conductors, and inter-cable hot shorts (between two separate cables) due to direct conductor-to-conductor contact. In addition, the panel separately evaluated those inter-cable hot short-induced spurious operations caused by multiple conductors shorting to a surrogate ground path, such as a raceway (i.e., other than direct conductor contacts). Also, the duration and their energy level (quality) of the hot shorts may play a major role in the spurious operation of an electrical device or equipment. The influencing parameters modulating this phenomenon of spurious operation are associated with the failure of a cable due to fire (i.e., a breakdown in the electrical insulation of the conductor in a cable, such that it no longer can perform its intended design function of maintaining the electrical integrity and continuity of its conductors), the routing configuration, and the conductor's configuration in the circuit of concern.

Although the findings from both the EPRI/NEI and the NRC/SNL tests are not applicable directly to the functional response of the power circuits, certain generic characteristics of the failure of cable insulation due to fire effects are independent of the circuit's application (e.g., a thermoset (TS) cable is more resistant to fire damage than is a thermoplastic (TP) cable). For power and control circuits, partial degradation of the cable's insulation (at the level of abnormal leakage current) may not cause failure in the circuit. For these circuits to trigger a complete failure, the value of the insulation's resistance must be below a certain threshold (typically at, or below 1,000 ohms based on the fact that CAROLFIRE test results were analyzed for 1,000 ohms). However, this is not valid for instrument circuits, since they rely on low-level electrical signals that represent various process- and diagnostic-parameters. A small amount of leakage current can impair the instrument circuit's performance measurably in a manner that has functional implications. Therefore, low-level degradation of the insulation should be considered in assessing an instrument's performance (e.g., 30,000 ohms insulation resistance corresponds to a 5% signal error in a standard 4-20 mA instrument loop) (Ref. 7).

The likelihood of conductor-to-conductor shorts varies with the cable's construction and physical configuration. Some parameters that the panel considered important in influencing the likelihood of conductor-to-conductor shorts within a cable (intra-cable shorts) include

- the number of conductors,
- conductor's size,
- insulating materials of the conductor and jacket ,
- armor or ground/shield conductor,
- cable raceway and routing configuration, and,
- raceway fill.

Some other parameters affecting the hot short may include the number of source and target conductors and their proximity to each other, along with the relative location of the ground plane.

Additionally, factors directly related to the type of electrical control circuit also may impact the likelihood of a spurious operation actually adversely affecting safe-shutdown. For example, a hot short to a solenoid must be maintained energized to keep its controlled device (e.g., solenoid operated valve (SOV)) in an undesired or spurious position. If the hot short subsequently changes to a different failure mode, such as a short to ground or open circuit, the solenoid will be de-energized, so returning its controlled device to its normal (de-energized) state. This scenario is not the case for control circuits that have a seal-in or latching feature, for example, pumps and some motor-operated-valve (MOV) circuits that require only a hot short of sufficient duration to actuate the latching circuit Components such as pumps and MOVs only require a hot short/spurious operation of a limited duration to cause a change of position for the component, e.g. pump start or valve open. Even if the hot short changes state, i.e. short-to-ground or open circuit, after this limited duration, the position of the pump or valve will not be altered. Other circuit-design factors that may also influence the likelihood of spurious operations that can impact safe-shutdown are the grounding scheme (e.g., ungrounded DC versus grounded AC circuits), pick-up and drop-out current and voltage levels, fuse ratings, and device connections, such as motor, breaker, switchgear, solenoids, and relays.

2.1.2 Definitions

The panel decided to define the following terms that were used throughout the PIRT discussions:

Cable – A conductor with insulation or a stranded conductor with or without insulation or other coverings (single-conductor cable) or a combination of conductors insulated from one another (multiple-conductor cable). (Ref. 22)

Cable Armor – A metallic element or envelope inserted in or around a cable sheath to provide mechanical protection against rodents, severe installation conditions, etc. (Ref. 22)

Cable Fire Damage – Cable fire damage (or failure) implies that the cable is no longer able to perform its intended function which is to maintain the electrical integrity and electrical continuity of the associated circuit sufficient to ensure proper operation of the circuit. For a cable to perform its intended function, each individual conductor within the cable must maintain both electrical integrity and continuity. Hence, cable failure implies that one or more of the cable conductors have lost electrical integrity or electrical continuity. (Ref. 19)

Cable Functional Damage – Functional damage of the cable is defined to be one of the following states: Short to ground (e.g., raceway, ground /drain conductor, metal foil shield wrap, or armored sheath), short to another cable co-located in the same raceway (inter-cable short), short to another conductor within the same cable (intra-cable short), or an open circuit (e.g., a fire-induced break in a conductor resulting in the loss of circuit continuity, fuse blow, or breaker trip), or short to another cable via a conductive ground plane (inter-cable, referred to as a ground equivalent hot short), such that the cable cannot perform its design function. (PIRT panel)

Circuit – A conductor or system of conductors through which an electric current is intended to flow. (Ref. 22)

Hot Short – Individual conductors of the same or different cables that come in contact with each other and that may result in an impressed voltage or current on the circuit being analyzed (definition per Regulatory Guide 1.189, "Fire Protection for Nuclear Power Plants" (Ref. 16)).

This mode of failure can be considered as a transient phenomenon associated with cable damage between an energized conductor (the source) and another conductor (the target) that may or may not be energized for the following cable configurations:

- **Intra-cable Hot Short,** conductor-to-conductor shorting within the same cable; (see Figure 3-2),
- **Inter-cable Hot Short,** conductor-to-conductor shorting between co-located cables in the same raceway; (see Figure 3-3), or
- **Inter-cable Ground Fault Equivalent Hot Short,** the inter-cable phenomenon that includes a source cable co-located with the target cable in the same raceway or different raceways wherein the interaction takes place via multiple ground fault equivalent hot shorts rather than direct conductor-to-conductor shorting; (see Figure 3-4).

Open Circuit – A fire-induced break in a conductor resulting in a loss of circuit continuity. (Ref. 13)

Spurious Operation – A circuit fault mode wherein an operational mode of the circuit is initiated (in full or in part) due to failure(s) in one or more of the circuit's components (including cables). For example, such modes include a pump (starting or stopping) or a valve spuriously repositioning.

Source Cable or Source Conductor – A cable or conductor that is energized (e.g., before the fire) and therefore, can produce a hot short should it make contact with a target conductor(s).

Target Cable or Target Conductor – A cable or conductor (initially energized or not) that, if energized by contact (directly or indirectly) with an appropriate source cable or conductor, would generate a hot short, and possibly, a spurious operation if the target cable or conductor was associated with equipment or device(s) that would operate spuriously.

2.1.3 Technical Positions by the PIRT Panel

The final disposition of the electrical expert PIRT panel's evaluation on some specific issues or scenarios was characterized as "incredible" or "implausible." For the purpose of the PIRT panel's disposition of an issue, the following define these terms:

<u>Incredible</u> – The term "incredible" used in conjunction with the phenomenon of a fire-induced circuit failure, signifies the PIRT panel's conclusion that the event will not occur. In these cases, the PIRT panel could find no evidence of the phenomenon ever occurring, and there were no credible engineering principles or technical argument to support its happening during a fire. Any likelihood value assigned to these types of phenomena would have little meaning.

Implausible – The term "implausible" when used in conjunction with a fire-induced circuit failure phenomenon, supports the PIRT panel's conclusion that the happening, while theoretically possible, would require the convergence of a combination of factors that are so unlikely to occur that the likelihood of the phenomenon can be considered statistically insignificant. In these cases, the PIRT panel could find no evidence of the phenomenon ever occurring neither in operating experience nor during a fire test. Any likelihood value assigned to these types of phenomena would have little meaning.

2.1.4 NRC Regulatory Issue Summary (RIS) 2004-03 – "Risk-Informed Approach for Post-Fire Safe-Shutdown Circuit Inspections"

This subsection is included to define the terminology "BIN 2" items that the panel frequently used during their deliberation process throughout their meetings.

Based on the results of the industry's (EPRI/ NEI's) cable-fire tests, modes of fire-induced circuit failure that could cause equipment to spuriously operate were defined and "binned" during a facilitated workshop conducted by the NRC in February 2003. Specifically, the failure modes binned are as follows:

<u>BIN 1 - Items to Be Considered During Inspection (Circuits most likely to fail)</u> includes spurious operation failure modes that were to be included in the scope of fire protection (FP) inspections, primarily because they are (a) based on the results of industry 's cable-fire testing (EPRI/NEI tests) that determined they were "likely" (e.g. conductor-to conductor faults within a single multi-conductor cable (intra-cable faults);" or (b) had a potentially high consequences (e.g., High Low Pressure Interface Valve circuits)

<u>BIN 2 - Items Deferred Pending Additional Research</u> includes cable and circuit faulting configurations for which the experimental evidence then was determined to be inconclusive. However, recent NRC/SNL tests on AC circuits (CAROLFIRE) and DC circuits (DESIREE-Fire) address most of these issues associated with the Bin 2 items.

<u>BIN 3 – Configurations That Are Unlikely or Least Likely to Cause Failure</u> and included in the first version of the RIS 2004-03 and circuit configurations that are unlikely to cause failure and do not need to be considered during future FP inspections.

2.1.5 Associated Circuits

Those safety-related and nonsafety-related Class 1E and non-Class 1E cables the physical separation of which is less than that specified in Section III.G.2 of Appendix R to 10 CFR Part 50 and have one of the following (Ref. 23, Enclosure 2):

- Common Power Source – A power source (e.g., switchgears, motor control centers (MCCs), fuse and circuit breaker panels) that is shared with the shutdown equipment (redundant or alternative) and is not electrically protected from the circuit of concern by coordinated breakers, fuses, or similar devices.

- Common Enclosure – An enclosure (e.g., raceway, panel, or junction box) that is shared with the shutdown cables (redundant or alternative) and (1) is not electrically protected by circuit breakers, fuses, or similar devices, or (2) will allow propagation of the fire into the common enclosure.

An associated circuit of concern for post-fire safe-shutdown may include any circuit or cable that is not needed to support the operation of the required shutdown equipment (i.e., a nonessential circuit), but could adversely affect the plant's ability to achieve and maintain safe-shutdown conditions should it be damaged by fire.

2.2 Evaluation of Cable Fire Test Results

2.2.1 Categories of Information Available for Cable Fire Tests

The PIRT panel broke down into three categories the physical configurations tested during the industry- and NRC-sponsored test programs, based on the information available from the tests:

1. Physical configurations for which the PIRT panel has significant test data. This category has sufficient data such that the panel can predict, with high certainty, the probability and duration of spurious operations, given thermally-induced cable damage. In this category are the following physical configurations:
    a. Control cables, with IEEE STD-383-qualified[8] TS and non-qualified TP insulations, used to control various power plant components via AC electric power. This category includes single conductor, multiple conductors, cables in trays, conduits and/or air drops in either grounded or ungrounded circuits.
    b. Control cables, with IEEE STD-383-qualified TS and non-qualified TP insulations, used to control various power plant components using DC electric power. This includes a single conductor, multiple conductors, cables in trays, conduits, and/or air drops in ungrounded circuits.
2. Physical configurations for which the PIRT panel has sparse data, but which the electrical experts believed reasonably can be represented by the existing test data based on energy level, cable type, and circuit design. This category has sparse test data from which the PIRT panel can predict, with moderate certainty, the probability and duration of spurious operations, given thermally-induced cable damage. In this category are the following configurations:
    a. Armored Control cables, with IEEE STD-383-qualified TS and non-qualified TP insulations, used to control various power-plant components using AC- or DC-electric power. This includes single conductor, multiple conductors, cables in trays, conduits and/or air drops in either grounded or ungrounded circuits.
    b. Three phase AC and two phase DC power cables due to the similarity in fire-induced failure characteristics to the cables fire tested for AC and DC control circuits. The results of the control circuit testing when coupled with the expert knowledge of the PIRT panel members was considered to be an acceptable combination of knowledge for the determinations made in this report relative to AC and DC power cables.
3. Physical configurations for which the PIRT panel has little or no data, and hence the electrical experts can offer only provisional estimates. Due to the lack of test data, the PIRT

[8] Environmentally qualified per IEEE STD-383, "IEEE Standard for Type Test of Class 1E Electric Cables, Field Slices, and Connections for Nuclear Power Generating Stations," 1974.

panel can predict only with low certainty, the probability of spurious operations, given thermally-induced cable damage. In this category are the following configurations:

a. Wiring inside electrical cabinets/panels
b. Trunk cables
c. Fiber optic cables
d. Electrical conductors used in digital control systems
e. Instrumentation and control circuit cables

2.2.2 Cable Fire Test Data Analysis

The EPRI/NEI test data analyses were analyzed thoroughly, and results are detailed in EPRI Technical Report 1006931, dated May 2002 (Ref. 11). However, the PIRT panel initially noted that the test data obtained from both CAROLFIRE (AC tests) (Ref. 9) and DESIREE-Fire (DC tests) (Ref. 10) performed at SNL under the sponsorship of the NRC had not been analyzed for direct use in this PIRT evaluation. Based on the PIRT panel's suggestions and oversight, all test data including both EPRI/NEI and NRC/SNL were analyzed for the following conditions:

For Intra-Cable Hot short-induced Spurious Operation and Duration

- Conductor Count
- Thermal Exposure Condition
- Cable Orientation
- Raceway Routing
- Raceway Fill
- Insulation Type (TS or TP)
- Insulation Materials
- Circuit Type (for DC tests only)
- Insulation-Jacket Material Combinations (TS-TS, TP-TP, TS-TP)[9]
- Control Power Transformer (CPT) Size (for AC circuits) and Fuse Size (for DC circuits)
- Circuit Grounding for AC circuits only
- Wiring Configuration
- Conductor Size
- Suppression Effects for AC circuits only
- Cable Shielding for DC circuits only
- Circuit Concurrence of Hot Shorts for both AC and DC circuits

For Inter-Cable Hot short-induced Spurious Operation and Duration

- Ground Fault Equivalent Hot Shorts for DC circuits only
- Inter-cable (direct cable-to-cable) interaction for both AC and DC circuits

The panel chose several other influencing parameters for the PIRT, but did not include them in their analyses of the test data since the tests' results would not directly exhibit their impacts on

- Cable Aging

[9] PIRT panel did not consider the TP-TS because the panel members did not know any US NPPs currently utilizing any such insulation-jacket material combination cables.

- Supply Voltage Level
- Fire Suppression Effect
- Latching versus Non-Latching Device Configuration

For these four parameters, the PIRT panel used their expert knowledge, phenomenological models, and operating experience in evaluating their effects on the hot short-induced spurious operation in applicable control circuits.

The panel also discussed each of the above items thoroughly so that the outcome of the test data analyses could be used directly in the PIRT process. The NRC staff analyzed the CAROLFIRE data on AC control circuits, including some selected EPRI/NRC data applicable to the specific analysis; the SNL staff analyzed the DESIREE-Fire data on DC control circuits. The results of both analyses then were presented to the panel members for evaluation. The NRC is in the process of publishing the final results of these evaluations in NUREG-2128 (Ref. 20).

2.3 Evaluation of Electrical Circuit Configurations

The electrical expert PIRT panel evaluated three types of electrical circuits (i.e., power, control, and instrument circuits). The panel initially had formulated a scoring scheme that considered all potential influencing parameters for both hot short and spurious operations associated with each of these types. However, after considering the impact of various influencing parameters, the panel concluded that the insufficient test data precluded a meaningful evaluation of power and instrument circuits, deciding that they could only score the control circuit sheets with high certainty.

For the power and instrument circuits, the panel dropped the ranking approach and used the expert elicitation approach for specific fire-induced failure modes. Particularly, for power circuits, the panel generated consensus technical positions on the credibility of certain failure modes. For instrument circuits, they again stated their technical position on credible failure modes and issues of concern. Additionally, since certain instrument circuit-failure modes could have a significantly impact safety in a fire event, they recommended undertaking testing for certain instrumentation and control (I&C) circuit configurations.

For control circuits, the PIRT panel completed detailed scoring sheets to rank the influencing parameters of fire-induced hot shorts that could entail spurious operations, using the following strategy to assess each influencing parameter:

- Review and discuss, as necessary, the cable's configuration with respect to the circuit of concern, the figures-of-merit (stated in Section 1.3 of this report), and test results presented in the draft NUREG-2128 (Ref. 20),

- Rank the applicability of each influencing parameter to current plant circuit designs,

- Grade the quality of test data available for the cable's configuration. If the influencing parameter is not adequately represented by the test data, then rank the ease of research needed for characterizing its impact, and,

- Denote the parameter's importance and state of knowledge for hot short-induced spurious operations and their durations for both intra-cable and inter-cable conductor shorts.

2.3.1 Influencing Parameters

The PIRT panel identified a range of factors that may affect the conditional probability of hot short-induced spurious operation in a control circuit. Given fire-induced damage to a cable, a particular mode of circuit failure might be observed. Various factors also might influence the timing of potential faults being observed and of fault-mode transitions (e.g., hot short transition to a short to ground or fuse blown). The influencing factors known to the PIRT panel can be roughly categorized into one of four broad groups as follows (Ref. 19):

- Physical properties and configuration of the cable,
- Routing of the cable on raceways,
- Electrical function of the circuit, and,
- Fire exposure conditions.

Based on detailed discussions of the various aspects of hot short-induced spurious operation, the PIRT panel developed the MICROSOFT® EXCEL scoring sheets (shown in Appendix B) for the intra-cable and inter-cable hot short-induced spurious operations, and their duration using the following influencing parameters:

1. Conductor Count (a. 1/C (one conductor); b. 2-6/C; c. 7-9/C; d. 10-15/C; e. >15/C)
2. Fire Exposure Condition (a. Flame; b. Plume; c. Hot Gas Layer; d. Time/temperature)
3. Cable Routing / Raceway (a. Cable Tray Vertical; b. Cable Tray Horizontal; c. Conduit Horizontal; d. Conduits Vertical; e. Air Drop; f. Tray type (Ladder/Solid))
   g. Panel Wiring (Note: treated separately due to lack of sufficient test data)
4. Cable Raceway Fill (a. Maximum Loading; b. Intermediate Loading; c. Minimum Loading (1 or 2 cables))
   d. Bundles (Note: treated separately since test data was available for different bundle configurations)
5. Conductor Insulation Material (TS/TP)
6. Cable Aging
7. Cable Jacket Insulation Material (a. Material (TS/TP); b. Coatings; each treated separately)
8. Time-Current Characteristics (Fuse/breaker size) Available fault current
   Note: CPT Size later was dropped due to inadequate support in NRC tests when compared with EPRI test findings.
9. Cable Grounding Configuration (for AC Circuits only) (a. Ground or Drain Wire; b. Shield Wrap – each treated separately).
10. Power Supply Voltage (for AC Circuits only) (a. < 100V; b. 120V; c. > 150V).
11. Armor Grounded versus Ungrounded (for AC Circuits); Armored versus Unarmored Cable (for DC Circuits)
12. Cable Wiring Configuration (a. Number of Sources; b. Number of Targets; c. Locations of Sources & Targets; d. Number of Grounds/Neutrals)
13. Conductor Size
14. Fire Suppression (a. Water Spray; b. Hose)

15. Latching versus Non-latching Device (a. Latching MOV; b. Non-Latching MOV)

16. Grounded versus Ungrounded Circuit (for AC circuits only).

As the base cases, the PIRT panel assumed that typically all AC circuits are grounded, while all DC circuits are ungrounded; they did not consider grounded DC circuits. However, since some plants have ungrounded AC circuits, they were included as one of the special cases (i.e., item 16 above) later in the deliberation of the PIRT panel. (See also footnote 7 on page 2-3).

2.3.2 Electrical Circuits Considered by the PIRT Panel

The following discussions address the PIRT panel's evaluation process of the three circuit types: control, power, and instrument circuits. In addition, several ancillary circuit-related issues or concerns associated with fire-induced safe-shutdown analyses are identified by the PIRT panel for discussion.

2.3.2.1 Control Circuits

Typical control cables used in NPPs have a voltage rating of 600 V for 120-125V range circuits. Primarily, multi-conductor cables with 3, 7, or 11 conductor configurations and 16-10 American Wire Gauge (AWG) conductor sizes are typically used in the control circuits. These cables are available armored or unarmored. Armored cable has a metallic outer sheath (or armor) made from interlocked aluminum or steel; however, unarmored control cables are more common in NPPs.

The PIRT panel used the scoring sheets to rank the influencing parameters on hot short-induced spurious operations. The PIRT panel also defined the following columns in the MICROSOFT® EXCEL scoring sheets for the likelihood of hot short-induced spurious operation for both intra-cable and inter-cable shorts, and its duration effect, given cable damage due to a fire:

- Effect of Parameters on the Likelihood – Intra-Cable Hot Short-Induced Spurious Operation
- Effect of Parameters on the Likelihood – Inter-Cable Hot Short-Induced Spurious Operation
- Effect of Parameters on the Likelihood – Inter-Cable Ground Fault Equivalent Hot Short-Induced Spurious Operation
- Effect of Parameters on the Duration – Hot Short-Induced Spurious Operation

The hot shorts of concern are those energized source conductors coming into contact with a separate target conductor, other than neutral or ground, with the potential to provide voltage and/or current to a device such as a relay or coil. This includes an energized source conductor coming into contact with a spare conductor. The only hot short of interest is one of sufficient quality (with sufficient duration and energy) to actuate the end device.

The spurious operations of concern are those that cause an inadvertent energization of a device wherein an operational mode of the circuit is initiated. In applying their quantification method, the PRA scenario defines one or more specific spurious operation devices of interest. In the context of interpreting fire-test data, the device of interest only includes the end devices subjected to the test, which were

- solenoids
- motor starter contactors
- breaker close and trip coils.

The PIRT panel's evaluation did not include the following modes as a spurious operation:

- energization of spare conductors
- energization of indicating lights (burden resistors simulating light bulbs).

For the "Effect of Parameters on the Likelihood – Intra-Cable Hot Short-Induced Spurious Operation" and "Effect of Parameters on the Likelihood – Inter-Cable Hot Short-Induced Spurious Operation," the panel made the following assumptions in ranking them:

- Fire damage has occurred, meaning in this context, that the insulation of the cable conductor was damaged to the point of functional failure.
- The hot short has occurred as per the definition above and may or may not be associated with the "device of concern":
    - solenoids
    - motor starter contactors
    - breaker close and trip coils.
- The duration of a hot short between two conductors in a circuit is long enough to cause this device to operate spuriously.
- The duration of a spurious operation is long enough to cause change of any sort in the state of the device.

For the "Effect of Parameters on the Likelihood – Inter-Cable Ground Fault Equivalent Hot Short-Induced Spurious Operation," the following assumptions were made for panel's ranking:

- Fire damage has occurred, i.e., insulation of the cable conductor was damaged to the point of functional failure.
- The hot short has occurred as defined above and may or may not be associated with the "device of concern":
    - solenoids
    - motor starter contactors
    - breaker close and trip coils.
- The duration of a hot short through a ground plane in a circuit persists long enough to cause a spurious operation of the device of concern.
- The duration of a spurious operation is long enough to cause any change in the state of the device of concern.

For the Effect of Parameters on the Duration – Hot Short-Induced Spurious Operation," the following assumptions were made for PIRT panel's ranking:

- Fire damage has occurred, i.e. the cable conductor's insulation has been damaged to the point of functional failure.
- The duration of hot short-induced spurious operation lasts long enough to cause any change in the state of the device of concern.

Cable tests indicate that spurious operations have a relatively high likelihood after fire-induced damage to a control cable. Several influencing factors were noted that could impact this behavior. Existing evidence implies that multiple concurrent spurious operations are possible and potentially likely after fire damage to multiple control cables that are susceptible to hot shorts. The PIRT panel developed scoring sheets that described the effect of each influencing parameter on the hot short-induced spurious operation, and its duration for both intra-cable and inter-cable configurations.

Using the collective expertise of the PIRT panel in analyzing fire-induced circuit failures and their level of knowledge, together with the results of industry and NRC cable-fire tests, a consensus score for each of the items was developed. This consensus was followed by an individual scoring by each of the panel members who gave comments or different views should a member's view differ from that of the majority opinion. Specifically, each panel member evaluated and provided on MICROSOFT® EXCEL scoring sheets with their independent scores for each influencing parameter for hot short-induced spurious operations, and their duration. If an individual score was very different from the consensus, the PIRT panel members offered comments explaining their opinion on the subject area.

2.3.2.2 Power Circuits

Typical safety-related power cables used in NPPs are applied at nominal operating voltages from 120 V to 4.16 kV. These cables are single-conductor or multi-conductor (Triplex) cable with three spirals wound individually insulated conductors and may include an uninsulated grounded drain conductor. Each conductor's size is 12 AWG or larger.

The most likely types of power cable faults (shorts to ground) typically lead to a loss of primary motive power to plant equipment or devices as a result of overcurrent protective device actuation. Continuously operated components such as pumps, fans, and motors will stop and/or be unable to start. Intermittent operating devices, such as MOVs, would be unable to move or would cease moving if they were moving when the cable failed. Devices that require continuous power to maintain position, such as a solenoid operated valve, would revert to the de-energized state or maintain the de-energized state if not energized at the time of fault.

Loss of primary motive power could result from several types of power cable failure modes, such as:

- Single or multiple phase-to-ground short circuits
- Phase-to-phase or three-phase short circuits.

In each case, the cable failures would, for a properly designed power system, lead actuation of circuit overcurrent protective features (e.g., breakers and/or fuses opening). Given the many ways that power cable failures might engender an open circuit fault, the loss of motive power will be the predominant fault mode subsequent to the fire-induced failure of power cables.

Finally, the PIRT panel decided not to include the power circuits in their evaluation process similar to the control circuits. Instead, they considered the following two power circuit fault modes (as described in Section 4):

- Three-phase proper-polarity hot short (ac) , and
- Multiple proper-polarity hot shorts leading to spurious operation of DC motors.

2.3.2.3 Instrument Circuits

Instrument circuits (also known as instrumentation and control circuits) can typically use single twisted shielded pair conductor cables or much larger multi-conductor cables consisting of 50 or more conductors. Each instrument conductor typically is size 16 AWG or smaller. These cables frequently enclose several “twisted/shielded pairs” of conductors contained within a protective outer jacket. The shielding blocks external sources of electrical “noise” generated by other plant equipment.

Instrumentation circuits are typically low-voltage (0-5 volts) or low-current loops (typically 4-20 milliamps) connecting various types of sensors to remote monitoring equipment (e.g., control room indicators) and actuation devices (e.g., interlocks and trip units) that automatically control plant equipment.

The PIRT panel discussed instrument circuits in detail. However, due to a lack of fire test data, the parameters influencing hot short-induced spurious operations could not be identified and ranked in the same manner as for the control circuits. Therefore, the PIRT panel recommended undertaking more research and testing in this area.

Based on some limited earlier cable-failure testing of instrument circuits at SNL (Ref. 21), the following circuit failure characteristics were noted:

- Instrument cables failed earlier than co-located control cables during the tests
- TP cable failed early and the instrument signal was lost abruptly
- TS cables experienced degradation and subsequent failure over a more extended period than did other cables, typically several minutes
- The behavior of an instrument circuit with specific degradation is predictable based on a simple circuit analysis.

The loss of instrument readings, and false or corrupted signals, may cause a loss of function for the system and may or may not have been identified as a part of the plant shutdown model in the Fire PRA. Therefore, the PIRT panel recommends further testing to identify the types of instrument systems that may be susceptible to fire-induced spurious operations. Section 5 reports the PIRT panel’s discussions of these issues and their recommendations for testing several analog current loop systems.

2.3.2.4 Ancillary Electrical Circuit Issues

The electrical expert PIRT panel evaluated several known issues or concerns associated with deterministic fire-induced safe-shutdown analyses that often form the basis for treating issues or concerns in Fire PRAs. The evaluations for these issues were considered as part of this project's ancillary objectives. The PIRT considered it appropriate to address these issues to ensure treatment within both deterministic and risk-informed analyses for the failure modes in question is consistent with the risk posed. They may or may not be associated with hot short-induced spurious operations; some have been categorized as legacy issues since the Browns Ferry fire accident in 1975, and subsequent regulatory guidance. The PIRT panel was asked to consider each of the following cases from their phenomenological- and electrical-engineering perspectives and provide their technical positions:

- Multiple high impedance fault (MHIF) on a common power supply (ac/dc)
- Open circuited secondary of current transformers (CTs)
- DC control power impact on common enclosure/common power supply
- Control power transformers (CPTs)
- Kapton-insulated cables
- Panel wiring
- High conductor count trunk cables

Section 6 of this report discusses the PIRT panel's technical positions on each of these issues.

2.4 PIRT Panel Evaluation Process for Control Circuits

The PIRT panel considered the following when evaluating the control circuits. The control circuit may be a motor-operated valve (MOV), a solenoid-operated valve (SOV), or a breaker-control circuit. The connected conductors within the circuit configuration can be TS- or TP-insulated and located on electrical tray raceways or in conduits. Section 2.3.1 lists the parameters that could influence a control circuit of concern or that are associated with the fire characterization. A description is given next of the process used to rank the identified parameters by the PIRT panel as possibly influencing the failure mode and duration of hot short-induced spurious operations after fire damage to electrical cables. The individual parameters were ranked according to their applicability, importance, ease of conducting research on them, and current state of knowledge.

"Parameter Applicability" considers if the particular influencing parameter is representative of existing cable configurations in NPPs. "Research Ease" addresses the ease of conducting any additional needed research to better understand the effect of this parameter on the hot short-induced spurious operation. The PIRT panel scored these two columns before evaluating the impact of each influencing parameter on this spurious operation. Then, they assessed and scored the following first two bullets (for AC circuits) or first three bullets (for DC circuits) for the modes of hot shorts (i.e., intra-cable, inter-cable, and inter-cable with ground plane interaction) and the last bullet for the duration of hot short-induced spurious operation:

- Effect of Parameters on the Likelihood – Intra-Cable Hot Short-Induced Spurious Operation
- Effect of Parameters on the Likelihood – Inter-Cable Hot Short-Induced Spurious Operation
- Effect of Parameters on the Likelihood – Inter-Cable Ground Equivalent Hot Short-Induced Spurious Operation
- Effect of Parameters on the Duration – Hot Short-Induced Spurious Operation

In the early stages of the project, each panel member used a "Number Scheme" for scoring for statistical analyses among all panel members, retaining it until the final consensus scores were determined, as presented in Appendix B. However, the final scoring scheme was converted to an equivalent "Letter Scheme" before the results are presented in Tables 3-1 and 3-2.

The AC and DC control circuits were evaluated in two separate MICROSOFT® EXCEL worksheets. The panel first discussed the importance of each influencing parameter on the circuit's failure mode (i.e., hot short-induced spurious operation). For each influencing parameter apposite to the cable configuration in an NPP, the panel members completed the stages of assessment as described in Tables 2-1 through 2-4, which illustrate the "Letter Scheme" and the "Number Scheme."

Table 2-1 on ranking parameter-applicability and Table 2-2 on research ease are applicable to each influencing parameter, irrespective of any of the hot short phenomena identified above (i.e., intra-, inter-, inter-cable ground-fault equivalent, or duration).

Table 2-1. Parameter Applicability Ranking

High (H or 3)	The specific physical configuration of the parameter exists in many US nuclear power plants
Medium (M or 2)	At least one example of the physical configuration of the parameter exists in US nuclear power plants
Low (L or 1)	No such physical configuration of the parameter are known to the panelist in US nuclear power plants

Table 2-2. Research Ease Ranking

High (H or 3)	Data needed readily is obtainable based on existing experimental capabilities
Medium (M or 2)	Data is obtainable but would require moderate, readily attainable extensions to existing capabilities
Low (L or 1)	Data is not readily attainable and/or would require significant development of new capabilities

During the next stage of the assessment, the PIRT panel ranked the parameter importance and the state of knowledge of each specific phenomenon. Table 2-3 describes this ranking with respect to the two figure-of-merits discussed in Section 1.3 of this report. Table 2-4 describes the criteria that the panel used to rank the state of knowledge.

Table 2-3. Parameter Importance Ranking

High (H or 3)	First order importance to figure of merit
Medium (M or 2)	Secondary importance to figure of merit
Low (L or 1)	Negligible importance to figure of merit.

Uncertain (U or 0)	Potentially important. Importance should be explored through reliable analyses and/or experimentally

Table 2-4. State of Knowledge Ranking

High (H or 3)	Plant-specific or testing database exists, or a highly reliable assessment can be made from existing knowledge. Data readily is available to support the parameter and its vulnerability to spurious operations.
Medium (M or 2)	Existing plant-specific or testing database moderately support the parameter and its vulnerability to spurious operations. Moderately reliable assessments can be made from existing knowledge.
Low (L or 1)	No existing plant-specific or testing database could support the parameter and its vulnerability to spurious operations. Reliable assessments cannot be made from existing knowledge.
Uncertain (U or 0)	The panel is unaware of any existing state of knowledge about this parameter

One primary objective of the PIRT panel was to identify cable configurations that would be vulnerable to hot short-induced spurious operation of certain end devices. The PIRT panel's ranking of these influencing parameters was used to aid in identifying the various control circuit configurations that are most vulnerable to hot short-induced spurious operations.

2.5 Technical Challenges

During the PIRT discussions on the influencing parameters, the panel faced several technical challenges described below:

- The EPRI/NEI and CAROLFIRE cable-fire tests on AC circuits used MOV control circuits without mechanical/electrical interlocks in their Surrogate Circuit Diagnostic Unit (SCDU) monitoring system; all DESIRE-Fire tests used interlocked MOV-circuits. Hence, analysis of the data from these tests must be interpreted appropriately when comparing the results of AC tests with DC tests.
- All AC tests used an MOV control circuits, and therefore, additional insight may be necessary when using these data to determine the effects on other AC-powered end devices or equipment.
- There are limited test results for power and instrument circuits. The PIRT panel used their experience and expertise to arrive at a technical position for certain power circuit failure modes and in developing recommendations for instrument circuits.
- No test data is available for panel wiring and trunk cables. Since these are common configurations at plants (e.g., panel wiring is present throughout the plant), the panel recognized that this situation posed a gap in knowledge. Additionally, both panel wiring and trunk cables often involve the close proximity of multiple conductors from different circuits. The potential interactions and effects of such configurations are not well understood.
- Fire testing undertaken by Duke Power included armored cables; however, even though some members of the panel were knowledgeable of the test results, the test documents are

proprietary, and therefore, not available for public use. Their knowledge of these findings was a factor in the PIRT panel's position on certain parameters; however, the test data did not get the same scrutiny as did other test data received.

- There are very limited test results for ungrounded AC circuits, even though several plants use ungrounded AC for control circuits.
- Knowledge of the effect of the following influencing parameters on hot short-induced spurious operations is inadequate (ranked "Low" in ranking sheets):
  - Conductor count
  - Fire exposure
  - Cable aging
  - Cable coating
  - Fuse/Breaker size
  - Drain or shield wire
  - Voltage level
  - Conductor size
  - Fire suppression

To resolve some of these technical challenges and to better understand the impact of certain influencing parameters on the hot short-induced spurious operation of certain end devices, the PIRT panel offered several recommendations for several future research areas, documented in Section 7 of this report.

3 PIRT PANEL EVALUATION OF CONTROL CIRCUITS

One mode of failure of control circuits is hot short-induced spurious operation the behavior of which may be dynamic and transient, changing its state throughout the course of a fire event. As the fire continues, multiple cables may fail at discrete times, and multiple circuit hot shorts may become part of the circuit failure. This pattern could entail the simultaneous behavior of two or more circuits experiencing concurrent spurious operations. With an adequately protracted fire exposure, conductor-to-conductor shorts are likely to transition into shorts to ground that eventually actuate an overcurrent protective device (i.e., blow fuse or trip breaker).

During the first PIRT meeting, the PIRT panel developed ranking worksheets in MICROSOFT® EXCEL involving all the influencing parameters listed in Section 2.3.1 for all three circuit types (i.e., control, power, and instrument), with separate worksheets for AC- and DC-power supply (i.e., six worksheets). The panel also agreed upon a scoring scheme commensurate with the objectives of this project and the figures-of-merit. Thereafter, the PIRT panel initially ranked the influencing parameters and then forwarded the worksheets to BNL for analysis. The analyses of these independent panel-member's rankings using the "Number Scheme" revealed that each person had considerable difficulty in interpreting the ranking scheme. Also, most encountered problems in filling out these worksheets for power and instrumentation circuits due to lack of adequate test data, and the inapplicability of many parameters to power and instrumentation cabling. During the second PIRT meeting, the panel discussed these drawbacks, and agreed to abandon the PIRT process for power and instrument circuits. For control circuits, the PIRT panel applied the PIRT process. However, because of the extreme difficulty in analyzing the raw data in the test reports, they decided that both the CAROLFIRE and DESIREE-Fire test results must be analyzed and organized such as to allow a clearer interpretation of the effects of each influencing parameter. They also combined the results of the EPRI/NEI tests in the overall data analysis; this action is documented in NUREG-2128 (Ref. 20).

As shown in Figure 2-1, the PIRT panel followed Steps 7 through 9 to identify those control circuits that would be vulnerable to hot short-induced spurious operations. To identify the most significant influencing parameters, the members first highlighted all plausible influencing parameters and ranked them to assess their impact on hot short-induced spurious operation and duration. During meetings, the panel discussed each influencing parameter in great detail and selected some of the significant ones to include in the control circuit characterization. Furthermore, they derived various circuit characteristics (such as the power source variations, hot short modes of failure) from fire tests (in Step 4) and from their past experience on the subject. Finally, the panel identified those simplified control circuit electrical diagrams typically used in NPPs to control certain end devices, specifically, the MOV, SOV and circuit-breaker circuits. The final control circuit configurations they selected included six with a single contact (or break) and seven with double contacts (or breaks).

3.1 Impact Assessment of Influencing Parameters

The PIRT panel spent a considerable time debating the impact of the influencing parameters on hot short-induced spurious operation of control circuits. Tables 3-1 and 3-2, respectively, present their consensus ranking of all influencing parameters for AC- and DC-control circuits.

PIRT PANEL EVALUATION OF CONTROL CIRCUITS

The panel made the baseline assumption that AC control circuits are grounded, and DC control circuits are ungrounded (see footnote 7 on page 2-3). In addition to individual scores for the subgroups associated with each influencing parameter, an overall score (in bold) is shown for the impacts of this parameter on the likelihood of spurious operation and its duration.

The following is a summary explanation of the PIRT panel's ranking given Tables 3-1 and 3-2. The column headings are described in Section 2.4. The following apply to both tables.

1. <u>Conductor Count</u>

Control cables typically contain 3, 7, or 11 conductors. Some trunk cables that are used for multiple control circuits contain as many as 37 or more conductors. While the number of conductors can influence the likelihood of spurious operation, the PIRT panel did not consider it to be a primary influencing parameter because the wiring configuration has a higher influence on the likelihood of spurious operation. Therefore, the number of conductors was considered a secondary factor in the wiring configuration parameter because of its effects on some of the wiring configuration's sub-categories (i.e., the number of sources, targets, and mitigating conductors (e.g. grounded or return)). Hence, the PIRT panel determined that conductor count could be ranked "Low" as an influencing factor, but its overall importance ultimately would be reflected in the wiring-configuration parameter (see item 12 below).

2. <u>Fire Exposure Condition</u>

A range of data was reviewed for direct flame impingement, plume, and hot gas layer (HGL) exposures. All Penlight[10] tests performed at SNL were subjected to radiant heating, a usage that closely simulated the presumed HGL behavior of the fire. However, the Penlight temperature profiles were designed to assure cable damage and the conditions for thermal exposure were significantly higher than that would be expected for an actual HGL in an NPP. Often the test temperature of the Penlight shroud was high enough to exhibit thermal conditions similar to plume- or flame-fire zones.

One surrogate for the exposure conditions explored in the data analysis was time to damage. Since the initial cable damage and subsequent degradation of the conductor's insulation occurs more rapidly for cable in the flame and more slowly for a cable in the HGL, the potential was evaluated of fire exposure conditions to affect the duration of hot short-induced spurious operation. Plots illustrating their effects are included in the data analysis NUREG-2128 (Ref. 20). The assumption is that the cable's behavior under fire more closely simulates that in the HGL condition may be accurate for comparing the thermal conditions, but the failure-mode data in Figures 2-5 and 4-9 of Ref. 20 does not show this relation. Rather, the data indicates that modes of fire-induced cable failure do not follow this assumption of simulating the HGL condition, and specifically, that the likelihood is that the radiant-failure mode is similar to the conditions of exposure to the plume and flame conditions. The PIRT panel determined that the fire exposure conditions seemingly play some role in the likelihood of spurious operation (ranked Medium), and a relatively strong role in the duration of spurious operation (ranked "High").

[10] Penlight are small-scale tests involving one to six lengths of cable exposed to grey-body radiant heating in a cylindrical exposure chamber in the CAROLFIRE and DESIREE-Fire test programs (Refs. 9 and 10) performed at SNL.

Table 3-1. Panel Consensus Ranking of Influencing Parameters for AC Control Circuits

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
1	**Conductor Count**			**L**			**L**			**NA**			**L**		
	a. 1/C	M	NA		NA	NA		L	M					L	M
	b. 2-6/C	H	H		L	M		L	M					L	M
	c. 7-9/C	H	H		L	H		L	H					L	H
	d. 10-15/C	H	H		L	M		L	M					L	M
	e. >15/C	H	H		L	L		L	L					L	L
2	**Fire Exposure Condition**			**M**			**M**			**NA**			**H**		
	a. Flame	H	H		M	H		M	H					H	H
	b. Plume	H	H		M	H		M	H					H	H
	c. Hot Gas Layer	M	H		M	H		M	H					H	H
	d. Time/Temperature	L	H		M	L		M	L					H	L

Table 3-1: Panel Consensus Ranking of Influencing Parameters for AC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
3	**Cable Routing/Raceway**			**L**			**L**			**NA**			**L**		
	a. Cable Tray Vertical	H	H		L	M		L	M					L	M
	b. Cable Tray Horizontal	H	H		L	H		L	H					L	H
	c. Conduit Horizontal	H	H		L	H		L	H					L	H
	d. Conduit Vertical	H	H		L	M		L	M					L	M
	e. Air Drop	M	H		L	M		L	M					L	M
	f. Tray Type (Ladder/Solid)	H	H		L	L		L	L					L	L
	g. **Panel Wiring***	H	M	**H**	H	L	**H**	H	L	**NA**			**H**	H	L
4	**Cable Raceway Fill**			**L**			**M**			**NA**			**M**		
	a. Maximum Loading	H	H		L	M		M	M					M	L
	b. Intermediate Loading	H	H		L	H		M	H					M	M
	c. Minimum Loading	H	H		L	H		M	H					M	H
	d. **Bundles***	H	H	**M**	M	H	**M**	M	H	**NA**			**M**	M	H

Table 3-1: Panel Consensus Ranking of Influencing Parameters for AC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
5	**Conductor Insulation Material**	H	H	**L**	L	H	**H**	H	H	**NA**			**L**	L	H
6	**Cable Aging**	H	H	**L**	L	L	**L**	L	L	**NA**			**L**	L	L
7	**Cable Jacket Insulation Material**														
	a. Material*	H	H	**L**	L	H	**M**	M	H	**NA**			**L**	L	H
	b. Coating*	H	H	**L**	L	L	**L**	L	L	**NA**			**L**	L	L
8	**Time-Current Characteristics - Fuses/Breaker Size**	H	L	**L**	L	L	**L**	L	L	**NA**			**H**	H	L
9	**Cable Grounding Configuration**			**H**			**H**			**NA**			**M**		
	a. Ground or Drain Wire	L	H		H	M		H	M					M	L
	b. Shield Wrap	M	H		H	L		H	L					M	L

Table 3-1: Panel Consensus Ranking of Influencing Parameters for AC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
10	**Power Supply Voltage**			**L**			**L**			**NA**			**L**		
	a. <100 V	L	M		L	L		L	L					L	L
	b. 120 V	H	H		L	H		L	H					L	H
	c. >150 V	L	M		L	L		L	L					L	L
11	**Armor Grounded versus Ungrounded Circuit**	H	H	**H**	H	L	**H**	H	L	**NA**			**M**	M	L
12	**Cable Wiring Configuration**			**H**			**H**			**NA**			**H**		
	a. Number of Sources	H	H		H	M		H	M					H	M
	b. Number of Targets	H	H		H	M		H	M					H	M
	c. Locations of Sources & Targets	H	H		H	M		H	M					H	M
	d. Number of Grounds/ Neutrals	H	H		H	M		H	M					H	M
13	**Conductor Size**	H	H	**L**	L	M	**L**	L	M	**NA**			**L**	L	L

Table 3-1: Panel Consensus Ranking of Influencing Parameters for AC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
14	**Fire Suppression**			**L-M**			**L-M**			**NA**			**U**		
	a. Water Spray	H	H		L-M	L		L-M	L					U	L
	b. Hose	H	H		L-M	L		L-M	L					U	L
15	**Latching versus Non-latching Device**			**L**			**L**			**NA**			**H**		
	a. Latching MOV	H	H		**L**	**L**		**L**	**L**					H	H
	b. Non-latching MOV	H	H		L	H		L	H					H	H
16	**Grounded versus Ungrounded Circuit**	M	H	**L**	L	M	**H**	H	M	**NA**			**M**	M	L

NOTES: **H – High; M – Medium; L – Low; U – Uncertain; N/A – Not Applicable**
*** PIRT Panel Ranked Separately from the Group**

Table 3-2. Panel Consensus Ranking of Influencing Parameters for DC Control Circuits

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
1	**Conductor Count**			**L**			**L**			**L**			**L**		
	a. 1/C	M	NA		NA	NA		L	M		L	M		L	M
	b. 2-6/C	H	H		L	M		L	M		L	M		L	M
	c. 7-9/C	H	H		L	H		L	H		L	H		L	H
	d. 10-15/C	H	H		L	M		L	M		L	M		L	M
	e. >15/C	H	H		L	L		L	L		L	L		L	L
2	**Fire Exposure Condition**			**M**			**M**			**M**			**H**		
	a. Flame	H	H		M	H		M	H		M	H		H	H
	b. Plume	H	H		M	H		M	H		M	H		H	H
	c. Hot Gas Layer	M	H		M	H		M	H		M	H		H	H
	d. Time/Temperature	L	H		M	L		M	L		M	L		H	L

Table 3-2. Panel Consensus Ranking of Influencing Parameters for DC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
3	**Cable Routing/Raceway**			**L**			**L**			**L**			**L**		
	a. Cable Tray Vertical	H	H		L	M		L	L		L	L		L	L
	b. Cable Tray Horizontal	H	H		L	H		L	H		L	H		L	H
	c. Conduit Horizontal	H	H		L	H		L	M		L	M		L	M
	d. Conduit Vertical	H	H		L	M		L	L		L	L		L	L
	e. Air Drop	M	H		L	M		NA	NA		NA	NA		L	L
	f. Tray Type (Ladder/Solid)	H	H		L	L		L	L		L	L		L	L
	g. Panel Wiring*	H	M	**H**	H	L	**H**	H	L	**M**	M	L	**H**	H	L
4	**Cable Raceway Fill**			**L**			**M**			**L**			**L**		
	a. Maximum Loading	H	H		L	M		M	L		L	L		L	L
	b. Intermediate Loading	H	H		L	H		M	H		L	H		L	H
	c. Minimum Loading	H	H		L	H		M	H		M	H		M	H
	d. Bundles*	H	H	**L**	L	H	**M**	M	M	**M**	M	M	**M**	M	M

Table 3-2. Panel Consensus Ranking of Influencing Parameters for DC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
5	**Conductor Insulation Material**	H	H	**L**	L	H	**H**	H	H	**L**	L	M	**M**	M	H
6	**Cable Aging**	H	H	**L**	L	L	**L**	L	L	**L**	L	L	**L**	L	L
7	**Cable Jacket Insulation Material**														
	a. Material*	H	H	**L**	L	H	**M**	M	H	**L**	L	H	**L**	L	H
	b. Coating*	H	H	**L**	L	L	**L**	L	L	**L**	L	L	**L**	L	L
8	**Time-Current Characteristics - Fuses/Breaker Size**	H	H	**L**	L	L	**L**	L	L	**L**	L	M	**H**	H	H
9	**Cable Grounding Configuration****			**NA**			**NA**			**NA**			**NA**		
10	**Power Supply Voltage**			**NA**			**NA**			**NA**			**NA**		
11	**Armored versus Unarmored Cable**	M	H	**L**	L	L	**H**	H	L	**H**	H	L	**M**	M	L

Table 3-2. Panel Consensus Ranking of Influencing Parameters for DC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
12	**Cable Wiring Configuration**			**H**			**H**			**H**			**H**		
	a. Number of Sources	H	H		H	M		H	M		H	M		H	M
	b. Number of Targets	H	H		H	M		H	M		H	M		H	M
	c. Locations of Sources & Targets	H	H		H	M		H	M		H	M		H	M
	d. Number of Grounds/ Neutrals	H	H		H	M		H	M		H	M		H	M
13	**Conductor Size**	H	H	**L**	L	M	**L**	L	M	**L**	L	M	**L**	L	L
14	**Fire Suppression**			**L-M**			**L-M**			**M**			**U**		
	a. Water Spray	H	H		L-M	L		L-M	L		M	L		U	L
	b. Hose	H	H		L-M	L		L-M	L		M	L		U	L
15	**Latching versus Non-Latching Device**			**L**			**L**			**L**			**H**		
	a. Latching MOV	**H**	**H**		**L**	**L**		**L**	**L**		**L**	**L**		**H**	**H**
	b. Non-latching MOV	**H**	**H**		**L**	**H**		**L**	**H**		**L**	**L**		**H**	**H**

Table 3-2. Panel Consensus Ranking of Influencing Parameters for DC Control Circuits (Cont'd.)

Identification	Influencing Parameter	Parameter Applicability	Research Ease	Effect of Parameters on the Likelihood - INTRA-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood - INTER-CABLE GROUND FAULT EQUIVALENT HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge	Effect of Parameters on the DURATION - HOT SHORT-INDUCED SPURIOUS OPERATION	Parameter Importance	State of Knowledge
16	Grounded versus Ungrounded Circuit**			NA			NA			NA			NA		

NOTES: H – High; M – Medium; L – Low; U – Uncertain; NA – Not Applicable

* PIRT Panel Ranked Separately from this Group

** Items 9 and 16 are marked "N/A" since the PIRT panel assumed that all DC control circuits at US NPPs are ungrounded

3. Cable Routing/Raceways

The state of knowledge for configurations other than cable trays and horizontal conduits is weak. In particular, no tests have been completed using panel wiring. Additionally, no tests have compared variations in tray type (e.g., no solid bottom trays have been tested). Also, there are very few tests of vertical-raceway orientations. The data analysis revealed, at most, a weak correlation between the routing configuration and the likelihood of spurious operation. For intra-cable shorting, there appeared to be no discernible effect. For inter-cable shorting, there was an indication that raceway type will have some effect, but since only a few spurious operations have been attributed to direct cable-to-cable shorting, i.e., inter-cable shorting, the findings from testing are inconclusive.

The PIRT panel determined that the parameter cable routing/raceways could be ranked “Low” as an influencing factor. One exception was panel wiring that has several unique characteristics that limited the PIRT panel’s ability to use their expert knowledge to extrapolating a position via existing test data. This low state of knowledge about panel wiring, coupled with the PIRT panel’s concern about the possible importance of panel wiring for locations, such as the Control Room, lead them to rank panel wiring as “High” to assure that it would be given adequate consideration for future research. A separate write-up on panel wiring was completed, with recommendations for further testing in Section 6.6. The PIRT panel discussed at great length whether hot shorts in conductor bundles should be treated as either intra-cable or inter-cable hot shorts. This discussion also appears in Section 6.6.

4. Cable Raceway Fill

The relative number of cables in a raceway is not expected to significantly affect the likelihood of spurious operations caused by intra-cable shorts; however, the number of cables determines the number of opportunities for inter-cable shorting; accordingly, it would impact the chance of spurious operation due to inter-cable shorts. More cables generally increase the likelihood of inter-cable shorting, while fewer lower it, or even preclude them entirely (e.g., via maintained spacing or single cables in conduit).

The exception to cable raceway multi-layer cable fill appears to be cables bundled together, such as trunk cables or panel wiring with tie-wraps (e.g., nylon zip ties). In the CAROLFIRE tests, bundled cables were used commonly to form well-defined thermal targets to support the objectives of fire modeling. These bundles seemingly experienced a higher number of spurious operations than did unbundled cable rows lying on a cable tray. The bundling arrangement is thought to have put additional pressure on the cables and conductors, so entailing more conductor-to-conductor shorts. Similar conditions to the bundled arrangement could exist at the bottom of a heavily loaded cable tray. However, overall the PIRT panel ranked the cable raceway fill as a “Low-Medium” influencing.

5. Conductor Insulation Material

The test data encompasses cables insulated with thermoset (TS) materials that include XLPE, EPR, SR and Kerite-FR, while thermoplastic (TP) cable insulation includes PE, PVC, and TEF. These materials commonly are found in the control cable’s insulation and jacket materials used in US NPPs electrical cables.

The insulation type (i.e., TS vs. TP) and specific insulation material had very little effect on the likelihood of intra-cable shorts entailing spurious operation. However, strong effect seemingly is apparent on the likelihood of inter-cable shorts leading to spurious operation. In particular, all test cases causing a spurious operation due to direct cable-to-cable shorting involved cables with TP insulation. No such cases were noted with TS insulated cables, although there were indications of hot short-induced voltages. There have been instances of TS cables producing a spurious operation on a TP cable, but none of TP cables generating a spurious operation on a TS cable. We note that the PIRT panel considers the critical factor is the type of insulation, not the jacket type, which is ranked separately.

Kerite-FR cable-insulation displayed a unique failure mechanism during fire-exposure tests (Ref. 24). The material is a thermosetting polymer, but when experiencing high-temperature electrical failure (from as low as 247 ^{o}C) it displays a failure threshold more typically associated with thermoplastic cable-insulation materials. While the thermal failure threshold of Kerite-FR is relatively low for a thermoset material, the mechanism of its failure does not appear to affects the relative likelihood of hot short-induced spurious operations compared to other thermoset cable insulations. Hence, the PIRT panel concluded that the conditional probability, given cable failure, of a hot short leading to spurious operation would be the same for a Kerite-FR insulated cable as for other thermoset cable insulations.

The CAROLFIRE project (Ref. 9) drew the following conclusions:

Bin 2 Item A – Inter-cable shorting for TS cables:

> "Inter-cable shorting between two TS-insulated cables that could cause hot shorts and the spurious operation of plant equipment was found to be a plausible failure mode, although the likelihood of this failure mode is low in comparison to intra-cable short circuits leading to spurious operation. While no detailed statistical analysis has been performed, it appears that the conditional probability (given cable failure) of spurious operations arising from this specific failure mode is small in comparison to that previously estimated for spurious operations from intra-cable shorting."

Bin 2 Item B – Inter-cable shorting between TP and TS cables:

> "Inter-cable shorting between a TP-insulated cable and a TS-insulated cable that could cause hot shorts and the spurious operation of plant equipment was found to be a plausible failure mode, although the likelihood of this failure mode is low in comparison to intra-cable short circuits leading to spurious operation. While no detailed statistical analysis has been performed, it appears that the conditional probability (given cable failure) of spurious operations arising from this specific failure mode is very small in comparison to that previously estimated for spurious operations from intra-cable shorting."

While these were the conclusions from CAROLFIRE, the PIRT panel arrived at different ones from their review. Specifically, the PIRT panel determined that an inter-cable hot short-induced spurious operation between two TS cables was implausible, and an inter-cable hot short-induced spurious operation in a TS cable by an aggressor TP cable was an incredible event (see Section 3.3.2).

In conclusion, the PIRT panel determined that the insulating material of cable conductors can influence the likelihood of inter-cable failures modes (ranked "High"), but had little effect on the likelihood for intra-cable mode and for duration (ranked "Low-Medium").

6. Cable Aging

The PIRT panel considered a limited set of test data on the damageability of aged and un-aged cables. The PIRT panel also discussed the mechanisms of cable aging and their potential impact on shorting behavior. The state of knowledge on this topic is low. Only one study investigating the effect of thermal aging on cable damageability was identified, and it did not cover fire-induced spurious operations. With the exception of one different opinion, the importance of this factor was considered to be low.

During the PIRT panels discussions related to the affect aging has on the likelihood of electrical cables spurious actuation as a result of fire damage, the panel did not reach unanimous consensus on this ranking. Six of the eight members opinion was that aging should have relatively little effect on the likelihood of spurious operation, given cable failure. This was based on their review of experimental data and expert judgment. They noted some changes in damage threshold, but this change was minimal and their opinion was that cable aging would not affect the failure mode likelihood.

One member believed that this parameter should have a similar level of importance to insulation type, i.e., between "Medium and high." This member believed that the effect of aging on spurious operation likelihood was, at best unknown, and likely important. This member judged that since aging clearly affects the properties of cable insulation (Ref. 25), this factor should have a similar level of importance to insulation type, i.e., between "Medium and High." Specifically, the member expressed their views as follows;

> I disagree with an importance rating of "Low" for this factor. Since aging affects the properties of both the cable jacket and cable insulation (cite Equipment Qualification (EQ) experience as a technical basis), it is unclear what the overall effects of aging will have on the probability of spurious operations. However, ranking this parameter as one of Low significance gives an unverified conclusion that aging effects have no significance.
>
> My overall contention is that both the jacket material and the conductor insulation properties can change significantly due to ageing effects. It appears inconsistent to rank conductor insulation effects on the likelihood of "Inter-Cable Hot Short Induced Spurious Operations" as High and then rank Ageing effects on the likelihood of "Inter-Cable Hot Short Induced Spurious Operations" as Low. My belief is that this factor will become a more important parameter as plants continue to age with license renewals and cables approach their end of life due to a combination of normal ageing and harsh environmental conditions. My recommendation is to conduct testing.

Another member was uncertain to the importance of this parameter on the likelihood of fire-induced spurious operations. This member believed that for several cases the effects of aging should have little to no effect on the fire-induced spurious operation likelihood. However, this member also believed that there are certain scenarios (e.g., inter-cable interactions) where aged cables may behave differently than the test data supports, due to the loss of insulation fillers and additives that volatize during the life of the cable. Therefore, this member could not generically say aging has no effect on spurious operation probability. This member also supported conducting additional research on the effects of aged cable to the likelihood of spurious operation and other fire related aspects (e.g., thermal damage threshold, flame spread, ignition, etc.).

7. Cable Jacket Material

This influencing parameter included the cable jacket's material and coatings. Testing has involved a range of jacket types, but there are only limited data from tests on cable coatings. Accordingly, the assessment of test data analysis was changed from considering the jacket material alone to an evaluation looking at the available combinations of insulation-jacket polymer type. This assessment created three bins of cables with (1) TP insulation and TP jacket, (2) TS insulation and TS jacket, and (3) TS insulation and TP jacket (mixed cable type). In addition, the PIRT panel noted that the NRC's preliminary study of cable coatings is underway at SNL. Since the physical configurations may be different, the PIRT panel separately scored the two subgroups, jacket material and coatings.

The PIRT panel concluded that the jacket material would have little or no effect on the likelihood of intra-cable shorts leading to spurious operation. They ranked the effect on inter-cable shorts as 'Medium' because so few direct cable-to-cable hot short-induced spurious operations have been tested; however, the PIRT panel believed that the jacket material could affect the probability of spurious operations.

Cable coatings or electrical raceway fire barrier systems (ERFBSs) were expected to have no effect on intra-cable shorting and, at most, a small effect on inter-cable shorting (ranked "Low" influence). Coatings are applied to the outside of the cable or group of cables so the impact on the cable itself is minimal. The most significant effect that might occur is a delay of the onset of damage. In addition, coatings may alter the effective exposure mode or the time/temperature relationship.

Publically available Duke Test data concluded that removing the jackets quickened the effects of fire damage but made no significant change to the number of spurious operations.

8. Time-current Characteristics – Fuses/Breaker Size

Effect of CPTs

The original ranking tables and spurious operation likelihood estimates contained in Section 10 of NUREG/CR-6850, EPRI TR 1011989 (Ref. 12) included a subcategory for circuits powered from a control power transformer (CPT). However, after reviewing all available data the PIRT panel elected to remove the distinction between circuits with and without a CPT. The reasoning and basis for this decision is detailed in Section 6.4 of this report.

Effect of Fuses/Breakers (on Duration)

The reasoning used for AC control circuits can also be applied to DC control circuits, as the same engineering principles apply. However, fault behavior for DC circuits is predictably different due to higher available fault currents and a wider range of fuse/breaker sizing for DC circuits. Additionally, DC control circuits are used in nuclear power plant applications to support emergency operations under loss of AC power conditions; thus, overcurrent protective devices tend to be larger so as to provide a bias toward power continuity in lieu of equipment protection. For the DC test configuration, even with complete cable failure, larger size control fuses (e.g., 15A or larger) did not clear. Instead, repeated short-lived but relatively high-energy arcing faults are possible which may physically sever the conductors of the arcing cable. In several cases involving these larger fuses, localized arcing resulted in conductors becoming severed in a short period of time (a few seconds or less). This left the conductors fully separated but still energized. The DC testing also showed some spurious operation signals that persisted for a much longer duration than any observed in the AC testing.

Because of the characteristics of cable failure, the PIRT panel felt that fuse/breaker size and timing characteristics would have a minimal effect on the chances of a hot short inducing a spurious operation (ranked “Low”); however, the PIRT panel did believe that once the spurious operation occurred, the actual duration of the spurious operation could be affected substantially by available fault current, fuse/breaker size, and time-current characteristics (ranked “High”). Most AC control circuit tests to date have been conducted with relatively small fast-blow fuses (i.e., 3 ampere). In the case of CPTs the fusing has always been applied on the CPT secondary side. In other possible configurations (e.g., larger fuses, and fused primary but un-fused secondary) spurious operations may persist for a longer duration.

9. <u>Cable Grounding Configuration (For grounded AC only)</u>

This influencing parameter refers specifically to the potential impact on the likelihood and duration of spurious operations given cable failure for:

(a) a drain wire (i.e., an un-insulated grounded conductor) or
(b) a grounded shield wrap of substantial physical characteristics (e.g., a zinc or copper spirally wound tape rather than an aluminized Mylar overwrap).

The presence of a substantial, readily accessible ground plane within a cable expectedly will increase the likelihood of short-to-ground faults over hot shorts. The PIRT panel considered limited data for shield-wrapped cables from the DESIREE-Fire program, and from one older NRC study on cable aging (Ref. 25) that involved a cable with a drain wire. Finally, the PIRT panel also considered publically available data on testing armored cables. The data from the publically available Duke Test of grounded AC circuits concluded that grounded armor and control-power source practically eliminates fire-induced spurious operations. Overall, the consensus of the PIRT panel is that the presence of these features would substantially reduce the likelihood of spurious operations for grounded circuits. Since these cable configurations facilitate the shorting of cable conductors to ground, the PIRT panel felt that this type of cable also would decrease the duration of any spurious operations that do occur. Therefore, the PIRT panel suggested a ranking of “High” for spurious operations, and “Medium” for influence on duration.

10. <u>Power Supply Voltage</u>

For typical grounded AC control circuits in U.S. plants, the voltage level varies very little. Most circuits are based on standard 120 Vac. The PIRT panel recognized the possibility of some variation in circuit voltages, ranging from a minimum of 24 VDC (for ungrounded DC circuits) and a maximum of 220 VAC for control circuits. Overall, the PIRT panel’s consensus was that variation over this range would have no substantive effect on either the likelihood or duration of spurious operations after a cable failure. Therefore, the panel assigned a “Low” influence ranking to the power-supply voltage.

11. <u>Armored Grounded versus Ungrounded Circuits</u>

We note that the PIRT panel considered this influencing parameter differently for AC control circuits and DC control circuits. As indicated in Tables 3-1 and 3-2, for the former, this parameter was assessed based on the grounded versus ungrounded AC control circuits. The latter were assessed based on armored- versus unarmored-cable configuration rather than the control circuits' configuration since the US NPP industry does not use grounded DC control circuits.

For grounded AC circuits
For armored cables, whether or not the circuit itself is grounded or ungrounded (i.e., whether or not the power source is grounded on the return side) appears to profoundly affect the likelihood of spurious operation. The data available is limited to the tests from EPRI/NEI, and insights from the Duke Test data set. This information suggests that in a grounded AC circuit, the likelihood of spurious operation, given a grounded armor cable, is much lower than for non-armored cables. This is attributed to the readily available mitigating ground plane via shorts to the armor.

Publically available Duke Test results revealed that the duration of the hot short-induced spurious operations of a 37/C armored cable was much longer than that in an 8/C armored cable. We note that the 37/C cable contained multiple circuits whereas the 8/C had only one.

For ungrounded DC circuits
The reasoning about armored cable for DC control circuits parallels that for AC circuits. The one unique aspect of the former is that essentially all of the existing DC power supplies (battery banks) are ungrounded, whereas most AC power supplies are grounded. Hence, the predominant cases for DC versus AC are reversed. Since DC circuits are ungrounded, the PIRT panel evaluated this parameter for an armored cable versus an unarmored cable. Parameter importance rankings paralleled those for AC control circuits with the exception of intra-cable hot short-induced spurious operations that were considered 'Low' for DC circuits due to the ungrounded configuration of a DC circuit. For AC circuits, this parameter was extremely important because grounded armor provided a readily available mitigating ground-plane that would blow a fuse in a grounded AC circuit.

12. Cable Wiring Configuration
We note also that the total number of conductors present in a multi-conductor cable might be a factor herein. One special case of this factor is the use of trunk cables that can house four or more circuits within a single cable. A separate discussion on this topic appears in Section 6.7.

The PIRT panel concluded that the wiring configuration was the single most important factor impacting both the likelihood and duration of fire-induced spurious operations. This configuration embodies several factors, including the total conductor count, the number of source conductors, the number of mitigating conductors (e.g., grounded conductors for a grounded circuit, or circuit return-leg conductors in an ungrounded circuit), and the number of spurious-operation target conductors of interest. For example, given more source conductors, more opportunities exist for a target conductor to be hit by a hot short. At the same time, if those source conductors have common fusing, there are potentially more opportunities for the source conductor to short to a mitigating conductor, so blowing a fuse. With more mitigating conductors present (grounds or return-leg conductors) the likelihood and duration of spurious operation signals both should decrease. Thus, the PIRT panel ranked this parameter effect on spurious operation as "High."

In section 3.4, the high importance of this parameter is reflected in the different circuit configurations and the arrangement of the probability tables. Two of the primary parameters considered are associated with wiring configuration: single-break design/configuration, and double-break design/configuration.

13. Conductor Size

Conductor size, within the realm of AC control circuits, varies over a fairly narrow range. Generally, control circuit cables would consist of 10 AWG conductors on the upper end of the size range, and 16 AWG on the lower end, with 12 and 14 AWG being most typical. Over this range, the PIRT panel concluded that the cable conductor’s size is expected to have little or no effect on either the likelihood of spurious operation or its duration (ranked “Low”).

14. Fire Suppression

Water sprays are likely to cause the formation of additional short circuits that may not have existed previously. For thermoplastic cables, water sprays might cause melted insulation to solidify, potentially "locking-in" conductor-to-conductor shorts. For thermoset cables, water sprays likely will disrupt the residual char layer, allowing more conductors to come into contact either with each other, with ground or interact electrically due to impurities in the water that could create a conductive shorting pathway.

There is very little evidence of the effects of water spray on the behavior of spurious operations in any of the tests. CAROLFIRE included a few tests wherein cables that had not yet failed were sprayed with water, at which time they did fail; however, all such cases involved Silicone Rubber or the silicone-based Vita-Link cables that proved highly resistant to fire-induced thermal damage in the absence of water. In at least one case, the water spray caused the generation of a spurious operation signal, while in another case, fuse-blow failures were observed.

Approximately half of the PIRT panel ranked this factor as “Low” importance, and the other half of the PIRT panel ranked it as “Moderate” importance for the likelihood of spurious operation. There was little direct evidence to support the PIRT panel’s decision. Overall, the effect of water suppression is not considered to be of primary importance to the likelihood of spurious operation, but may be of moderate importance for duration because water sprays may mitigate previously formed spurious operation failures by inducing ground fault equivalent hot shorts. In a practical sense, the PIRT panel also was unable to offer any practical mechanism for incorporating the use of fire-fighting water in the estimates of either the likelihood or duration of spurious operation since the timing of water application, and whether or not water would be applied in any given fire, depends highly on both plant practices and the specific fire event.

15. Latching versus Non-latching Device

Circuit designs that utilize a latching or seal-in feature require only a momentary signal to lock-in the actuation signal. The latching relay itself will maintain the actuation signal until it is either interrupted by events related to the control logic (e.g., a limit switch or timer) or there is a loss of control power to the coil of the latching relay (that may or may not be independent of the control power that activates the latching feature).

The consensus of the PIRT panel was that the latching feature essentially should have no impact on the likelihood of a spurious-operation signal being generated after cable failure (ranked “Low”), but that there is a direct, overriding impact on the duration of the resulting actuation signal (ranked “High”). The duration is not driven by the modes of cable failure and the effects factors that drive other non-latching circuits; rather, it is driven by those circuit design features that define the trip behavior of the latching relay coil. Since the behavior of latching versus non-latching circuits is independent of the fire damage experienced, this characteristic is not addressed any further in this document.

16. <u>Circuit Grounded versus Ungrounded (For ungrounded AC only)</u>
For a grounded circuit, a single short between an energized source conductor (a "hot" conductor) and ground may cause fuse-blow failures that would reduce the likelihood of a hot short leading to spurious operation. This also could mitigate hot short signals formed previously (i.e., impacting the hot short's duration). In contrast, for an ungrounded circuit, a single short to ground on either the "hot" or "return" side of the circuit will not cause a fuse-blow failure. Ground fault equivalent hot shorts (or a direct short between a hot- and return-conductor) are required to cause such a failure.

In grounded circuits with CPTs, the common return of the CPT secondary is grounded. Then, two CPTs (similar to two battery banks in DC) that already share a common ground (grounded circuits) are considered compatible power sources because a single hot short from one source circuit to a second target circuit can actuate the target circuit. For ungrounded circuits, the CPTs are not considered compatible power sources in their nominal state. That is, a single hot short between circuits cannot trigger a spurious operation. In ungrounded circuits, ground fault equivalent hot shorts might cause normally incompatible power sources (e.g., separate CPTs) to become compatible power supplies. For example, shorts to ground on the return side of two ungrounded CPTs will form a current return path between the two circuits allowing a separate single hot short between the circuits to cause an actuation signal.

The last effect is that ungrounded circuits require direct shorting (i.e., conductor-to-conductor) or indirect shorting (e.g., ground fault equivalent hot shorts) between the energized- and return-conductors of the power supply to cause a fuse-blow failure. For grounded circuits, as noted above, a single short between an energized conductor and ground can do so. Consequently, there may be some secondary effect on the potential duration of any spurious operation signals that occur for ungrounded versus grounded circuits. The effect is considered of secondary importance because the duration/mitigation of the spurious operation signals appears to be dominated by the cascading catastrophic breakdown of the cables; this appears to occur over a short time and causes essentially all conductors to short together, and often shorting to ground as well. For either grounded- or ungrounded-circuits, a catastrophic cable breakdown will blow the fuses.

For grounded AC control circuits, circuit grounding is considered of primary importance only for the inter-cable shorting behaviors (ranked “High”). This is considered to be true since the presence of a ground within the control cable is expected more likely to result in a fuse blow within the cable prior to an interaction with a target or source conductor in an adjacent and separate cable. Several behaviors interact in this case, so complicating the situation.

3.2 Summary of Influencing Parameters Importance

In analyzing the results given in Tables 3-1 and 3-2, the PIRT panel developed an overall consensus that certain parameters have LOW to MEDIUM impact on the phenomena of hot short-induced spurious operation and their duration based on their evaluation of the test data, included that from the NRC/SNL and EPRI/NEI tests, along with PIRT panels' expert judgment. Therefore, in identifying the control circuit configurations the PIRT panel did not consider the following parameters capable of influencing the vulnerability of hot short-induced spurious operations and their duration:

- Conductor count
- Fire Exposure Condition (on spurious operation probability)
- Cable Routing/Raceway (except Panel Wiring)
- Cable Raceway Fill (except Bundles)
- Conductor Insulation Material (for Intra-Cable spurious operation probability and duration)
- Cable aging (with differing views)
- Cable Jacket Insulation Material
- Time-Current Characteristics (for spurious operation probability only)
- Power Supply Voltage
- Conductor size
- Fire Suppression

The above influencing parameters are considered to have a LOW to MEDIUM impact on spurious operations and duration for the following reasons:

(1) The wiring configuration is a surrogate to the conductor count and the PIRT panel's consensus was that the likelihood of a spurious operation was influenced more by the configuration of the conductors' wiring (number of source, targets, and common-power-supply return conductors), rather than the number of conductors.

(2) Since FIGURE-OF-MERIT 1 assumed that the fire already has damaged the cable, the only impact of the fire exposure is associated with the duration of the spurious operation.

(3) Raceway or routing (i.e., tray, conduit, air drop) has very little effect on hot short-induced spurious operation phenomena.

(4) Raceway fill has little effect on intra-cable hot shorts. However, cables in bundled configurations (e.g., panel wiring, bundled cable groups separated within a cable tray) have displayed a higher number of spurious operations in fire tests compared with unbundled cable in raceway.

(5) Cable insulation does not affect spurious operations caused by intra-cable hot shorts, but it significantly decreases spurious operations caused by inter-cable hot shorts.

(6) Both CAROLFIRE and AC DESIREE-Fire tests found that the effect of CPTs on spurious operations is contrary to the findings of the EPRI/NEI test results. The PIRT panel could not determine the reason for this discrepancy but recommended using the data from all test programs to develop best-estimate conditional probabilities of spurious operation.

(7) Limited specific test data was available for the effect of fire suppression on spurious operation or duration. Fire suppression may likely have some effect on circuit response but those effects are not yet explicitly known.

(8) The effects of other parameters such as cable aging, power supply voltage, conductor size are found to be insignificant.

Parameters that could have HIGH impact on the hot short-induced spurious operation phenomena and duration include

- Fire Exposure Condition
  - For duration
- Cable Routing/Raceways
  - Panel wiring only
    (NOTE: Due to the limited data on panel wiring, this parameter is not considered in the following sections. This parameter was ranked "High" primarily due to the sparsity data, and the suspicion of PIRT Panel members that this parameter could be important. A high ranking was given to this parameter to assure it was properly considered in future research.)
- Cable Raceway Fill
  - Bundles only for intra-cable hot short induced spurious operations (Note: The PIRT panel considered bundles important even though it is ranked Medium)
- Conductor Insulation Material
  - For Inter-cable hot shorts (TS versus TP)
- Time-Current Characteristics
  - Fuses/Breaker Size on duration
- Cable Grounding Configuration
  - Ground or Drain Wire, Shield Wrap
- Armor Grounded versus Ungrounded Circuit (for AC) and Armored versus Unarmored (for DC)
- Cable Wiring Configuration (Number of Sources, Target, Ground/Neutral and their Locations)
- Latching versus Non-latching devices (e.g., MOVs) for duration
  - This parameter is not considered beyond this point, since the behavior relative to this parameter is independent of fire damage.
- Grounded versus Ungrounded Circuits for AC only
  - For inter-cable spurious operations.

3.3 Control Circuits Vulnerable to Hot Short-Induced Spurious Operations

This section describes the process that the PIRT panel used to identify electrical control circuits that would be vulnerable to hot short-induced spurious operation from fire damage. The process included evaluating the results from the PIRT panel's ranking of influencing parameters, the results of fire tests, variations in circuit power supply, and the three typical hot short failure modes of concern for control circuits identified from fire tests. The information described is not considered exhaustive, but, rather, representative of common configurations found in NPPs.

3.3.1 Evaluation of Fire Test Results

Three major test programs have considered fire effects on cables: The EPRI/NEI (Refs. 7 & 11), CAROLFIRE (Ref. 9), and DESIREE-Fire (Ref. 10). In all three, a cable's electrical functionality was assessed with two different electrical-monitoring systems. One system, the SNL Insulation Resistance Measurement System (IRMS) measured the insulation resistance of individual cable conductors (or groups of conductors), so providing a direct measure of the electrical integrity of a cable's insulation. The IRMS can detect the onset of cable degradation and determine the specific pattern and timing of shorts occurring among the conductors of one or more cables. The second system, the Surrogate Circuit Diagnostic Units (SCDUs)[11], involved the control circuit simulators wherein a hot short could entail the spurious operation of AC motor-operated valve (MOV) circuit-motor contactors. In the DESIREE-Fire tests, eight DC-powered control circuits, including the MOV, were monitored using the control circuit simulators. Seven of these comprised two reversing MOV circuits, two small pilot SOV circuits, one 1-inch SOV, one valve coil for a large direct-acting SOV, and two medium voltage switchgear-breaker units. The eighth circuit was a special purpose system built to look for inter-cable hot shorts. We note that the MOV circuits used in DESIREE-Fire included an interlock system, whereas both EPRI/NEI and CAROLFIRE did not use either electrical- or mechanical-interlocks in their MOV circuits.

The systematic review of the AC and DC test data (Ref. 20) identified that the insulation material (TS versus TP) was an important factor affecting the probability of inter-cable hot shorts and that the wiring configuration had an effect on both intra- and inter-cable hot shorts. Other parameters, such as fire-exposure conditions, raceway fill, and fuse size greatly can affect the duration of the hot short-induced spurious operation. Additionally, the grounding of the circuit (increased probability of a blown fuse), or the presence of a ground plane near the source conductor(s), can influence the likelihood of experiencing a hot short-induced spurious operation. Because of this ground-plane interaction, the parameters of the cable's construction, such as the presence of a drain conductor, shield wrap, or armor, and that of the cable routing parameters, such as trays and conduit raceways (assuming that these cable construction- and routing-parameters typically are grounded to the plant ground) play a measureable role in predicting the likelihood of hot short-induced spurious operations in a control circuit. Finally, the PIRT panel concluded that the likelihood of the mode of failures in panel wiring and armored cables would differ from the base case of a standard raceway configuration, and therefore, should be included in identifying the control circuits to be evaluated.

The analysis of the test data found only limited information pertaining to fire-induced inter-cable failures. Such data is presented in the data analysis report (Ref. 20) for both AC- and DC-circuits. The results show that the likelihood of experiencing these inter-cable hot shorts is lower than intra-cable; however, several cases exist in both the EPRI/NEI and CAROLFIRE tests where the former were experienced. The data analysis for the DESIREE-Fire tests, on the other hand, identified a newly observed (but previously postulated in NUREG/CR-6834 (Ref. 19)) failure mode wherein multiple shorts to ground cause a DC circuit to spuriously operate. This failure mode is referred to as "ground fault equivalent hot shorts" and is the only inter-cable failure mode observed in DC circuit testing. This failure mode can impact circuits routed in dedicated conduits since this particular phenomenon occurred between cables co-located on the same raceway, as well as between cables located on different raceways provided they both belonged to the same ungrounded common-power supply. The results from the data analysis of the DESIREE-Fire testing now show that these events occurred quite frequently during the intermediate-scale testing.

A similar scenario observed in DESIREE-Fire testing is discussed in Appendix A of NUREG-2128 (Ref. 20). Since these tests were performed in Penlight with the cables physically

[11] Surrogate Circuit Diagnostic Units (SCDUs) were used in the "Intermediate-scale" open burn test series in CAROLFIRE and DESIREE-Fire test programs, and in EPRI/NEI tests to simulate where a hot short could lead to spurious operation of an end device such as a motor contactor.

separated from each other, the only route for inter-cable interaction is through the ground via the cable tray.

NUREG-2128 (Ref. 20) examined both AC and DC circuits for concurrent hot shorts (or spurious operations). The configurations of the AC test circuits eliminated the possibility of a single cable causing multiple concurrent hot shorts affecting multiple circuits, since all AC test-involved cables were connected to a single MOV circuit. Thus, when reviewing the test results, two cables are required to experience a hot short simultaneously to be considered concurrent hot shorts. Because of this and the physical arrangement of cables within the SNL intermediate-scale testing facility, the concurrence of hot shorting has not been observed in any individual AC test. In some cases, the concurrence between two circuits was missed by only a few seconds, but adhering to the strict definition of concurrent hot shorts, this phenomenon was not observed in any AC circuit testing. This does not rule out the concurrence of spurious operations for AC control circuits, but it does point to its low probability.

Twelve intermediate-scale tests performed in DESIREE-Fire included six to seven DC circuits per test. The results were analyzed to identify times when hot short-induced spurious operations occurred concurrently. Five different types of DC surrogate circuits were tested, namely, a solenoid operated valve (SOV), motor operated valve (MOV), 1-inch valve solenoid, a large coil similar in size to a power-operated relief valve, and a medium voltage circuit breaker, referred to as switchgear (SWGR). Most of the five circuits were included in every intermediate-scale test. Section 4.15 of NUREG-2128 (Ref. 20) denotes that in DC intermediate-scale testing, several concurrent spurious operations occurred within the same test.

3.3.2 Considerations for Defining Control Circuit Configurations

As discussed in the previous section, the PIRT panel assessed test results on control circuits. They employed a very basic circuit model as the base configuration that consisted of a single contact and relay for a very basic single-break design, and two contacts and a relay for a double-break design. It was felt that these two basic circuits could best illustrate all of the different hot short-induced spurious operations. Furthermore, by using a very basic circuit, the failure modes and probabilities could easily be extrapolated for more complicated circuits. Figure 3-1 presents simplified circuit schematics of a single contract- and double contact-circuit powered from a 125 VDC ungrounded (or possibly 120 VAC distribution system) power system.

Another parameter explored by the PIRT panel was the variations in the power source (i.e., AC or DC power supply). They considered both grounded and ungrounded circuits for the AC control circuits powered from a CPT and only the ungrounded circuit for the DC control circuits. In the discussion of the typical circuit designs and their behavior relative to the three types of fire-induced circuit failures that could cause a spurious operation, the information available for ungrounded 125 VDC circuits is extrapolated to the case of ungrounded 120 V AC distribution circuits (i.e., ungrounded 120V AC circuits that are powered from one or more distribution panels). These variations in power source and the three hot short failure modes of concern that could lead to a spurious operation are discussed below.

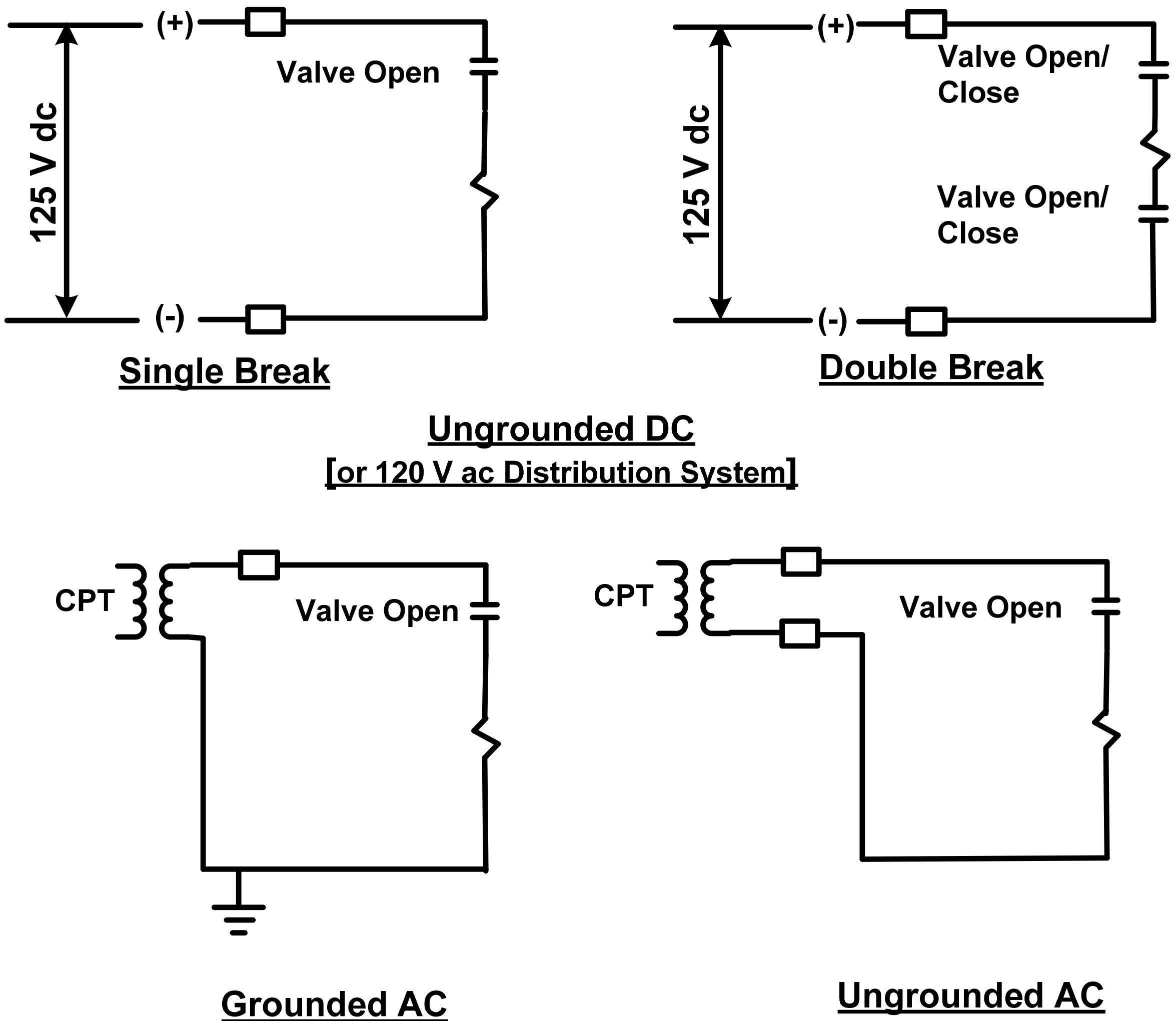


Figure 3-1. Simplified circuit schematics of single and double break circuits: Ungrounded; Grounded; Distribution Bus; Powered from CPT.

Power Source Variations

The following three different single phase power source configurations of control circuits are considered:

- Grounded AC control circuits,
- Ungrounded AC control circuits, and,
- Ungrounded DC control circuits.

Each involves certain unique characteristics that may impact the likelihood and duration of spurious operations after cable failure. Each power source also carries implications relative to the modes of cable failure that might lead to spurious operation and the likelihood that those modes might in fact occur in an actual fire.

Grounded AC Control Circuits
The first power source considered is grounded AC. Control circuits typically operate at 120 VAC grounded, and circuit power may be supplied either by a common AC electrical bus (e.g., through a breaker distribution panel), or from the electrical bus via a dedicated CPT. Using CPTs is common practice in MOV circuits. In this application, the primary (input) side of the CPT typically draws power from two phases of the primary power-source (e.g., 480 VAC Bus) feeding the MOV's drive motor, steps that power down to 120 VAC on the secondary (output) side of the CPT and feed that power to the control circuit. The common return side of the CPT secondary typically is connected to ground for AC-grounded control circuit applications powered from a CPT. Thus, the control circuit is parasitic on the primary power circuit that it actually controls.

The CPT is a power-limited device, so placing a hard limit on the total power available to the circuit (the product of current and voltage). Hence, as the current flow increases beyond a certain point, the voltage begins to decline below the CPTs nominal output voltage. If the voltage drops below the minimum pickup voltage for the actuation device (i.e., MOV contactor), then no spurious operations could occur. The EPRI/NEI test data show a significantly reduced rate of spurious operations for tests where the CPTs were used compared to those without them.

Grounding the common return-side of the power-supply circuit provides an opportunity for power to return to the supply source via the ground plane. Hence, when evaluating a given circuit, any other grounded AC power source of similar voltage is considered a compatible source. For example, any grounded CPT can feed power to any other grounded AC control circuit, even if the target circuit normally is powered by a separate dedicated CPT.

The ungrounded leg of the circuit that is attached to the power supply will be referred to as the "hot" leg. With a grounded AC source, a low resistance short between the hot leg and ground will trigger circuit-protection features (e.g., trip a circuit breaker trip, or blow a fuse). Consequently, a hot short equivalent ground-fault interaction is incredible for a grounded AC circuits because hot-leg power cannot be passed from one conductor to another via the ground plane without triggering circuit protection.

Grounded AC circuits have circuit-fault protection in the form of fuses and/or breakers, but their configuration can vary. For circuits powered by a common AC bus, a fuse or breaker will be located in the circuit's hot leg. For circuits powered by a CPT, a fuse also will be provided in the hot or ungrounded leg of the circuit on either the primary- or secondary-side of the CPT. The PIRT panel's judgment was that fusing on the secondary side was practiced more commonly, although cases of primary-side-only fusing are known to exist. Given fusing only on the primary side of the CPT, the circuit may be somewhat less sensitive to fire-induced fault currents, although a substantive fault current still should cause the fuse to blow.

Ungrounded AC Control Circuits
Ungrounded AC control circuits are considered less common than grounded AC circuits. The PIRT panel identified a few specific applications of ungrounded AC distribution bus at NPPs, with all being associated with a battery bank to AC-power inverter systems. While using an ungrounded AC distribution bus is infrequent, nevertheless, it was considered in evaluating failure modes.

No testing has been undertaken of control circuits powered by an ungrounded AC distribution bus; hence, their behavior essentially is unknown. In lieu of actual test data, the PIRT panel concluded that an ungrounded AC distribution bus would behave similarly to an ungrounded DC one with respect to the likelihood of hot short-induced spurious operations. The reasoning underlying this conclusion is that the relative likelihood that the required hot shorts would form before circuit protection is triggered is driven more powerfully by the grounding configuration than it is by the observed differences in faulting behavior between AC and DC power cables. This supposition would tend to imply similar behavior relative to the likelihood of spurious operations.

Concerning the duration of spurious operations, the PIRT panel judged the behavior of circuits powered by ungrounded AC distribution buses to mirror that of circuits powered by ungrounded DC circuits. This judgment was based on a minimal data set, uncommon configuration, and lack of specific circuit design configurations. The PIRT panel judged that using the ungrounded DC circuit duration probability would conservatively bound durations for circuits powered from ungrounded AC distribution buses. Likewise the PIRT panel judged that the duration for circuits powered by an ungrounded AC CPT should mirror that of grounded AC CPT circuits. The reasoning for this conclusion is that the duration of an actuation signal would be governed more powerfully by factors such as fuse sizing and by the relative energy of the conductor-shorting behavior than it would be by the grounding's configuration. Hence, the duration of a spurious operation in an ungrounded AC CPT powered circuit should have more in common with that in a grounded AC CPT powered circuit than with that in an ungrounded DC circuit. In summary, for those cases involving an ungrounded AC distribution bus, the panel's recommended treatment is to assess likelihood using the corresponding likelihood values developed for ungrounded DC circuits. Therefore, to assess the duration of the spurious operation signal involving ungrounded AC CPT circuits the PIRT panel suggests using the corresponding values developed for grounded AC CPT circuits and to use the values developed for ungrounded DC circuit to bound ungrounded AC distribution circuits.

Ungrounded AC applications at NPPs primarily are associated with CPTs with an ungrounded secondary, and the PIRT panel knew of several plants using this configuration. Hence, this configuration, ungrounded CPTs, was included in the example circuits in Section 3.4.

For an ungrounded AC circuit, the two legs of the circuit commonly are referred to as the "positive" and "neutral" legs. With an ungrounded source, a single short to ground involving a conductor energized to either the positive or neutral legs will not trigger the circuit-protection features, but will ground one leg of the power source, at least temporarily. Circuit protection will be triggered given direct shorting between the positive- and neutral-legs, or by concurrent shorts to ground on both legs.

One unique aspect of ungrounded AC circuits on separate CPTs is that a single hot short cannot feed power between circuits because each CPT has its own electrically independent power-return path. For one ungrounded source CPT to activate a target circuit normally powered from a separate ungrounded CPT requires concurrent faults involving both legs of the source circuit. That is, shorts must connect both the positive- and neutral-legs of the source circuit to the appropriate conductors in the target circuit to allow power to flow between them. The panel noted that ground fault equivalent hot shorts could be the mechanism for making one of these connections.

Ungrounded DC Distribution Systems (also, ungrounded AC distribution systems)
Ungrounded DC battery banks commonly are used in the U.S. nuclear power industry. The typical battery voltage is 125 Vdc, but some applications also use 250 Vdc. In all cases known to the PIRT panel, involving motors and MOVs, station batteries are ungrounded[12].

Several noteworthy general observations were made during the DESIREE-Fire testing (Ref. 10):

- The arcing observed in conjunction with the cable faulting was more energetic for DC-powered cables than for this behavior in AC-power cables. Both AC- and DC-powered cables displayed arcing, but the arcs formed by the faulting DC-powered cables were more substantial, more sustained, and more damaging.
- Faulting of the DC-powered cables often entailed destructive damage to the cable conductors (open circuit/conductor breakage): it was not been observed at this level for AC-powered control cables.
- In some cases, the DC-powered cables remained energized even after experiencing destructive damage as described above. This behavior was commoner for tests with larger (15A, 25A, or 35A) fuses.
- For any given DC-circuit, the two paired fuses (one on the positive leg and one on the negative leg) did not necessarily clear simultaneously. Many factors contribute to this behavior. For example, the time/current clearing relationship varies somewhat even within a single batch of like fuses, so that one fuse may clear more quickly than another after the same fault current. Also, some fuse blows resulted from circuit-to-circuit interactions through the ground plane (ground fault equivalent hot shorts) so that the two fuses involved in the fault might be of different sizes (e.g., the fault currents might be routed through a 10A fuse from one circuit, and a 5A fuse from another circuit). Then, the lower amperage fuse typically would clear leaving the higher amperage fuse intact.
- In general, more long-duration hot short-induced spurious operations were observed for the DC-powered circuits than for corresponding AC-powered circuits. In at least one case from DESIREE-Fire (i.e., Penlight Test # 38, Ref. 10), a spurious operation persisted beyond the thermal exposure period and until the DC battery bank was manually isolated from the damage cable/circuit, and this behavior had not previously been observed in AC-testing.

Ungrounded DC circuits are similar in some ways to ungrounded AC circuits. For example, a single short to ground involving a conductor energized to either the positive or negative battery potential will not trigger circuit-protection features; rather, one side of the battery bank will become grounded at least temporarily. Also, the hot short equivalent ground-plane-interaction failure mode is possible for DC circuits. The PIRT panel concluded that there are three main differences between AC- and DC-power sources that could impact the likelihood and duration of spurious operations.

First, the energy level associated with shorting in DC control circuits is higher than that in AC circuits. In testing, the DC shorting behavior observed was far more energetic than were the shorts in AC circuits. Both AC and DC circuits generate arcs when short circuits form, but the arcs formed during DC testing were substantially more energetic and persisted for longer. The

[12] However, there are other DC circuits that are grounded, such as the BWR 24 Vdc +/- nuclear instrument batteries that have the center tap grounded.

arcs formed in DC testing often were destructive, damaging the raceways and breaking the copper conductors (conductor open circuit failures).

Second, the same battery bank typically power many DC circuits. Accordingly, we can assume that when multiple cables are co-located in a common raceway, there likely will be other cables present that are powered from the same bank. Any such cable is considered to be powered by a compatible power supply. Hence, under certain conditions, a single hot short can lead to a spurious operation.

Third, DC control circuits may be fused at substantially higher amperages than a similar AC control circuit. Using 3 A fuses, for example, is considered quite typical for AC circuits. For DC control circuits, typical fusing may range from 5-35 A. Testing demonstrated for DC control circuits, larger fuses (e.g., 15 A or more) may not clear, even after severe damage to the cables. Several cases were observed where cable conductors had open circuited (broken) due to arcing, and yet they remained energized (fuses did not clear).

Another consideration for DC control circuits involves single- or double-break (or -contact) designs. In the former, the control switch that actuates the circuit is only switching the “high” (or positive) side of the power circuit; the return (or negative) side of the circuit normally is closed. In a double-break design, the control switch opens and/or closes both the circuit’s high- and the return-sides. In this design, there is just one target of interest (the SOV solenoid), but with a double break design, two hot shorts are required to operate the valve. One side of the solenoid must short to the high side of a compatible power source, and the concurrently, the other side of the solenoid must short to the return side of that same power source, or another compatible one.

Because ungrounded systems (both AC and DC) do not have a pathway to ground, a return path for current always is needed. In other words, current from a different current source cannot enter a circuit because there would be no exit path for it to back to the common return to complete the circuit.

Due to this characteristic of ungrounded circuits, the following points should be considered whenever evaluating these types of circuits for the effects of an inter-cable or ground-fault hot short:

1. For any spurious operation involving one hot short, the voltage/current source of the aggressor cable must be the same as that of the target cable.

2. For any spurious operation involving two hot shorts of proper polarity (double-break design), the positive leg’s hot short and that of the neutral leg both must be connected to the same voltage/current source.

<u>Hot Short Failure Modes Leading to Spurious Operation</u>

There are various cable faults (conductor shorts) that may engender the spurious operation of plant equipment. The actual failure modes of interest depend on both the specific circuit-design and the cable configuration. The PIRT panel focused on hot short-induced spurious operation of electro-mechanical devices. This choice excluded cases wherein a single short (other than a hot short) to ground, or a conductor’s open-circuit might cause a device to reposition. It also excludes cases involving spurious activation of an indicating light, since this is not considered to be an “actuation” of an end device. The analysis of test data identified three primary fire-induced failure modes (i.e., electrical conductor shorting behaviors) that may lead to hot short-induced spurious operations: they are illustrated in Figures 3-2 through 3-4. These figures provide an illustration of the various failure modes and are not limited to the specific conductor shorts shown.

1. Intra-cable shorting: Electrical shorting between the conductors of a multi-conductor electrical cable (Figure 3-2). The shorting may involve individual conductor pairs and/or larger groups of conductors within the cable. More than one shorting pair or group may form concurrently. In most cases, the conductors will all belong to one circuit; however, cases exist (such as trunk cables) where conductors for multiple circuits are located within one cable.

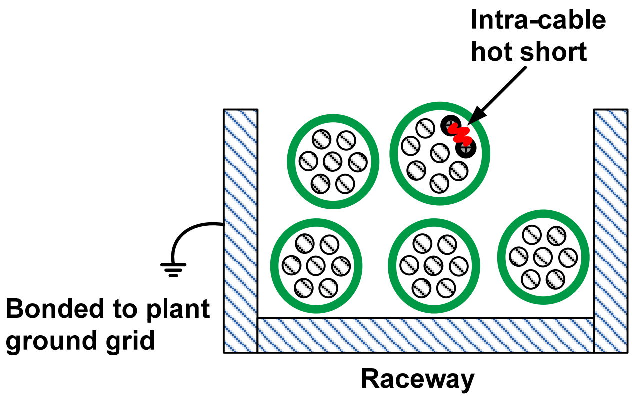


Figure 3-2. Intra-Cable Hot Short

2. Direct inter-cable shorting: Direct conductor-to-conductor shorting between electrical conductors associated with different electrical cables, independent of the ground plane (Figure 3-3). Again, shorting may involve individual conductor pairs, or groups of conductors.

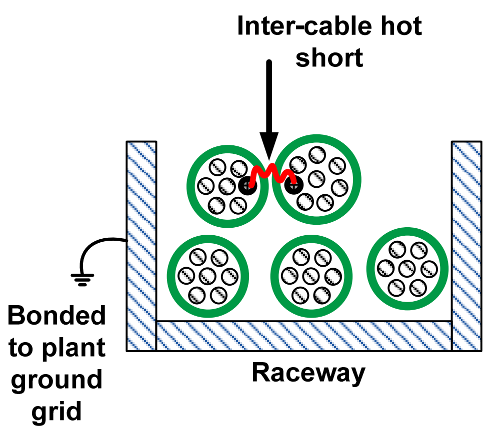


Figure 3-3. Inter-Cable Hot Short

3. Ground fault equivalent hot short: Shorting between multiple conductors and ground such that energy is transferred from one conductor to another via the ground plane. This mode is also referred to as “ground fault equivalent hot shorts.” This is an important AC/DC ungrounded circuit fault mode (Figure 3-4).

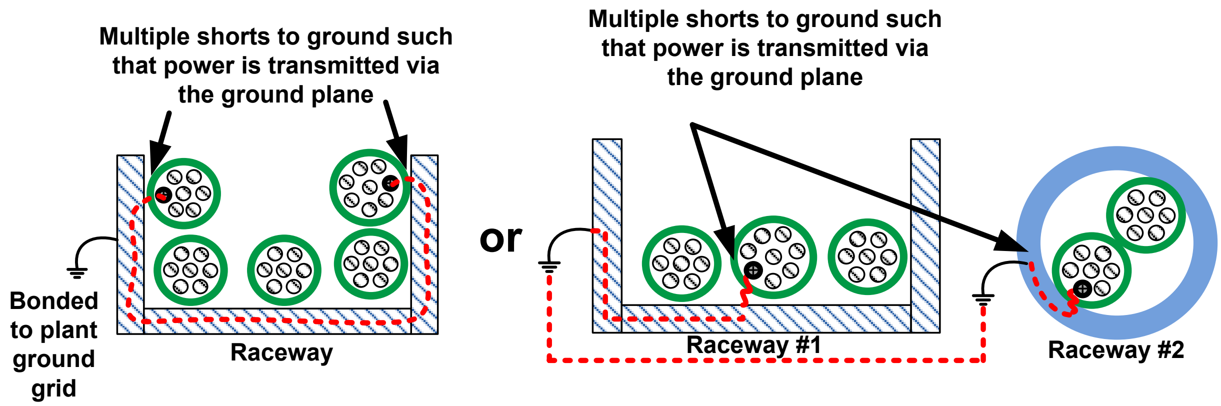


Figure 3-4. Inter-Cable Ground Fault Equivalent Hot Short

Figure 3-4, inter-cable ground fault equivalent hot short, is a complex failure mechanism that was observed in DC testing. This case is only applicable to circuits powered by an ungrounded source that might include an ungrounded DC battery bank, an ungrounded AC CPT, or an ungrounded AC-power distribution source. This case postulates that one leg of the power source becomes grounded due to conductor shorting resulting from fire-induced failures, allowing power transmission via the common ground plane to another conductor that also is grounded. The ground plane may be available via grounded shield-wraps, grounded drain-wires, cable armoring, metal raceways (e.g., trays, conduits), or grounded conductors within a cable (e.g., grounded spare conductors). All grounds are assumed to be associated with the same plant-wide ground plane.

The successful transmission of power from one circuit to another due to ground fault equivalent hot shorts does require a compatible power source to be involved (i.e., one able to activate the spurious operation target). A compatible power source must (1) provide nominally the same voltage, (2) provide the minimum pickup-power load for the target device, (3) match the target circuit relative to AC- or DC-power (i.e., AC power cannot activate a DC device or vise-versa), and, (4) allow power flow back to the source via that leg of the power supply remaining ungrounded.

A given circuit may be vulnerable to hot shorts caused by one or more of these failure modes. For example, some circuits may spuriously operate due to either intra- or inter-cable fire-induced hot shorts. In some cases a combination of conductor shorting modes must occur before triggering a spurious operation. For example, spurious operation in some cases may result from multiple intra-cable shorts or from an intra-cable short combined with a concurrent inter-cable short. The PIRT panel considered various cases and combinations.

Cable Insulation Material

While the type of cable-insulation material makes little difference in the probability of intra-cable hot short-induced spurious operations, it affects the probability of inter-cable hot short-induced spurious operations. Because of this, the electrical expert PIRT panel undertook a technical evaluation of the credibility of inter-cable failure modes for different insulation types.

For a single-break design circuit, only one inter-cable hot short of the right polarity would be necessary. In an ungrounded circuit containing a “double break” switch design two proper polarity hot shorts must occur simultaneously to cause a spurious operation. This proper polarity failure mode is also applicable to instances in which:

- Both positive- and negative-leg fuses blow or are removed,
- A two-pole circuit breaker opens under fault or is manually opened.

We note that for the purposes of this discussion, TS and TP refer to the insulation on the cable conductors. The PIRT panel discussed four different configurations of cable-to-cable (i.e., inter-cable) hot shorts as follows:

1. Thermoset source cable induces a spurious operation in a thermoset target cable (TS → TS): Based upon reviewing the fire-testing research and their expert judgment, the PIRT panel concluded that an inter-cable hot short, causing a spurious operation for DC ungrounded circuits involving thermoset cables, was implausible. While there was research demonstrating the plausibility of the occurrence of an inter-cable hot short among thermoset cables, its probability was a very low. Even in the test cases showing some interaction between two separate cables, the induced voltage/current was very small and intermittent. Because of this, the PIRT panel concluded that an inter-cable, consequential, spurious operation between two thermoset cables was implausible. Based on this conclusion, they further concluded that a spurious operation caused by two inter-cable hot shorts was incredible and need not be considered.

2. Thermoset source cable induces a spurious operation in a thermoplastic target cable (TS → TP): The CAROLFIRE test data documented a few instances where inter-cable hot shorts were caused by a TS-source cable partially energizing a TP-target cable. Although no spurious operations were observed under this configuration, the PIRT panel could not develop any logic for excluding this configuration from causing spurious operations. The physical argument for this configurations possibility was that TP cables typically fail from fire damage prior to TS cables (i.e., TS cables typically fail a higher temperatures than TP cables) and the failure mode sometimes results in the loss of cable insulation. Once a TP cable fails, with its conductors exposed, and becomes de-energized, an inter-cable hot short from a TS cable could energize a conductor(s) in the TP cable, thereby possibly causing a spurious operation (provided compatible power sources among the cables). Hence, the PIRT panel concluded that a TS-source to TP-target inter-cable spurious operation signal is plausible, although it would be fairly low in probability. The PIRT panel again used similar logic to the discussion for TP-source to TS-target hot shorts (see item 4 below):

   - Thermoplastic cable would be damaged earlier causing the fuses for this cable to clear much earlier in the fire. The thermoplastic conductors would be de-energized, but when the thermoset cables finally burn to failure, the thermoset cable conductors could cause a voltage/current to be induced in the thermoplastic cable conductors should they be exposed by loss of insulation capability.

   - Since thermoset tends to char and fail at higher temperatures than thermoplastic cables (i.e., TS fail after TP), it makes an inter-cable induced voltage/current much less probable. As explained in the following sections, thermoplastic cables would be expected to have already become de-energized prior to the failure of the thermoset cables. Therefore, thermoplastic to thermoset inter-cable hot shorts are considered to be incredible. Additionally, due to the charring characteristics of thermoset cables, thermoset to thermoset inter-cable hot shorts are considered to be implausible. In this latter case, intra-cable failures are expected to precede inter-cable failures.

The combination of these factors and the research results made the PIRT panel conclude that inter-cable TS-source to TP-target spurious operations are possible, but of low probability. Based on this conclusion, they further concluded that a spurious operation caused by two inter-cable hot shorts was implausible and need not be considered.

3. Thermoplastic source cable induces a spurious operation in a thermoplastic target cable (TP → TP): During discussions, the PIRT panel concluded that thermoplastic to thermoplastic inter-cable consequential spurious operations were plausible. A small number of such cases have been observed in testing during both the EPRI/NEI and CAROLFIRE programs. Thermoplastic insulation tends to melt away from the conductors in a thermoplastic cable, thereby allowing more direct access to the conductors by external cables. The possibility of concurrent inter-cable consequential hot shorts across the conductors of two cables producing a spurious operation in an ungrounded circuit is judged to be low, but not as low as the probability of spurious operations caused by intra-cable shorting for TP → TP cases than for TS → TS cases.

4. Thermoplastic source cable induces a spurious operation in a thermoset target cable (TP → TS): Finally, since no instances of thermoplastic cables producing a spurious operation on a thermoset cable have been recorded, this type of interaction also was ruled as incredible. It should be noted that CAROLFIRE specifically set up test to allow for and then monitored for such interactions and none were observed. The PIRT panel speculated that this lack of credibility primarily reflected two factors:

   - Thermoplastic cable would be damaged earlier, causing the fuses for this cable to clear much earlier in the fire. By the time the thermoset cables burned to failure, the thermoplastic cable would no longer have power to its source conductors.
   - Thermoset tends to char rather than melting like thermoplastic. The charred thermoset poses an added barrier to inter-cable hot shorts. While induced currents can occur across the charred insulation, the current path is not of the same quality as a conductor-to-conductor short. As previously mentioned, this results in a much lower probability for a consequential hot short failure mode.

Table 3-3 provides a synopsis of the panel's evaluation of the inter-cable failure mode. (See Section 2.1.3 for the definitions of IMPLAUSIBLE and INCREDIBLE).

Again, this evaluation considers only the insulation on cable conductors. Since the probability of inter-cable hot shorts for TP → TS is considered incredible, the PIRT panel did not include this insulation combination category in its failure mode consideration in Section 3.4.

Table 3-3. Inter-Cable Failure Mode Categorization

Conductor Insulation Source→Target	Number of Needed Inter-Cable Hot Shorts*	Possibility
TS→TS	1	IMPLAUSIBLE
	2	INCREDIBLE
TS→TP	1	Possible
	2	IMPLAUSIBLE
TP→TP	1	Possible
	2	See NOTE
TP→TS	1	INCREDIBLE
	2	INCREDIBLE

*1 - single break (or contact) design; 2 - double break (or contact) design

NOTE:

Single inter-cable hot shorts involving TP→TP interactions were observed in the test data. Although multiple concurrent inter-cable hot shorts did not produce a spurious actuation in any test, the test circuits were not configured to look for this specific failure mode. The possibility of getting concurrent inter-cable hot shorts is considered to be a very low likelihood event. The PIRT Panel did not classify the two inter-cable hot short TP→TP cable interactions as implausible, because it was in their judgment that the likelihood of this configuration lie somewhere between a possible and implausible classification. Qualitatively the PIRT panel judged the likelihood of TP→TP interactions higher than the likelihood of TS→TP interactions. It is the PIRT panels' judgment that concurrent hot shorts for TP→TP cable interactions would be very short lived based on the failure characteristics of thermoplastic cable, which involve rapid loss of form (via melting of the insulation) and melting away of the insulation.

3.3.3 Control Circuit Configuration Scenarios

To qualitatively assess the control circuits for hot short-induced spurious operation, the PIRT panel formulated 13 individual base case scenarios (6 with single break or contact circuit configurations and 7 with double break or contact circuit configurations) consisting generally of the following broad categories of cable's physical properties and configuration, and cable routing configuration:

- TS-insulated conductors (both source and target conductors),
- TS- or TP-insulated cable jacket,
- Nominally a 7-Conductor, unarmored cable,
- Cables routed on cable trays or in conduits,

In these 13 cases, the electrical source for the circuit was varied with the individual hot short induced spurious operation failure mode (AC grounded, AC ungrounded, or DC ungrounded). Grounded AC circuits powered from a CPT (as a target) are susceptible to only intra-cable and inter-cable hot shorts. Inter-cable hot shorts via ground equivalent hot shorts, are not possible, since a fire-induced fault current due to grounding will cause the fuse to blow or the breaker to trip.

For ungrounded AC or DC power supplies, the circuits are susceptible to all three hot short failure modes: intra-cable, inter-cable, and ground fault equivalent hot shorts. Thus, three basic hot short failure modes are applicable to ungrounded control circuits.

The following thirteen different hot short induced failure modes that could occur in control circuits due to a fire consist of two modes for grounded AC circuits and three modes for ungrounded AC/DC circuits requiring a single contact, and five modes for ungrounded AC/DC circuits requiring double contacts:

For AC grounded control circuits (with a single break or contact), conductor-to-conductor hot short modes of failure include:

1. Intra-cable within any raceway configuration
2. Inter-cable (cable-to-cable) between any two cables within any raceway configuration

For DC (or AC) ungrounded control circuits (with a single break or contact) and proper polarity, conductor-to-conductor hot short modes of failure include:

3. Intra-cable within any raceway configuration
4. Inter-cable (cable-to-cable) within same raceway cables
5. Inter-cable (via ground plane) within same raceway cables
6. Inter-cable (via ground plane) between different raceway cables

For DC (or AC) ungrounded control circuits (with double breaks or contacts) and proper polarity, conductor-to-conductor hot short modes of failure include:

7. Intra-cable within any cable and Intra-cable within any cable
8. Intra-cable and Inter-cable (cable-to-cable) within same raceway cables
9. Intra-cable and Inter-cable (via ground plane) within same raceway cables
10. Intra-cable and Inter-cable (via ground plane) between different raceway cables
11. Inter-cable (cable-to-cable) and Inter-cable (cable-to-cable) within same raceway cables
12. Inter-cable (cable-to-cable) and Inter-cable (via ground plane) within same raceway cables
13. Inter-cable (cable-to-cable) and Inter-cable (via ground plane) between different raceway cables

All the above failure modes consider a single target conductor and a single source conductor for each contact.

3.4 Examples of Control Circuits Vulnerable to Hot Short-Induced Spurious Operations

The first part of this section discusses tables that the electrical expert PIRT panel provided for using in the probabilistic assessment of hot short-induced spurious operations. They represent the conditional probability categories that the PIRT panel believed important for Fire PRA applications. However, it is recognized that these tables ultimately could be changed by the expert elicitation PRA Panel to facilitate their portion of this project.

The second part of this section shows figures representing the basic circuit configuration and failure modes that the PIRT panel believes should be considered. They give simple representations of the circuits to aid in understanding the different hot short-induced spurious operations.

Finally, the last part of this section discusses certain inherent characteristics of cables in the control circuit configurations that can limit the probability of hot short-induced spurious operations. While not specifically stated in these tables, it is important to recognize that these characteristics exist before analyzing deterministic effects and probabilities. Specifically, the behavior of AC ungrounded, DC ungrounded, and AC grounded circuits are discussed.

The control circuit used as the base case for all figures and table sets described in this section is considered to be representative of both AOV/SOV and MOV circuits. These types of circuits commonly are used in NPPs and they are consistent with the common circuit-configuration tested by both EPRI/NEI and NRC/SNL. The circuit provided, because of its simplicity, can readily be used to explain the behavior of all hot short-induced spurious operations in NPPs. Any differences between the spurious operation probabilities of the AOV/SOV versus the MOV circuit that could affect the probability of a fire-induced hot short, spurious operation (i.e., one versus two spurious operation targets in the circuit) will be addressed by the follow-on expert elicitation PRA panel.

3.4.1 Control Circuit Configuration Example Sets

Based upon Section 3.3, several control circuit configuration figures are developed to capture the thirteen base cases. Additionally, a number of spurious operation probability tables are also given. Three sets of tables are created. The first set of tables addresses the probability of a single hot short-induced spurious operation. This set of tables and the resulting probabilities can be applied directly to any single contact (single break design). In other words, these tables will give probabilities that directly apply to Cases 1 through 6 in Section 3.3. The second set of tables takes the results of the first set and combines them to address the remainder of the cases in section 3.3 (Cases 7 through 13). Since all of the cases in the second set of tables involve two hot short-induced spurious operations, this second set of tables address the double break design circuits.

Additionally, for the first two example sets of tables, since it is determined that the failure mechanism for a surrogate ground plane induced hot short is the same whether the aggressor cable is in the same raceway or a different raceway as the target cable, the raceway is not considered to change the probability of the failure mode itself. However, if the aggressor cable is in a different raceway from the target cable, other factors (e.g., the nature of the fire, the locations of the two raceways) could greatly affect the probability and duration of a spurious operation. Since these factors are plant dependent and not generic, the difference in probability would have to be determined on a case-by-case basis. NUREG-2128 (Ref. 20) offers information about the number of ground fault equivalent hot shorts that are from conductors within the same raceway versus conductors between two different raceways.

Finally, the third set of tables specifically addresses the duration of a hot short-induced spurious operation.

3.4.1.1 Control Circuit Example Set One

In example set one, three tables are developed. These tables and the associated circuit diagrams are organized as shown in Table 3-4, below.

Table 3-4. Control Circuit Example Set One with Single Break Design

Figure	Control Circuit Power Source	Probability Estimation
3-5	Grounded AC powered from a CPT	Spurious Operation
3-6	Ungrounded AC powered from a CPT	Spurious Operation
3-7	Ungrounded DC (or AC distribution bus)	Spurious Operation

Each table starts (refer to Figures 3-5, 3-6, and 3-7) with a base case control circuit configuration and then varies different configuration elements that potentially could affect the probability of the failure modes (i.e., hot short-induced spurious operations). The base-case cable configuration in a control circuit consists of the following:

1. Single circuit in a single cable;
2. Nominally a 7-conductor, unarmored, TS insulation; and
3. Only one target conductor of interest present (e.g., valve open target).

The different configuration variables for a cable that are used for the tables are as follows:

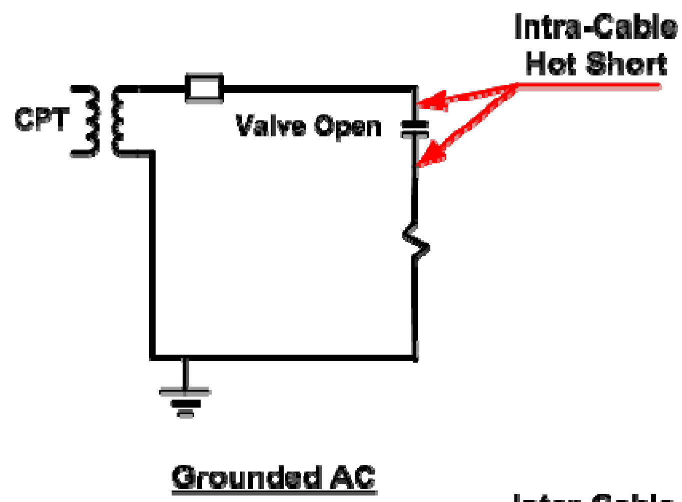
1. Thermoplastic insulated target cable;
2. Cable with a grounded metal foil shield wrap;
3. Cable with an un-insulated grounded drain wire; and
4. Armored 7/C cable.

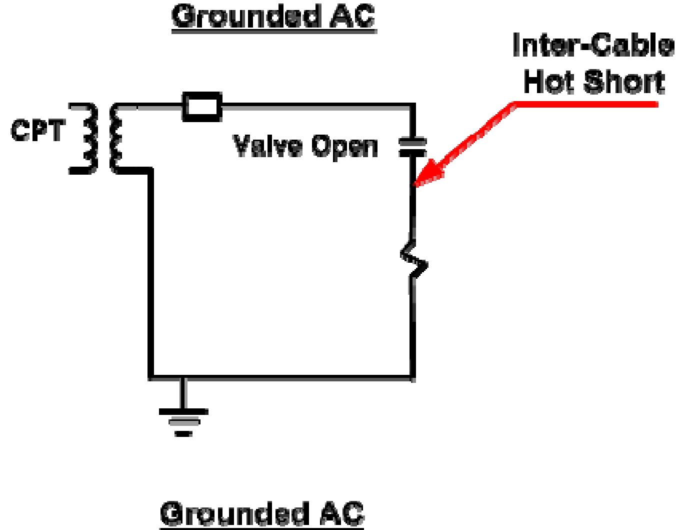
The PRA panel will use these tables to estimate the probability of a hot short-induced spurious operation. Since there are primarily three hot short failure modes that induce spurious operations, i.e., intra-cable-, inter-cable-, and inter-cable ground fault equivalent hot shorts, these are included in every table to estimate their probability. Finally, an aggregate of all the probabilities of a spurious operation of a control circuit in consideration is provided in the last column.

The ungrounded AC table is applicable to CPT-powered circuits (see Figure 3-6). Ungrounded AC distribution circuits should be treated the same as ungrounded DC circuits. A single ground-fault-equivalent hot short is not considered in the table for ungrounded AC CPT circuits because no return current path is available. It also was not considered for a grounded AC circuit because a ground on the source of the aggressor circuit would cause a blown fuse (see Figure 3-5).

The PIRT panel believed that the probability of spurious operation could be greatly affected in the panel-wiring's configuration; however, little data was available to support this premise. Consequently, the PIRT panel determined that this parameter should not be included in the tables, but recommended it as a high priority for future research.

One additional clarification needs to be made regarding the scope of the ground fault equivalent hot short column in Figure 3-7, Table 3-6, and Table 3-7. The ground fault equivalent hot short phenomena is meant to capture the possibility of conductors shorting to a ground plane (raceway, grounded armor/shield, grounded conductors) resulting in a circuit spurious operation. During the development of the probability tables it became apparent that this phenomenon could be counted in multiple columns (intra- and ground fault equivalent hot short). For instance, a conductor shorting to a grounded conductor (intra-cable short) would have the same electrical effect as the same conductors shorting to a grounded cable raceway, grounded armor, or other grounded medium (other than a conductor). Thus, the question arose, which column should account for intra-cable conductor shorts to grounded conductors. To minimize confusion, the PIRT panel recommends that the probability of all intra-cable hot shorts should be considered in the column labeled "Single intra-cable hot short" in Figure 3-7, and "Intra + Intra cable short" in Table 3-6 and Table 3-7. Thus, a scenario which involves an intra-cable hot short between a grounded conductor and another conductor, both within the same cable, should be considered an intra-cable hot short and not be considered a ground fault equivalent hot short. Although the circuit response would likely be the same, this distinction minimizes the likelihood of any double counting during the development and application of the conditional spurious operation likelihoods.

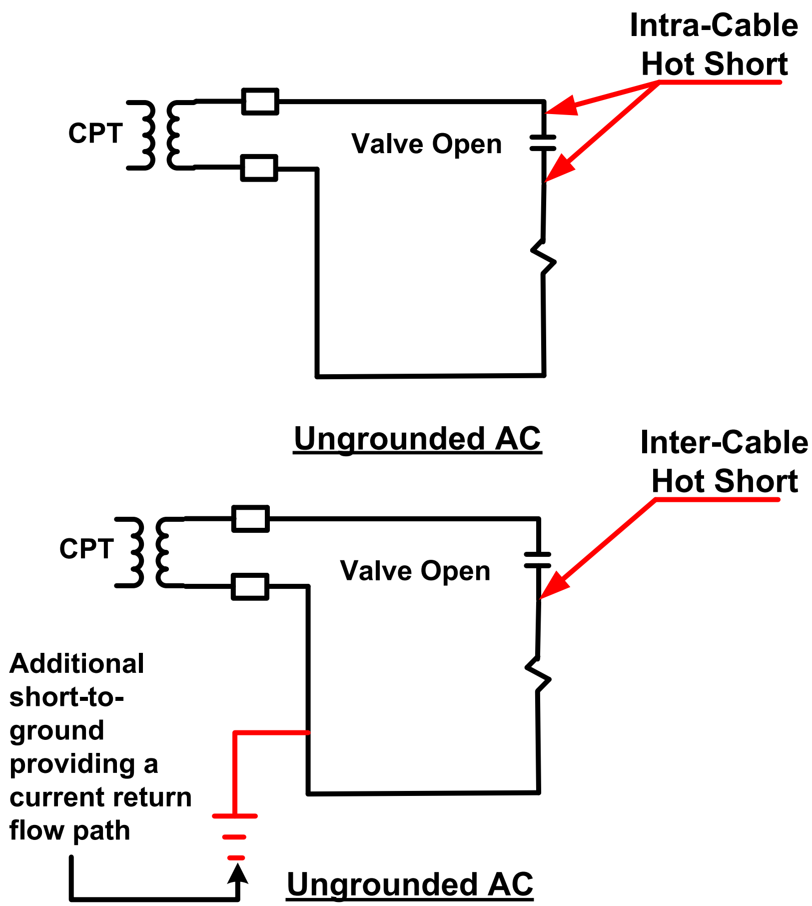




Grounded AC power source (from a CPT) spurious operation probability table.*				
Cable Configuration		Conductor shorting modes of interest		
		Single intra-cable hot short	Single direct inter-cable hot short	Aggregate result for all possible failure modes
Base Case (TS insulated source and target Cables)				
TP Cable	TP insulated source and target cables			
	TS insulated source and TP insulated target cables			
Cable includes a grounded metal foil shield wrap			N/A	
Cable includes an un-insulated grounded drain wire				
Armored 7/C Cable			N/A	

*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.

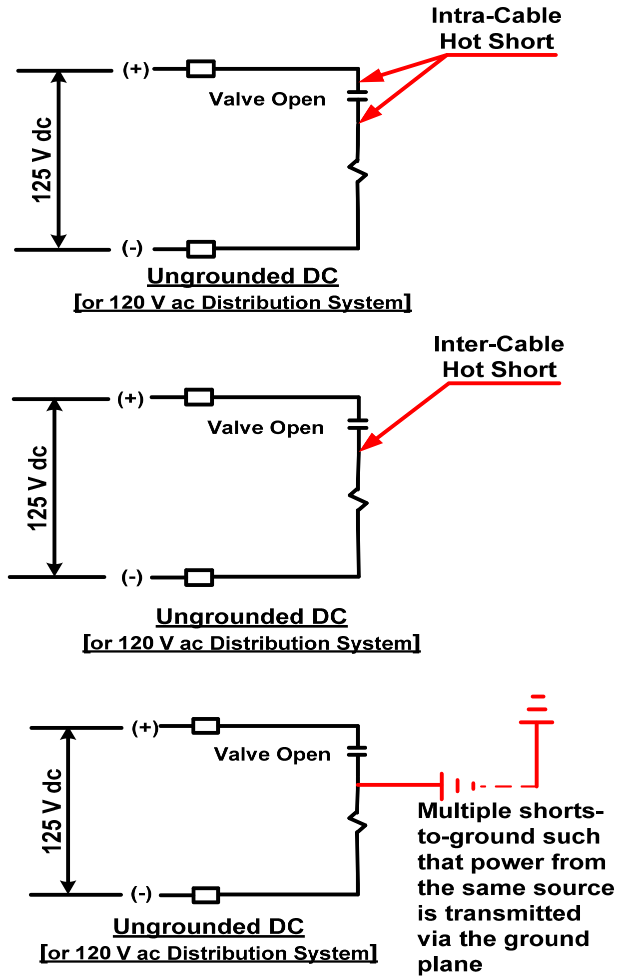
Figure 3-5. Grounded AC circuit schematics and probability table



Un-grounded CPT AC power source spurious operation probability table.*				
Cable Configuration		Conductor shorting modes of interest: Single intra-cable hot short	Single direct inter-cable hot short	Aggregate result for all possible failure modes
Base Case (TS insulated source and target Cables)				
TP Cable	TP insulated source and target cables			
	TS insulated source and TP insulated target cables			
Cable includes a grounded metal foil shield wrap			N/A	
Armored 7/C Cable			N/A	

*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.

Figure 3-6. Ungrounded AC circuit schematics and probability table



Un-grounded DC power source spurious operation probability table (also applies to ungrounded AC distribution bus)					
Cable Configuration		Conductor shorting modes of interest			
		Single intra-cable hot short	Single direct inter-cable hot short	Ground fault equivalent hot shorts	Aggregate result for all possible failure modes
Base Case (TS insulated source and target Cables)			[shaded]		
TP Cable	TP insulated source and target cables				
	TS insulated source and TP insulated target cables				
Cable includes a grounded metal foil shield wrap			N/A	◊	
Armored 7/C Cable			N/A	◊	

*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.
◊ Intra cable shorts that mimic the fault mode of ground fault equivalent hot shorts are included under the intra-cable short column.

Figure 3-7. Ungrounded DC circuit schematics and probability table (also applies to ungrounded AC distribution bus)

3.4.1.2 Control Circuit Example Set Two

As previously stated, example set two addresses failure modes involving two hot short-induced spurious operations; therefore, this second set of tables addresses the double-break design of control circuits. Once the probability for the single-break design tables was determined, the probabilities for the hot short across a single contact can be used to derive the combinations needed to initiate a spurious operation in a double- contact/break designed circuit. The following hot short-induced combinations were considered:

1. Intra-cable + Intra-cable;
2. Intra-cable + Inter-cable;
3. Inter-cable + Inter-cable;
4. Intra-cable + Ground fault equivalent hot shorts;
5. Inter-cable + Ground fault equivalent hot shorts.

We note that "Ground fault equivalent hot shorts" in combination with another "Ground fault equivalent hot shorts" does not exist because it would result in a blown fuse. Additionally, since cable-to-cable interactions were being considered, three rows representing different cable insulation material types from the base case [TS (intra) and TS→ TS (inter)] were included: TP (intra); TS→ TP (inter); and TP→TP (inter). Figures 3-8 through 3-11 show the associated tables and figures.

Example set two encompasses two different tables. Grounded AC control circuits were excluded because the panel members were unaware of any applications of a double-break design for a grounded circuit. This primarily is because a grounded AC target does not need two hot shorts to produce a spurious operation. Instead, in this case, it would be caused by a single hot short on the upstream side (positive) of the relay, and a ground on the other side. However, the case of a grounded AC circuit causing a spurious operation on an ungrounded AC circuit was included as a possibility for causing a spurious operation in an ungrounded AC circuit design. The tables are organized as given in Table 3-5 below.

Table 3-5. Control Circuit Example Set Two with Double Break Design

Table/Figure	Control Circuit Power Source	Probability Estimation
Table 3-6 & Figure 3-8	Ungrounded AC powered from a CPT	Spurious Operation
Table 3-7 & Figure 3-9	Ungrounded DC (or AC distribution bus)	Spurious Operation

Table 3-6. Double break ungrounded AC probability table

Double Break Ungrounded AC Powered from a CPT*							
Cable Configuration		Conductor shorting modes of interest					
		Intra + Intra cable short	Intra + Inter cable short	Inter + Inter cable short	Intra + ground cable short	Inter + ground cable short	Aggregate result for all possible failure modes
Base Case (TS insulated source and target Cables)				N/A		N/A	
TP Cable	TP insulated source and target cables						
	TS insulated source and TP insulated target cables						
Cable includes a grounded metal foil shield wrap			N/A	N/A	◊	N/A	
Armored 7/C Cable			N/A	N/A	◊	N/A	

*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.

◊ Intra cable shorts that mimic the fault mode of ground fault equivalent hot shorts are included under the intra + intra cable short column.

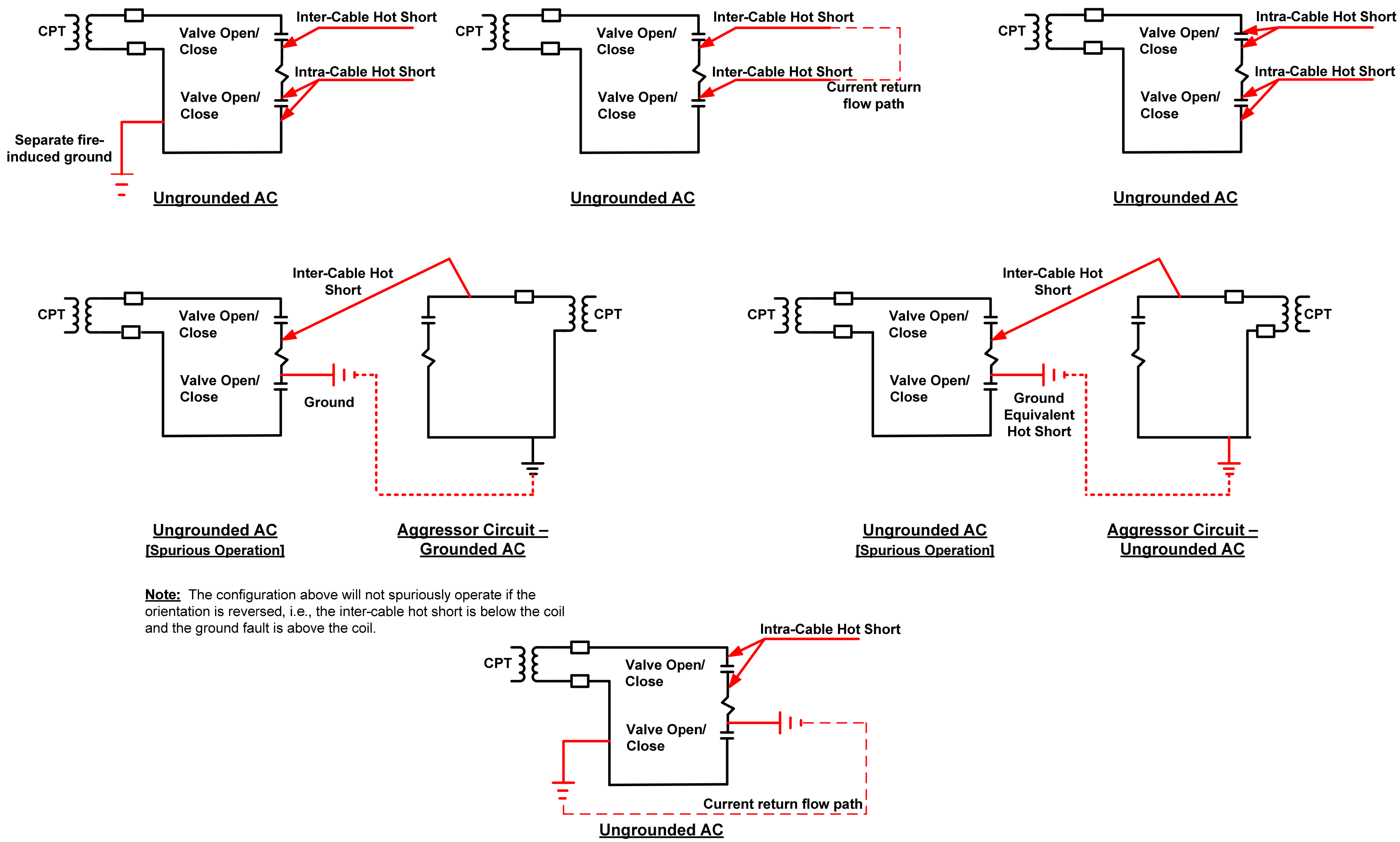


Figure 3-8. Double break ungrounded AC schematics

Table 3-7. Double break ungrounded DC probability table

Double Break Ungrounded DC*							
Cable Configuration		Conductor shorting modes of interest					
		Intra + Intra cable short	Intra + Inter cable short	Inter + Inter cable short	Intra + ground cable short	Inter + ground cable short	Aggregate result for all possible failure modes
Base Case (TS insulated source and target Cables)				N/A		N/A	
TP Cable	TP insulated source and target cables						
	TS insulated source and TP insulated target cables						
Cable includes a grounded metal foil shield wrap			N/A	N/A	◊	N/A	
Armored 7/C Cable			N/A	N/A	◊	N/A	

*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.

◊ Intra cable shorts that mimic the fault mode of ground fault equivalent hot shorts are included under the intra + intra cable short column.

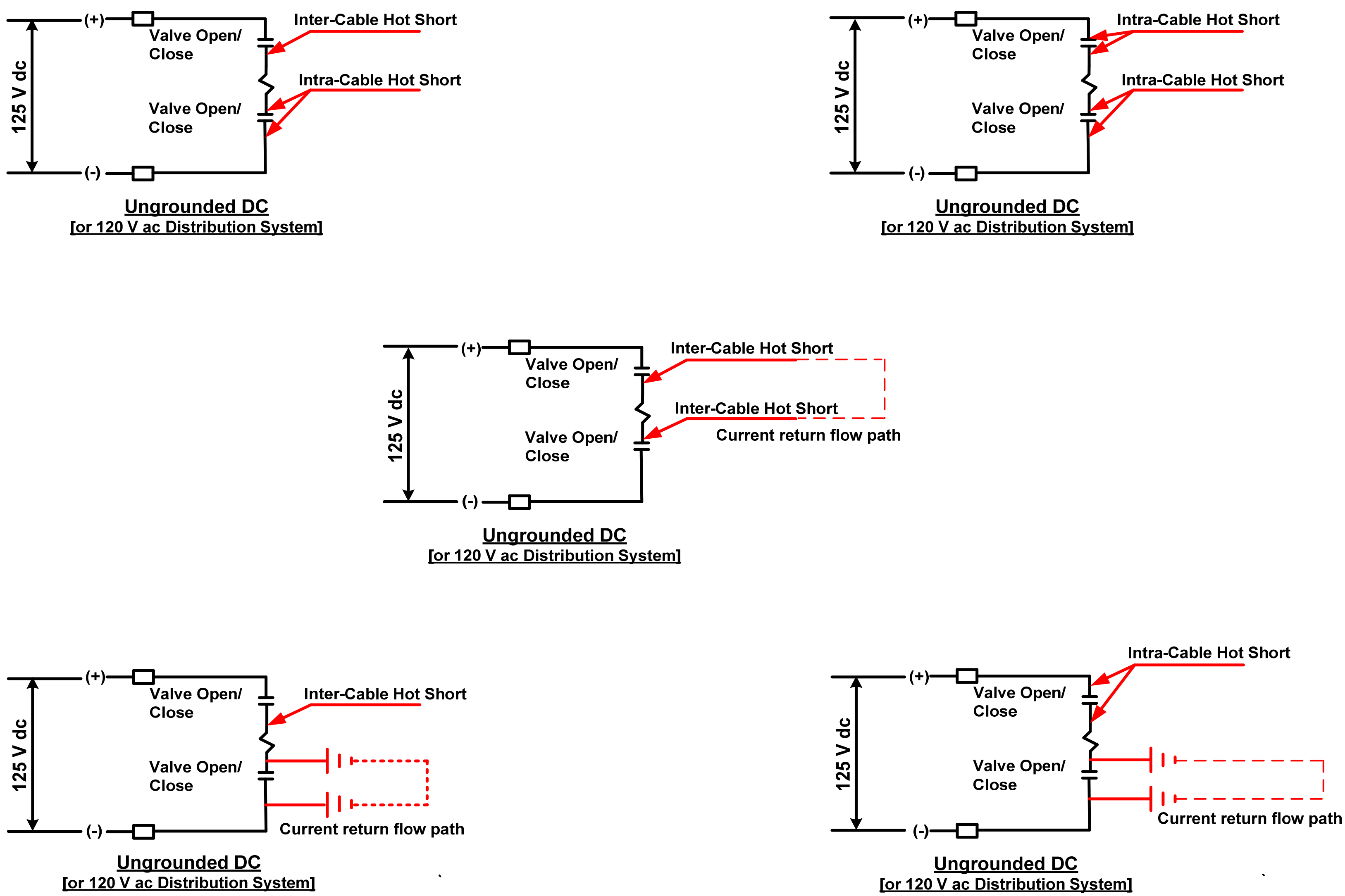


Figure 3-9. Double break ungrounded DC schematics

3.4.1.3 Control Circuit Example Set Three

Finally, example set three contains tables specifically designed to address the DURATION of a hot short-induced spurious operation (and the duration of hot shorts). Table 3-8 presents the logical arrangement of the duration tables. The PIRT panel indicated that fuse/breaker size parameter impacts the duration of DC spurious operations and as such the ungrounded DC duration tables identified in Table 3-8 have been split. For circuits with fuses ≤ 10 amps duration data exists for both spurious operation and hot shorts, while circuits with fuses > 10 amps only hot short duration data is available. This is a result of all fuses >10 amps used in testing were associated with the circuit breaker which by design only allows for a momentary spurious operation. The PIRT panel believed that the hot short and spurious operation duration data for ≤10 amps case may support extrapolation for spurious operations in the >10 amp case.

Table 3-8. Control Circuit Example Set Three for Spurious Operation DURATION

Table	Control Circuit Power Source	Duration Estimation
3-9	Grounded AC powered from a CPT	Spurious Operation Duration
3-10	Ungrounded AC powered from a CPT	Spurious Operation Duration
3-11	Ungrounded DC power source ≤10 amp fuse	Hot Short Duration
3-12	Ungrounded DC power source ≤10 amp fuse	Spurious Operation Duration
3-13	Ungrounded DC power source >10 amp fuse	Hot Short Duration

The duration tables are set up differently than the probability tables, since the physical influencing factors that most affect spurious operation duration differ from those that affect probability. The variables chosen for the tables were based upon the parameters from the ranking tables that were determined to be highly important to the duration of a spurious operation. Such parameters included the following:

1. Fire exposure condition;
2. Panel wiring;
3. Time-current characteristics – Fuses/Breaker Size;
4. Cable Wiring Configuration (sources, targets); and
5. Latching versus Non-latching Device.

Panel wiring, time-current characteristics, and the configuration of the cable wiring were eliminated from consideration in this table set because there were insufficient data to realistically determine a number to assign for duration based upon these parameters.

Latching versus non-latching also was eliminated from the tables because it is considered primarily to depend upon the circuit design, and not on the cable's failure characteristics. This parameter is a toggle event with pre-determined results. If the device is latching, the spurious operation will continue until the fuse blows. If the device is non-latching, the signal will stay in until the spurious operation clears, or the fuse blows. In either case, the fact that the circuit is latching or non-latching has little effect on the characteristics of cable damage. The true arbiter of the duration of spurious operation is the behavior of the cable and the ultimate time for the fuse to blow. Consequently, these tables are constructed with the following variables for fire exposure conditions:

1. Flame;
2. Plume; and
3. Hot Gas Layer.

Furthermore, there are no duration tables that specifically address a single-break or double-break design as there is for spurious operation probability. This is because there appears to be no way to easily correlate the duration of a single hot short-induced spurious operation with that of a spurious operation caused by two concurrent hot shorts.

The ground fault equivalent hot shorts failure mechanism is represented as "N/A" in the grounded AC circuits because it cannot occur without blowing a fuse.

Additionally, the DESIREE-Fire tests show that for fuses greater than 10 amps in ungrounded DC circuits, it may not necessarily blow. Consequently, power would be fed to the source conductor for a much longer time. Because of the potential effects this could have on the duration of hot short and spurious operation the associated tables are separated into "≤10 amp fuses" and "> 10 amp fuses" for ungrounded DC. However, because of the circuit configuration for the testing that is conducted using fuses over 10 amp fuses (a circuit-breaker configuration), spurious operation data is not available from the DESIREE-Fire testing. For these cases, only the hot short duration was measured. Because of this, the electrical expert PIRT panel determined that tables would provide the probability of hot short duration for both greater than and less than 10 amp fuse sizes. No such table was possible for the former category due to the dearth of data.

Table 3-9. Spurious Operation Duration - Grounded AC Power Source

Spurious Operation Duration - Grounded AC Power Source			
Flame Zone Location	Conductor shorting modes of interest		
	Intra-cable	Inter-cable	Ground fault equivalent hot shorts
Hot Gas Layer			N/A
Plume Region			N/A
Flame Region			N/A

Table 3-10. Spurious Operation Duration - Ungrounded AC Power Source

Spurious Operation Duration - Ungrounded AC Power Source			
Flame Zone Location	Conductor shorting modes of interest		
	Intra -cable	Inter-cable	Ground fault equivalent hot shorts
Hot Gas Layer			
Plume Region			
Flame Region			

Table 3-11. Hot Short Duration - Ungrounded DC power source ≤10 Amps Fuse Size

Hot Short Duration - Ungrounded DC Power Source <10 Amps			
Flame Zone Location	Conductor shorting modes of interest		
	Intra -cable	Inter-cable	Ground fault equivalent hot shorts
Hot Gas Layer			
Plume Region			
Flame Region			

Table 3-12. Spurious Operation Duration - Ungrounded DC Power Source ≤10 Amps Fuse Size

Spurious Operation - Duration Ungrounded DC Power Source <10 amps			
Flame Zone Location	Conductor shorting modes of interest		
	Intra-cable	Inter-cable	Ground fault equivalent hot shorts
Hot Gas Layer			
Plume Region			
Flame Region			

Table 3-13. Hot Short - Duration - Ungrounded DC Power Source >10 Amps Fuse Size

Hot Short Duration Ungrounded DC Power Source >10 Amps			
Flame Zone Location	Conductor shorting modes of interest		
	Intra -cable	Inter-cable	Ground fault equivalent hot shorts
Hot Gas Layer			
Plume Region			
Flame Region			

3.4.2 Control Circuit Configurations for Single and Double Break Designs

The PIRT panel used electrical control circuit diagrams and physical circuit configuration layouts to assist with the discussion of numerous issues and in understanding how various parameters affect the likelihood of hot short-induced spurious operations. Furthermore, the PIRT panel determined that providing these circuit diagrams and physical layout illustrations will be valuable for the reader of the report and the follow-on expert elicitation by the PRA panel. These eight specific cases of the control circuit configurations for both single and double break designs are presented in Appendix C of this report.

4
PIRT PANEL TECHNICAL POSITIONS ON POWER CIRCUITS

This section addresses the motive power to AC and DC motors; the control circuits are addressed in Section 3. Additionally, for DC systems only DC compound-wound type motors were evaluated, since these are the type of motors that exist in US NPPs. The electrical expert PIRT panel did not identify applications of interest for either a series- or a shunt-wound DC motor configuration.

4.1 Background

In general, short circuit behavior for power circuits is relatively well understood and is documented in countless industry standards, guidelines, and texts. However, some unique failure modes that are considered by the PIRT panel to be legacy issues were evaluated. Because of the lack of test data for power circuits, the PIRT panel could not apply the PIRT evaluation process to them. Instead, the PIRT panel decided to undertake a separate evaluation by providing consensus technical positions. The panel considered that much of the data on cable fire test for control circuits provided adequate insights to support the conclusions drawn in the consensus technical positions. The two power circuit failure modes that the PIRT panel investigated were three phase proper polarity hot shorts in AC power circuits and proper polarity hot shorts on DC compound-wound motors. Three phase AC cabling is common throughout a nuclear plant, and DC compound-wound motors are used for MOVs in a variety of applications.

During discussions, the PIRT panel unanimously concluded that three-phase power consequential hot shorts in AC power circuits are incredible. Additionally, they deemed that consequential DC power hot shorts to a DC motor are incredible. The following discussions contain the rationale behind the panel's consensus positions and conclusions for these failure modes.

4.2 Three Phase AC Power Circuit

For the following reasons, the PIRT panel determined that the potential for a fire to cause a hot short on all three phases in the proper sequence and thereby cause a spurious operation of a motor is incredible. (Refer to Figure 4-1 for the following discussion).

For a three-phase short to occur that would cause a motor to spuriously operate, the motor's three-phase cabling would have to impinge upon by another three-phase "aggressor" cable in the same raceway. This must occur downstream of the motor control center (MCC) or bus powering the motor since the motor's starting contacts (which are only closed when the motor-control circuitry drives the motor) or motor circuit breaker located within the MCC or bus would prevent any short upstream of the control device (contactor or circuit breaker). This aggressor cable also would have to be one that was supplying a continuously running load; otherwise, the aggressor cable normally would be de-energized and, therefore would be inconsequential. Furthermore, the aggressor cable would have to be supplying a load of such magnitude that the over-current protective relaying (specifically, the time over-current feature) would not trip when the valve motor initially started running, since now the upstream power supply would be supplying both its normal load, and the considerable starting current of that impinging upon the motor.

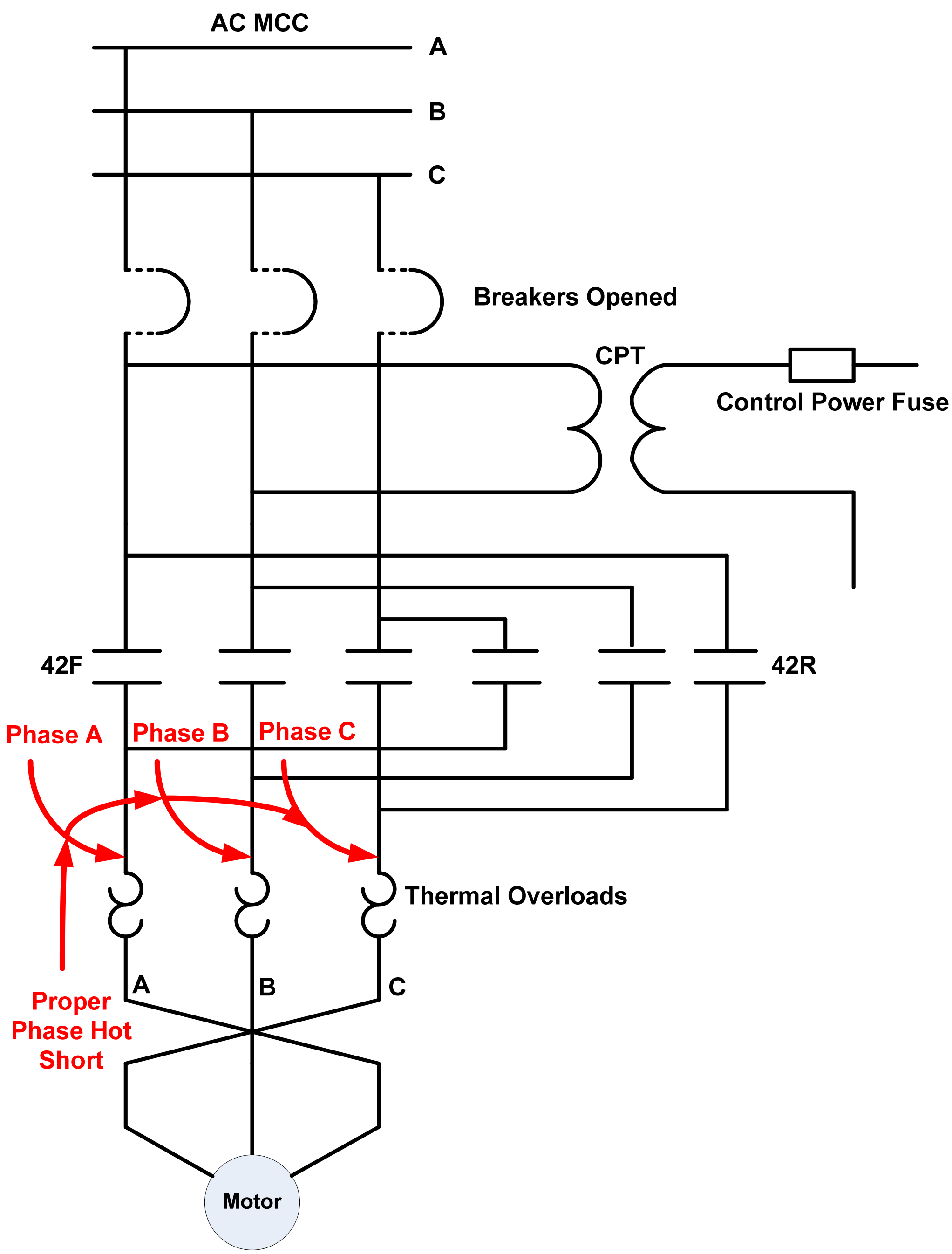


Figure 4-1. Typical simplified AC 3-phase motor (power circuit)

Additionally, to cause the three-phase motor to operate, the aggressor cable would have to short all three of its phases to the three phases on the cable for the motor. Furthermore, for a valve motor, these three phases would have to be shorted to the motor's power cabling in the exact sequence such that the motor's valve would fail in the undesired position (i.e., open for a boundary-isolation valve) position; this scenario has a 1 out of 2 probability assuming three hot shorts of diverse phases were to occur.

The conductors for the three-phase motor, as well as the aggressor's conductors, also could not at any time be shorted to ground or shorted to each other. Since three-phase cabling normally is in a triplex configuration (three conductors, each separately insulated, wound around each other – similar to rope), for three shorts to occur, the insulation would have to be broken down sufficiently on all three phases in both cables such that a direct short would occur; however, the rest of the cables would have to be insulated sufficiently such that any other area of insulation breakdown would not result in a ground or a short to any of the other conductors within the cables. This scenario is deemed to be incredible, regardless of the cable's type of insulation or grounding configuration. For some large motors, single-conductor cable may be used. In these cases the cables are usually placed within the tray to provide some separation for heat dissipation. In this case the single cables are in direct contact with the raceway. In conduit the cable might be touching, but physical limitations on fill in most all cases preclude more than one set of three-phase cables per conduit.

In the cable-fire testing for control circuits, there were very few inter-cable hot shorts. The predominant failure mode was a short-to-ground. When hot shorts did occur, an intra-cable hot short was the most likely one. Such hot shorts, however, were often, in a finite amount of time, followed by a short-to-ground that blew the control power's fusing. The test data clearly imply that the likelihood of a single inter-cable hot short is very low. To postulate the occurrence of the multiple inter-cable hot shorts without any intra-cable interaction places the postulated three-phase hot short scenario into the incredible category.

Therefore, based upon the unique characteristics of three-phased cabling and loads, a consequential three phase short is considered **incredible** and need not be considered.

4.3 DC Compound-Wound Motor Power Circuit

Similar arguments demonstrate that consequential hot shorts on a 250 VDC reversing motor of a motor-operated valve also are incredible. Figure 4-2 illustrates DC compound-wound motors. The power circuit of a typical reversing DC compound-wound motor must energize a series field, a shunt field, and armature to operate the motor to operate. The polarity of the armature determines the direction of the motor's movement. To move this type of motor, a unique combination of an inter-cable and two intra-cable hot shorts would have to occur. For example, as shown in Figure 4-2, conductor 1 would have to receive power through an inter-cable short. Additionally, conductor 2 would have to short to conductor 3 to put the series winding in series with the motor's armature. Additionally, conductor 4 would have to short with conductor 1 to provide the proper parallel voltage to the shunt field's winding. These hot shorts must happen concurrently to cause the motor to run. Furthermore, conductors 2 and 3 could not simultaneously hot short to conductors 1 and 4. Also, it is unlikely that these faults could occur without conductor grounding causing fuses and/or breakers to open. Because of these unique conditions that would have happen, the PIRT panel considered that consequential hot shorts in the power circuitry of a DC compound-wound motor is **incredible** and need not be postulated.

However, it is noted that this analysis only applies to the power circuit for a DC motor. The control circuit should be analyzed similarly to any other DC control circuit subject to fire damage.

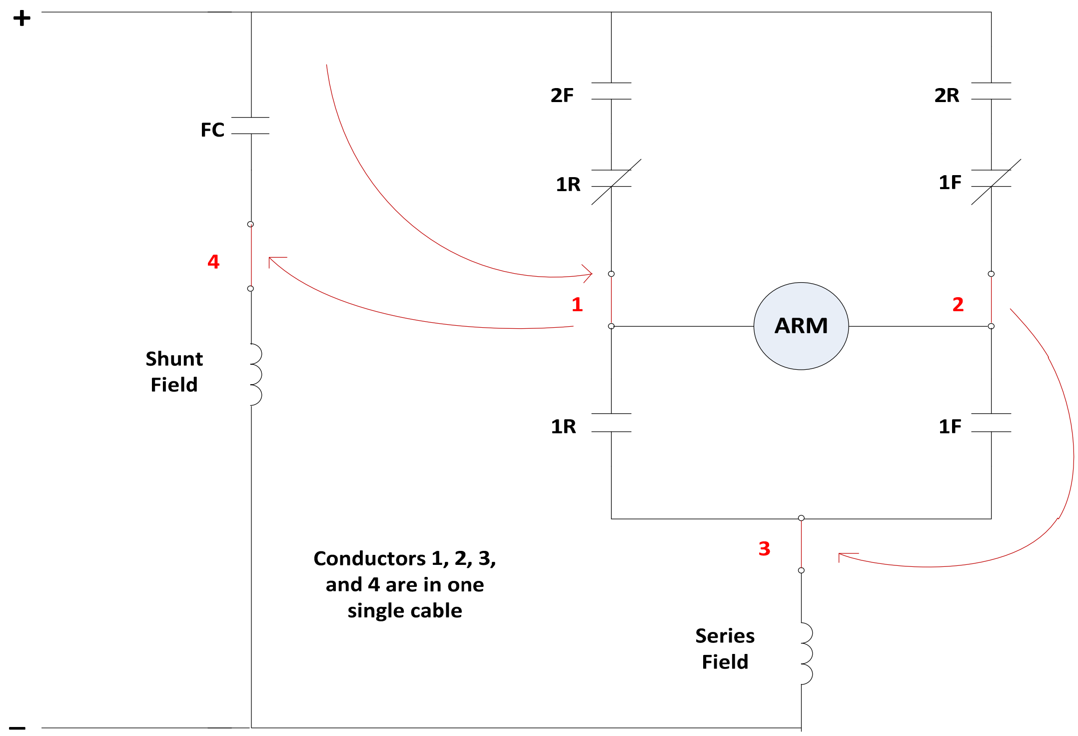


Figure 4-2. Typical Simplified DC Compound-Wound Motor (Power Circuit)

5 PIRT PANEL EVALUATION OF INSTRUMENTATION AND CONTROL CIRCUITS

5.1 Background

Industrial instrumentation and control (I&C) systems are used extensively throughout today's commercial nuclear power plant as a way to provide indications and control of temperature, pressure, speed, and other critical parameters. Over the years, many communication standards and system architectures have been employed to accomplish this functionality. At a very high level, these standards include analog-, and digital-signals and their combinations, also known as hybrid signals. Communication protocols vary from mechanical analog (pneumatic, hydraulic, mechanical linkage), electrical analog (modulated voltage or current signals) to more complex digital signals, such as field bus, RS-232, RS-422, and Transmission Control Protocol (TCP) over Ethernet. Note that RS-232 and RS-422 are the traditional names for a series of standards used in telecommunication circuits, and TCP is the protocol upon which major internet applications rely.

A fire directly affecting the cabling associated with low-energy I&C systems may cause open circuits, conductor-to-conductor bolted or resistive hot shorts (inter-cable or intra-cable), or shorts to ground. The effects of these failure modes may drive the process variable downscale (zero), upscale (span), or may produce values (steady or varying) between zero and span. This unpredictability in the failure state of the process variable may elicit undesired automatic- or human-responses that possibly might complicate or compromise the overall response to the effects of the fire (shutdown or safe and stable).

For I&C circuits, the electrical expert PIRT panel discussed the different types of control circuits and the potential failure mechanisms during a fire event. Because of the limited amount of testing undertaken, the panel decided to concentrate on identifying potential plausible failure modes of high significance for the prevalent instrumentation configurations throughout the industry. They then recommended future research in the areas where the configurations were common and the consequences of fire-induced failures could be very high.

5.2 Instrumentation and Control Circuit Evaluation

The PIRT panel discussed several different types of instrumentation control circuits during their discussions, ruling out a number of them for further consideration/research for several reasons. Table 5-1 gives a synopsis of the different types of circuits that the panel evaluated. The table briefly describes the configuration of each instrument control circuit, its usages in the nuclear industry, and the panel's recommendations for future research.

Table 5-1. Different Types of Instrumentation Circuits

No.	Instrumentation Control System Type	Description	Usage in the Nuclear Industry	PIRT panel Recommendation
1	Current Loop	In a current loop instrumentation control-system, the current produced by the loop's power supply is sent around the loop, flowing through every device and load resistor in the circuit. Variations in the loop current are determined by changes in the process parameter, as measured by the instrument. The transmitter produces the output signal, either in the form of a 4-20 mA or a 10-50mA current that can be used for indication, operation, and other functions.	Current loops are used throughout the industry in a variety of control applications. The most common instrument loops in the nuclear industry are the 4-20 mA ones.	Since the 4-20 mA current loop is prevalent in the industry, and the signal is transmitted through an electrical cable, very little prior testing has been conducted on the effects fire on the cables. Therefore, the PIRT panel highly recommended undertaking further research. Testing on the 10-50mA current loop, although not as prevalent at NPPs, was also recommended.
2	Full Pneumatic	Full pneumatic-control systems utilize mechanical transducers to convert the process variable into a pneumatic signal for transmission around the plant via pneumatic tubing. Control pressures generally are 3-15 psig but can be amplified via mechanical amplifiers to greater pressures and volumes for the purposes of opening valves.	Used before the advent of the current loop (pre-1950s). Found later in some commercial nuclear power plants for the trip logic of the emergency diesel generator.	Since these systems do not use electrical wiring, the PIRT panel did not recommend their future testing.

Table 5-1. Different Types of Instrumentation Circuits (Cont'd.)

No.	Instrumentation Control System Type	Description	Usage in the Nuclear Industry	PIRT panel Recommendation
1	Current Loop	In a current loop instrumentation control-system, the current produced by the loop's power supply is sent around the loop, flowing through every device and load resistor in the circuit. Variations in the loop current are determined by changes in the process parameter, as measured by the instrument. The transmitter produces the output signal, either in the form of a 4-20 mA or a 10-50mA current that can be used for indication, operation, and other functions.	Current loops are used throughout the industry in a variety of control applications. The most common instrument loops in the nuclear industry are the 4-20 mA ones.	Since the 4-20 mA current loop is prevalent in the industry, and the signal is transmitted through an electrical cable, very little prior testing has been conducted on the effects fire on the cables. Therefore, the PIRT panel highly recommended undertaking further research. Testing on the 10-50mA current loop, although not as prevalent at NPPs, was also recommended.
2	Full Pneumatic	Full pneumatic-control systems utilize mechanical transducers to convert the process variable into a pneumatic signal for transmission around the plant via pneumatic tubing. Control pressures generally are 3-15 psig but can be amplified via mechanical amplifiers to greater pressures and volumes for the purposes of opening valves.	Used before the advent of the current loop (pre-1950s). Found later in some commercial nuclear power plants for the trip logic of the emergency diesel generator.	Since these systems do not use electrical wiring, the PIRT panel did not recommend their future testing.

Table 5-1. Different Types of Instrumentation Circuits (Cont'd.)

No.	Instrumentation Control System Type	Description	Usage in the Nuclear Industry	PIRT panel Recommendation
3	Electro-Pneumatic	Electro-pneumatic control systems use an electrical process variable signal and convert it to a proportional pressure signal via an electro-mechanical transducer.	Used extensively for valve control.	Electrical portion is similar to the current loop in that a 4-20 ma signal is transmitted through a cable. Future research recommended by the PIRT panel is addressed in number 1 above under Current Loop. Since the pneumatic portion does not employ electrical cabling, the PIRT panel did not recommend this type of system for future testing.
4	Electro-Hydraulic	Electro-hydraulic systems employ a standard electrical control system via transducers. A typical example would be the conversion of an electrical process variable into a proportional hydraulic pressure for moving valves such as in the turbine control system.	Electro-hydraulic controls are found throughout the nuclear industry in the turbine control system and in the control system for many turbine driven pumps.	Electrical portion is similar to the current loop; therefore, future research is recommended by the PIRT panel and is addressed in number 1 above, Current Loop. Since the hydraulic portion does not employ electrical cabling, the PIRT panel did not recommend this type of system for future testing.

Table 5-1. Different Types of Instrumentation Circuits (Cont'd.)

No.	Instrumentation Control System Type	Description	Usage in the Nuclear Industry	PIRT panel Recommendation
5	Digital Control	Digital-control systems employ high-order communication protocols, often with complex error-checking and loop-regeneration capabilities. In general, the cabling is shielded, twisted pair, or more recently, specialty cabling that can carry power and other signals within the same cable. Sophisticated isolation- and synchronizing- capabilities often ensure seamless transfer when a fault is detected on a cable. Some protocols support the programming of loops so that they enter a "hold last state" mode upon loss of communications.	While digital-control systems are frequently used in non-nuclear industrial applications, they are not as common in the nuclear industry. This is primarily due to the complexity of the systems, and as a result, the uncertainty of, and vulnerability to, common-cause failures due to software related problems. Digital systems primarily are used in non-safety and important- to-safety applications, such as feedwater-control and turbine-control systems. (use same type as in rest)	Because of the many variations of standards, protocols, cable media, adaptability, and programmability, a bounding testing- configuration for digital systems would be difficult to establish. Additionally, error- checking schemes are employed by digital- control schemes that largely decrease the likelihood of fire-induced cable faults. Consequently, the PIRT panel does not recommend testing the cabling of digital- control systems . However, overheating effects of digital devices due to a fire may be a concern. It is important to understand the potential effects of exceeding the temperature ratings of the digital devices and the ultimate effects to the system that is being controlled. This is discussed in Section 5.3.2 of this report.
6	Combination Analog and Digital	In this control system, digital data is carried over the same wires that the analog loop utilizes for control purposes with the digital signal riding in the carrier analog signal. Generally, the digital data is used to convey data such as system/device health, and environmental information.	While this type of device is "state-of-the-art" and often used in the non-nuclear industry, the PIRT panel was not aware of any nuclear plant that presently employs this type of system.	Since this type of system is rarely, if ever, used in the nuclear industry, the PIRT panel do not recommend further research.

5.3 Specific Concerns involving Instrument Current Loops

The PIRT panel determined that testing of instrument current loops was extremely important considering the potential consequences of fire-induced failures. The panel also was primarily concerned that the failure modes and effects on instrument circuits could be substantially different than those on control circuits.

5.3.1 Instrumentation Cabling

Although the general state of knowledge of the mechanisms of cable failure is fairly comprehensive, testing has focused on cables carrying control circuit energy levels rather than on cables carrying the very low energy-levels found in instrumentation circuits. The low energies of instrumentation circuits could cause them to perform and fail differently under fire-induced fault conditions than those of higher energy control circuits. For instance, while control circuits progress relatively quickly through fault states due to arcing-fault energies, this same progression may not be experienced as readily in the lower-energy instrumentation circuits. The time required before a fault state occurs in the circuit and its duration may differ substantially from that of control circuits. Furthermore, various wiring methods, circuit designs, and the use of shielding (tied to ground or to the power-supply neutral) may be the dominating influences over the failure modes and effects seen as a fire damages the cable.

In an instrumentation circuit, a fire-induced change in the process variable may have cascading effects that trigger varied reactions; including changing the valve’s position, initiating automatic function, and indicating incorrect process variables. Based upon knowledge of Equipment Qualification (EQ) testing and fire testing on instrument cabling, various modes of failure could exist. (NOTE: The instrument-cable fire testing – NUREG/CR-6776 (Ref. 21), Cable Insulation Resistance Measurements Made during Cable Fire Tests - was not conducted on actual applications of nuclear-power-plant instrument circuits; nevertheless, it afforded some insight into the potential failure-modes of this type of cabling as discussed in Section 2.3.2.3 of this report). Specifically, there is the possibility that instead of an instrument failing in only two functional failure-modes, e.g., either indicating high or low, it might fail in an intermediate mode before complete failure. This would result in a false reading that could cause an operator to make an incorrect diagnosis, or it could mask an indication of a problem in the plant. This potential human-factors effect, if proven to be a likely concern, has not been well analyzed.

Figure 5-1 shows a simple 4 mA to 20 mA, 2-wire input control loop with power supply, pressure transmitter and pressure indicator. Wire-to-wire shorts between the combinations of nodes 1 through 4 on the figure may cause the loop to fail high state, low state, or in an intermediate state that could provide a “false-normal” indication. Because of the low energies involved in instrumentation circuits, it may be possible for failure states to exist for a prolonged, and possibly, indefinite period of time.

Some of the panel's specifically identified instrumentation concerns on cable failure concerns are listed below:

1. If the power for the loop is provided by a power supply that is physically independent of the loop’s transmitter, a conductor-to-conductor short across the transmitter possible could drive the loop current high (20+ mA). The effect of this failure mode is contrary to the belief that loop currents cannot be driven high by intra-cable shorting.

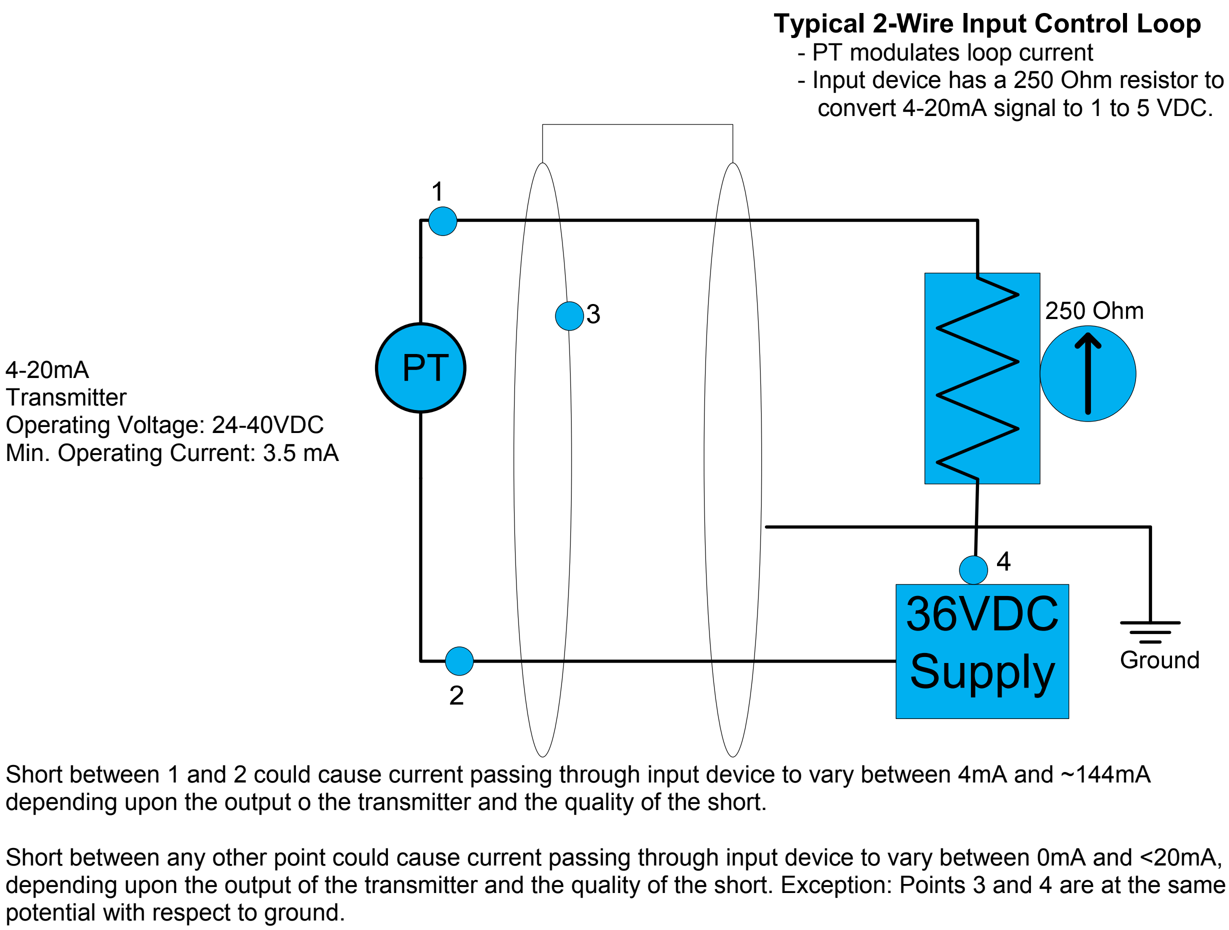


Figure 5-1. Typical 2-Wire Input Control Loop

2. Depending upon the electrical relationship of the shield with respect to the signal conductors, it may be possible for leakage current to occur between the two. This may occur as a result of intra-cable shorts, or a combination of intra- and inter-cable shorts. It even may be possible to re-reference a shield, via an inter-cable short, to allow the flow of current from one loop to another through the shield or ground plane. This failure mode would challenge the concept that the shield will protect the target loop from the influences of external loops.

3. The leakage of signal current could be induced by intra-cable short(s) between the signal conductors within a shielded twisted pair cable. Due to the low- energy characteristics of instrumentation circuits, a prolonged short condition might be established, producing an erroneous signal, fixed or variable, that is in the high-, low-, or midscale-range. This failure mode would be contrary to the concept that internal shorting is always of low impedance, and will quickly drive the circuit to a single-failure state.

5.3.2 Instrumentation Circuit Electronic Devices

Fire-induced effects on the electronic devices in instrumentation circuits (e.g., transmitters, input/output modules, process modules may be extremely detrimental to the instrumentation circuit's functionality. Specifically, as these devices are exposed to the heat of the fire, the ability of the device to properly handle input-to-output relationships may become unpredictable due to the heating effects on its electronic components. Although the effects of heating individual electronic components has been well documented (e.g., changing resistance values, component catastrophic failure, and microprocessor instability), the effects of these component failure modes on the device's function is not as well understood.

For digital circuits, while it is safe to assume that a fire-induced failure (hot short, open circuit, short to ground) of an Ethernet cable will not produce properly sequenced communication packets in accordance with the communication protocol, it may not be safe to assume that this situation would pertain when the sending or receiving device itself is exposed to the fire.

Additionally, in many cases, redundant digital controllers for important to safety-control systems, such as the feedwater control system, are located in the same fire area and zone. This type of configuration allows fire-induced heat-up of the room to have a common-mode adverse effect to redundant controllers. Since most digital controllers have a specific temperature rating, it is important to understand the potential effects on the controllers, and ultimately on the system that is being controlled, should a fire cause this limit to be exceeded.

5.4 Summary of Research Recommendations

Due to the low state of knowledge and potentially high consequence of fire-induced failure on instrumentation current loop circuits, additional testing is recommended

The PIRT panel considered that the following circuits should be included in the testing:

- 10 mA to 50 mA instrumentation circuits
- 4 mA to 20 mA instrumentation circuits
- 1 VDC to 5 VDC instrumentation circuits.

Even though the PIRT panel did not recommend testing fire-induced effects on the components of instrumentation circuits, such as transmitters, power supplies, and indicators, the state of knowledge in this area is low and the potential effects could be highly significant. Therefore, it is essential that fire-induced effects on the instrument loop's components should be adequately evaluated when addressing spurious operations. This statement also applies to digital controls. While ultimately there may be value in such testing, the PIRT panel concluded that more immediate need for testing lay in the area of instrumentation cabling.

6
PIRT PANEL TECHNICAL POSITION ON ANCILLARY CIRCUIT ANALYSIS RELATED ISSUES

The electrical expert PIRT panel evaluated several known open issues or concerns associated with deterministic fire-induced safe-shutdown analyses. These issues are considered as legacy issues related to safe-shutdown circuit analyses; however, the failure modes in question do in some cases impact the Fire PRA since they can affect the cable selection processor impacts due to associated circuits. The PIRT panel evaluated each of these cases in great detail from the perspectives of both fire protection and electrical engineering. They developed technical positions on each issue that were evaluated as part of the expert elicitation process by the PIRT panel. Their technical positions are detailed in this section for the following technical issues:

- Multiple High-Impedance Faults (MHIFs)
- Open Circuit Secondary of Current Transformers (CTs)
- DC Control Power Common Enclosure/Common Power Supply
- Control Power Transformers (CPTs)
- Kapton-Insulated Cables
- Panel Wiring
- High Conductor Count Trunk Cables

6.1 Multiple High-Impedance Faults

6.1.1 Background

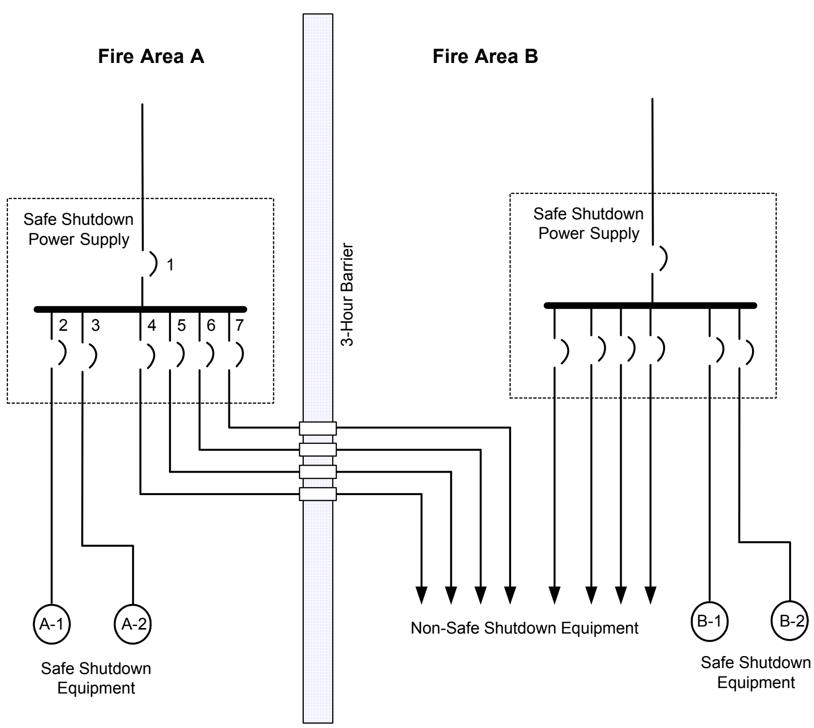
The Multiple High-Impedance Faults (MHIFs) circuit failure mode is a variation of the concern with common power supply associated circuits (see Figure 6-1). A MHIF exists when multiple circuits powered from the same distribution bus experience circuit fault conditions resulting in a short-to-ground, or conductor-to-conductor hot short, where residual resistance in the faulted connection maintains the fault current level below the long-term set point of the component's circuit breaker but the summation of the multiple faults is high enough to trip the feeder breaker to the distribution bus (Ref. 16). Such a circuit is considered to pose a risk to safe-shutdown if a fire-induced fault on a non-safe-shutdown circuit causes the loss of a safe-shutdown power supply due to inadequate electrical-coordination between upstream and downstream overcurrent protective devices (e.g., relays, circuit breakers, fuses).

A Coordination Study is the accepted method for evaluating the potential impact of common-power-supply associated circuits. It involves reviewing the tripping characteristics of the protective devices associated with the electrical power-distribution equipment of concern, in this case, the post-fire safe-shutdown or Fire PRA power supplies. The protection devices are considered to "coordinate" if the downstream (feeder or branch circuit) device trips before the upstream one (supply circuit) over the entire range of possible fault current. In conducting a traditional coordination study, each circuit fault is evaluated as a single event.

The concept of MHIFs deviates from baseline assumptions associated with conventional electrical coordination. The MHIF failure mode is based on presuming that a fire can cause short circuits that generate abnormally high currents below the trip point of the individual overcurrent-interrupting devices for the affected circuits. Faults of this type are defined as high impedance faults (HIFs). Under the assumed conditions, circuit overcurrent-protective devices will not detect and interrupt the abnormal current flow. It follows that if several circuits experience a HIF, the cumulative current flow could exceed the trip setting of the supply breaker or fuse, causing it to trip. Figure 6-1 depicts the MHIF concern.

6.1.2 PIRT Panel Recommendations on MHIF

The panel discussed relevant characteristics of cable faults, as observed during the various fire tests, and concluded that the generic methodology for "Analysis of Fire-Induced Multiple High Impedance Faults" provided in NEI 00-01, Rev. 2, Appendix B.1, "Justification for the Elimination of Multiple High Impedance Faults," (Ref.13) provided a technically sound basis and conclusion regarding the probability of MHIFs. Specifically, the analysis determines that the probability of MHIFs developing during a fire "is sufficiently low such that they do not pose a plausible risk to post-fire safe-shutdown when certain criteria are met." The PIRT panel agreed with the arguments and reasoning given in this analysis. A summary of that reasoning is given in the next section.



Safe-shutdown components A-1 and B-1 are redundant, as are A-2 and B-2. A fire in Fire Area B is assumed to render B-1 and B-2 inoperable, and thus A-1 and A-2 are credited as available for safe-shutdown. Circuit Breakers 4 – 7 supply non-safe-shutdown equipment via circuits that traverse Fire Area B. The fire is assumed to create high impedance faults on several of these circuits simultaneously. The nature of the faults is such that an abnormal current is produced in each circuit, but in each case the current is not sufficient to cause the affected branch feeder breaker to trip. The cumulative effect of the fault current flowing in each branch causes the incoming supply breaker (Circuit Breaker 1) to trip before the downstream breakers are able to isolate the individual faults. The safe-shutdown power supply is de-energized, causing a loss of power to the credited safe-shutdown equipment, A-1 and A-2.

Figure 6-1. MHIF Example

6.1.3 Summary of Technical Analysis on MHIF

The technical validity of MHIFs is based primarily on the premise that the insulation in a cable, during a fire, can degrade to a point such that low-level fault currents will be produced. Since this occurs on multiple cables, this phenomenon implies that a low-level fault would not ultimately cascade into a complete failure of the cable's insulation, and that the electrical protective device for the affected circuit would not trip. Additionally, if arcing faults, which have higher impedances than bolted faults, are considered to be type of HIF and thus a contributor to the probability of the MHIF phenomena, then it would have to be assumed that the arcing condition would remain as a relatively constant condition for a prolonged period of time. Both of these assumptions were analyzed and demonstrated to be contrary to the observed behavior of fire-induced faults for voltage levels at or greater than 110 V.

Cable Insulation Behavior during a Faulting Condition

For 120 VAC systems, when the insulation resistance of a cable and the resulting leakage current reaches a certain level, the fault will cascade such that the rate of degradation of the insulation's resistance increases significantly, causing fault resistance to drop rapidly, and leakage current to rise quickly. This ultimately leads to a complete failure of the cable, thereby opening the upstream protective device. For thermoplastic insulated cables, this failure occurs within seconds, and although the cascading failure appears to take slightly longer for thermoset-insulated cables, it is still rapid from the perspective of a growing fire. Should the leakage current never reach the level needed to cause this cascading effect, the current will be sufficiently low such the distribution feeder device (upstream of the protective device for the cable in the fire) could not be tripped provided the devices meet conventional coordination criteria.

For systems operating at or above 480 V, high impedance faults manifest themselves as arcing faults. For 125 VDC systems, the cable insulation breakdown behavior was amplified in comparison to the 120 VAC since DC power is more energetic and constant (non-sinusoidal) thereby delivering more energy to the developing fault. Accordingly, the 125 VDC circuits failed rapidly and often produced significant localized damage. It is also noteworthy that 125 VDC often experienced arcing faults in short bursts, typically 1-2 seconds in duration.

Arcing Fault Behavior

For 480 VAC and above systems, the energy level is high enough to sustain an arcing fault. The minimum plausible fault current produced by these faults will be detected by an adequately designed protective scheme and the fault will be cleared. The energies produced by arcing faults for this class of power system cannot be sustained by the hardware for extended periods before physical destruction of the conductor, insulating materials, and surrounding equipment result in wide spread catastrophic damage.

For 125 VDC and 250 VDC circuits, expectedly either the protective device will clear, or the conducting material in the cable will vaporize due to intermittent but highly destructive arcing, thereby resulting in an open circuit at the fault location. Either way, the high impedance fault condition will not exist for any appreciable length of time.

6.1.4 Applicability

The PIRT panel determined that the MHIF phenomenon does not need to be considered as long as certain criteria are met. Of critical importance is using certain robust design criteria outlined in NEI 00-01, Rev. 2, Appendix B.1, "Justification for the Elimination of Multiple High Impedance Faults," (Ref. 13) that ensure high impedance faults do not persist in an electrical system for extended periods of time. These criteria include the use of properly coordinated protective devices as outlined in IEEE STD 242 (Ref. 27), "IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (Buff Book)," and the use of proper protective devices that are designed and constructed according to applicable industry standards and applied within their vendor ratings.

Additionally, the PIRT panel felt it important to highlight that appropriate testing and maintenance be performed on these protective devices. Periodic maintenance and testing ensures that breakers/relays are operating within expected tolerances and can perform their intended design function. This is achieved by, as a minimum, following accepted industry guidelines and specific vendor recommendations for maintenance and testing of the breakers/relays. If the vendor did not provide maintenance and/or testing recommendations or the recommendations are outdated due to vintage, then an accepted industry consensus standard for testing and maintenance is considered acceptable.

Finally, Regulatory Guide (RG) 1.189, Revision 2 (Ref. 16), Section 5.5.2, states "Information in NEI 00-01, Appendix B.1, may be used to address multiple high impedance faults when used in a manner consistent with this guide." Section 5.5.2 of RG 1.189 applies to Alternative or Dedicated Safe-shutdown methodologies. However, if the technical concepts in NEI 00-01, Appendix B.1 are valid for alternative and dedicated safe-shutdown, the same concepts are considered valid for all fires, regardless of the shutdown methodology. The consensus position of the electrical expert PIRT panel was that the guidance in NEI 00-01, Rev. 2 (Ref. 13), Appendix B.1, can be safely applied to fire safe-shutdown methodologies throughout the plant.

6.2 Open Circuit Secondary of Current Transformers

Current transformers (CTs) represent a theoretical fire safety concern should the secondary side of the current transformer suddenly become open circuited. When under load, an open circuit on the transformer's secondary will produce a voltage transient that can potentially exceed the dielectric strength of the CT insulating materials or connected components, which could result in failure of the CT and potentially initiate a secondary fire.

6.2.1 Background

CTs are used throughout the electrical distribution system to monitor current levels at select locations and provide signals to metering and overcurrent protection circuits. CTs are physically located at the primary electrical conductor (i.e., bus bar or cable) and provide a signal from their secondary winding that is proportional to the current flowing through the main (primary) conductor. CTs measure the primary current through magnetic coupling and thus do not have a physical connection to the primary circuit they are monitoring.

Current transformers are designed to transform high primary current into low secondary current, which is more suitable to delicate instrument circuits. As an example:

CT Ratio:	800:5
Primary Current:	240A
Secondary Current:	240A x (5/800) = 1.5A

The CT transforms current in the primary windings by producing an electromagnetic flux in the transformer coil that, in turn, causes a current to flow in the secondary windings. The primary current, when transferred to the transformer's core, consists of a magnetization current that generates the core flux and a core-loss current. These two currents combine to make up the transformer's "excitation current." During normal CT operation, current flowing through the secondary winding produces an opposing flux.

A rise in CT excitation current will entail a proportional rise in the secondary current. However, when the excitation current increases to a certain level, the CT core reaches saturation, and no longer behaves proportionally. Then, a rise in the excitation current produces a significantly smaller increase in the secondary current.

Conversely, the voltage of the secondary depends upon the secondary current, and the impedance (burden) of the meter and relaying circuitry. Since the secondary current primarily is a function of the CT turns-ratio and excitation current, as the CT burden increases, the secondary voltage rises. Theoretically, the secondary voltage is as high as needed to maintain a constant primary-to-secondary current ratio. A sudden opening of the secondary circuit can cause high voltages in the current transformer secondary side as the CT attempts to maintain the voltage and current relationships dictated by the transformer turns ratio. This condition can potentially generate voltages that exceed the dielectric strength of the current transformer materials or connected components.

Brookhaven National Laboratories (BNL) raised the concern about CT secondary circuits in a letter to the NRC date July 21, 1983 (Ref. 39). The BNL letter postulated a scenario in which potentially high voltages induced on the secondary winding of a CT as a result of open circuiting the CT secondary due to fire ultimately causes the CT to fail in a manner that could start a secondary fire or damage safe-shutdown equipment in the immediate vicinity.

6.2.2 Current Transformer Characteristics with an Open Circuit Secondary

Devices such as current coils of meters or relays are constructed of a few turns of relatively large wire. As a result, they have low impedance (burden) and effectively act as a short circuit across the CT secondary. Thus, during normal operation, CTs effectively operate with their secondary shorted. It is for this reason that short circuit type faults are not of concern in this evaluation. It is not, however, intended that CTs operate with the secondary side open when primary current is present. Under open circuit conditions, the primary current becomes solely exciting current, which in turn raises the core flux density of the CT to saturation and induces a high voltage in the secondary. Electricians are cautioned to ensure that the secondary winding of a CT is either closed through the instrument circuit or that it is shunted (short-circuited) at the terminals.

The operating characteristics of a CT are such that the voltage at the secondary terminals of a CT remains low as long as the secondary circuit is closed. When a CT secondary is open-circuited (analogous to an infinite burden), the current flowing in the primary winding becomes the only exciting current. Without a secondary-side opposing flux, the transformer core may be driven into saturation on alternate half cycles. The flux form approaches a square wave, having amplitude equal to the saturation flux of the core with a 180° reversal of the flux each time the core is driven from saturation in one direction to that in the other direction. The time rate of change of flux (dØ/dt) during these reversals induces high voltage spikes into the secondary windings. In each half cycle, there is a relatively high voltage crest that endures for a short portion of the half cycle. The magnitude of this voltage crest increases with rising primary current, but its duration decreases accordingly (Figure 6-2).

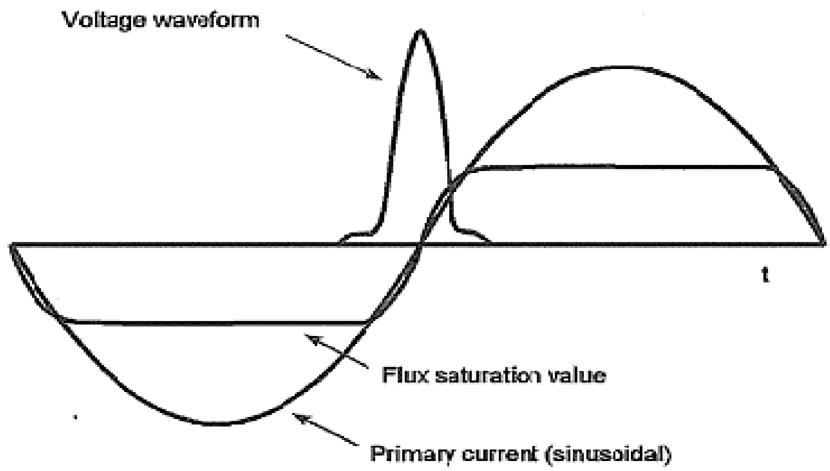


Figure 6-2. Voltage Waveform with Open Secondary

Although the voltage peak may be significantly high, very little power is available as explained below:

1. The governing power equation is P(t) = V(t) x I(t). Until the circuit arcs or faults, there is no significant power output; power is expended in the CT only as core losses.
2. The instant the circuit arcs or faults, an opposing flux produced by the current in the secondary limits the voltage peak. A generalized description of the circuit is that voltage declines as current rises.
3. As the current approaches the CT rating, the voltage profile also approaches the normal CT value. The power waveform will appear as a spike with an overall average power approximately equal to the maximum power of the CT during normal operation.

The turns-ratio of a CT affects the amplitude of the voltage spike during open-circuit conditions. The higher this ratio, the greater the voltage spikes. Normally, CTs can withstand the maximum expected voltage, including the abnormal voltages expected with an open-circuit secondary. CTs with a lower turns-ratio (1200:5 or lower) are not expected to be damaged by an open circuit, while those with a high one (greater than 1200:5) may experience insulation damage and conceivably could fail. Failure, in this case, would most likely involve breakdown of the insulation, the secondary windings to short to the core. Thereupon, the open-circuit condition is removed and the high voltage terminated. Even though this case is the most likely outcome, the

PIRT panel could not rule out the possibility of catastrophic failure for CTs with higher turns ratios.

6.2.3 Plausibility of CT Induced Secondary Fires

For secondary fires to occur due to an open-circuited CT, a combination of damages would need to occur. These effects are listed below:

1. The fire would have to produce an open circuit in the cable carrying the CT secondary conductors.
2. The open circuit in the CT secondary conductors would need to occur before the power cable associated with the CT shorted and caused the circuit's breaker to open. In this case no primary current would flow; hence there is no risk of voltage spikes even if the CT conductors open.

   However, for the case where the open circuit condition would need to occur rapidly such that no arcing or transient current flowed in the circuit at the point of fire-induced failure. The voltage transient then would cause arcing or catastrophic failure of the CT.
3. The resulting arcing or catastrophic failure of the CT would have to cause a secondary fire.

Each of these factors is addressed below:

1. <u>Fire Induced Open Circuit</u>

For a fire to produce an open circuit in the secondary, it first must burn through the associated cable jacket and insulation, and then burn open one or more of the copper conductors (melting temperature of approximately 1980°F) without creating any type of short circuit. An open circuit also could be caused by falling debris or some other event resulting from the fire. Regardless of the mechanism, intuitively, the jacket and insulation of the cable first must be damaged before the conductors lose continuity. While a fire can cause open-circuit conditions, the likelihood of this is low.

2. <u>Arcing or Catastrophic Failure of the CT</u>

Once the CT conductors open, a high voltage is assumed to exist. Since the fire has removed or severely damaged the cable's insulation fire at the open-circuit location, this is the most likely point of least resistance in the circuit. Since any arcing that may result from the high voltage is assumed to occur at the point of least resistance, the most probable location for arcing is where the cable is damaged. Because the open circuit location is by definition within the area of damage, arcing damage at the open circuit is presumed captured by the deterministic or PRA analysis and does not pose a threat beyond that already assumed.

As soon as an arc forms at the location of cable damage, the CT circuit voltage will drop because of the development of secondary flux opposing the primary current. As the voltage drops, the arc will be extinguished, allowing the process to be repeated. This faulted condition will continue until the CT's associated load is de-energized and primary current ceases to flow.

A majority of the CTs installed at the plant have a turns ratio of 1200:5 or lower. For the low ratio CTs, the induced voltage arising from an open circuit on the secondary side is not expected to cause damage to the CT or connected components. And, if the high voltage was to cause arcing, it would most likely do so at the fault location, as described above. High ratio CTs at the plant are primarily associated with the main generator, switchyard, and differential schemes. In the extreme case, the higher ratio CTs could potentially experience insulation damage or failure because of the secondary open circuit voltage. If the insulation fails, the most likely location of that damage would be the insulation between winding turns, which in turn is expected to cause the CT secondary to short to the core, effectively terminating the high voltage condition as described previously. The CT secondary is expected to short to the core, effectively terminating the high voltage condition as described previously. If the CT shorts through its insulation to the core, the end result is that the CT is non-functional but is effectively shorted as desired. Other than internal CT damage, no further adverse effects are expected to occur as a result of the open circuit condition.

Finally, a series of CT failure tests was sponsored by a utility in 1982. The tests were conducted by a 3rd party laboratory, Electrical Test Laboratory, Inc. (Ref. 28). These tests provide evidence that secondary open circuits in lower turn ratio CTs (up to and including 1200:5) do not damage the CT. Specifically, the report concluded that while the CT would pose a danger to personnel, the CT itself would not be damaged by the open circuit voltage. The bounding test case was a 1200:5 CT with 1200A simulated primary current. This case produced a crest voltage spike of 850 V, which did not damage the CT or connecting cables. It is observed that this voltage is well below the typical breakdown voltage for low-voltage cabling and components.

It is noteworthy that open-circuited CTs concern the electrical industry; however, the concern is primarily for personnel safety and not catastrophic failure of the CT. It is due to the large number of CTs that are left in an open-circuit condition both during and after maintenance work. For this personnel hazard to exist, the open-circuit condition would have to occur without the CT failing.

3. <u>Secondary Fire</u>

If an open circuit in the secondary of a CT were to cause the CT to fail, that failure still would have to produce a secondary fire. Since CTs are located inside electrical enclosures, this means that the effects would have to extend beyond the enclosure. This is not impossible, but is judged to be of low likelihood given the low energies involved and the general construction features of switchgear.

<u>Operating Experience Review</u>

The PIRT panel spent considerable effort researching nuclear and non-nuclear sources for any evidence of open circuits on CT secondary initiating a fire. The PIRT panel reviewed the NRC Licensee Event Report (LER) based fire event database and identified 10 events related to CTs. A more detailed evaluation of these events did not identify any instances where CT open circuits (from a fire or other source) resulted in a fire. Concurrent with the NRC review of CT events, EPRI staff also performed a similar search using its fire events database. The results of the EPRI efforts also did not identify any fires caused by open circuits in the secondary of a CT.

The electric power industry continues to endorse a policy of extreme caution not to open circuit the secondary side of an energized CT. It is helpful to understand that this policy is primarily intended to protect personnel and delicate instruments from dangerous voltages. Catastrophic failure and fire initiation do not surface as a credible concern. In this context, General Electric's Manual of Instrument Transformers, GET-97D (Ref. 29), states

"Although the insulation of most transformers will, in general, withstand open-circuit conditions, the resulting voltages are dangerous."

Other anecdotal information was identified during the research effort, including input from several switchgear manufacturers:

1. In a November 1984 NRC memo to Auxiliary Systems Branch (ASB) personnel (Ref. 30), the ASB Chief states in Section 2.2.4 of the memo:

   "In October 1982. BNL identified a problem with open-circuit operation of current transformers (CT) which could exacerbate the consequences of a control room fire. The concern stems from the fact that a control room fire could result in a breakdown of the power feeder insulation and cause a second fire. Attachment 7 contains the detailed description of the problem along with the applicant response to a PSB question on the subject. The Power Systems Branch has reviewed this concern and concluded that the BNL concerns were overly conservative and recommended no further action on this issue. Therefore, the ASB reviewer should be aware of this concern; however, no other action is required."

2. Bechtel Power Corporation stated in an October 16, 1984 letter (Ref. 31):

   "...the subject concern (CT open circuit causing a fire) is not credible... This conclusion is based on the CT manufacturer's information that the maximum open-circuit secondary voltages will not exceed CT insulation rating with full load current flowing through the primary winding."

3. Brown Boveri stated in an October 22, 1984 letter (Ref. 28):

   "In over 35 years of experience with current transformer design, test and application, the writer cannot recall a single incident wherein a fire was caused by an open-circuited current transformer. This experience, plus analysis of the rather particular circumstances necessary to allow such a fire to start, supports a stand that a fire caused in this fashion is unlikely."

4. Additionally, other industry experts with a vast amount of experience in this area have also confirmed that they have not known of a CT-induced fire (Ref. 32).

6.2.4 PIRT Panel Recommendations

All information considered, it was the judgment of the PIRT panel that the concern of a secondary fire resulting from an open circuited CT secondary is more theoretical than real. Based on the availability of objective test data for CTs with a turns ratio of 1200:5 and below, the panel determined that the unique combination of low probability events makes this failure mode (secondary fire caused by a CT secondary open circuit) incredible for CTs with low turns ratios (1200:5).

The PIRT panel also judged the likelihood of secondary fires from higher ratio CTs to be very low. However, in the absence of test data along with the concern becoming more pronounced as turns-ratio increases, the panel concluded that the failure mode could not be classified as incredible. To permanently resolve the concern, the PIRT panel recommends that additional testing be performed.

The panel also simplified that the assessment applies to CTs used in medium voltage and low voltage switchgear typically installed in NPPs, but does not apply to extremely high ratio pedestal-style CTs used in high voltage switchyards.

6.3 DC Control Power Common Enclosure/Common Power Supply

One of the more important uses for DC power is to supply control and/or protective devices in high- and medium-voltage switchgear and load centers. These power supplies can be lost as a direct result of fire damage to the major DC power-supply components (e.g., batteries, chargers,) or to electrical cables. It is noteworthy that the loss of DC control power to switchgear or load centers results from fire damage (shorts to ground) and not spurious operations.

The loss of DC control power to switchgear and/or load centers can result in a loss of overcurrent protection for protective circuit designs that rely on relaying functions (overcurrent protection, circuit breaker coordination, selective tripping) requiring power to actuate the circuit breaker trip mechanism. In particular, loss of DC control power directly affects the design capability to protect against issues of common power supply and common enclosures (i.e., “Associated Circuit” issues for the deterministic rules of Appendix R, “Other circuit issues” under the performance-based rules of NFPA 805). It is noted that some breakers contain self-powered trip units and are thus not susceptible to this concern.

With a loss of DC control power from fire damage, the ability of the switchgear or load center to rectify problems in common power supply is removed. Since the switchgear (load center) no longer has power to the trip circuits for the contained circuit breakers, electrical coordination within the switchgear is lost. Electrical faults on the load-side of the power circuits supplied from that switchgear must be cleared by protective relaying in the upstream power supply, potentially resulting in the loss of electrical power to all loads on the switchgear. We note that this will occur even if the protective devices on the switchgear are adequately coordinated, i.e., the coordination scheme design is satisfactory but there exists no control power to implement the desired selective tripping.

Additionally, the inability of a breaker to clear a faulted circuit on a low-voltage or medium voltage three-phase power circuit could lead to cable over-heating and secondary fires, which pose a common enclosure concern in the plant during a fire. The PIRT panel determined that this could be generic concern for the industry; however, the PIRT panel had no way to categorize the safety and risk significance of this issue since it is highly plant specific.

The PIRT panel acknowledged the switchgear control power issue as a legitimate concern, but determined that this area of analysis did not fall within the primary charter for the panel. However, since the loss of control power to switchgear is a very real concern with respect to preserving the electrical coordination and protection scheme, it is recommended that the common power supply and common enclosure concern for switchgear be addressed through an appropriate mechanism/forum.

A related but more general perspective on coordination issues contemplated by the panel involved the DC testing in which larger fuses (30 A) did not clear under relatively energetic faults. The panel ultimately concluded that the fault current in these cases could be low enough to allow a fault to persist for several seconds, which is sufficiently long to produce significant localized damage. The panel ultimately acknowledged that engineering analysis can provide design limits for maximum available fault current at locations within a power distribution system, but exact predictions of fault current are not realistic given the many variables at play. Accordingly, long-standing industry guidelines for assuring coordination over the entire range of available fault current are important to maintaining the validity of a coordination scheme.

6.4 Control Power Transformers

Control power transformers (CPTs) often are used to supply power to a control circuit, in particular for motor-operated valve (MOV) circuits. The CPT places a limit on the total power available to the circuit (power is the product of voltage and current). Hence, as the current flow increases beyond a certain point, the transformer core enters a saturation condition in which the output waveform becomes highly distorted and voltage begins to degrade below the nominal voltage; should voltage drops below the minimum pickup level for the actuation devices, then no spurious operations can occur.

The original EPRI/NEI Tests (Ref. 7) indicate that supplying power via a CPT had an effect on spurious operation likelihood as compared to a direct connection to a line power source (spurious operations were reduced by roughly a factor of two when using a CPT). Of the 18 tests conducted, eleven tests used the laboratory power supply, two tests used an isolation transformer for the inter-cable testing circuit, and the remaining five used CPTs for a total of 20 MOV circuit trials powered from CPT’s (Ref. 19).

In explaining the differences between circuit responses powered from a CPT versus the laboratory power distribution supply, Section 12.1.5.1 (3rd bullet) of EPRI TR 1003326 (Ref. 7), states the following:

> “Differences in power supply characteristics do not appear to influence the failure mode. However, significant fewer spurious operations occurred for the test circuits powered by CPTs. This result is not self evident from the hot short statistics, which show an identical rate of hot shorts for the two different types of power supplies. Hence, although power supply characteristics do not appear to influence the likelihood of hot shorts, they do significantly affect the likelihood that a hot short will produce a spurious operation.”

The theory behind these observations is that when a cable is damaged, the ensuing hot short development involves several conductors and paths to ground. The summations of these leakage currents suffice to either degrade the CPT’s voltage output so that there is insufficient voltage available to energize an actuation device, or the upstream protective devices (fuses) could clear due to the elevated current. This effect was not present when using a laboratory power supply. The phenomenon behind this effect was apparent in the test data and involved a rapid voltage collapse as parasitic current leakage paths developed. The spurious operation probability values developed by the EPRI expert panel (Ref. 11) and, in turn, cited in NUREG/CR-6850, EPRI TR 1011989, for a circuit powered by a “properly sized CPT” are based on this set of test results.

One of the research follow-up items identified in RIS 2004-03 (Bin 2 Item D) (Ref. 8) was to clarify what a "properly sized CPT" would be in the spurious actuation context. The CAROLFIRE project (Ref. 9) investigated this question and reached the following conclusions:

> Bin 2 Item D – Presence of CPT in the Power Source "… derived from one aspect of the NEI/EPRI testing where a substantial reduction in the spurious actuation likelihood was observed given the use of control power transformers (CPTs) compared to the case with effectively unlimited power available to the control circuit. The CPTs used by NEI/EPRI were sized at 150 VA which represented 150% of the nominal power required to actually operate the simulated MOV control circuit in its normal mode of operation.
>
> The CAROLFIRE tests evaluated a range of relatively larger CPTs ranging from 166% to 333% of the nominal design load required to operate the circuit. In these tests, there was no observed effect on spurious actuation likelihood, and as noted previously, roughly 70% of the cable failures led to spurious actuations signals of at least momentary duration. The CAROLFIRE tests did experience some cases of voltage decay prior to fuse blow, but in most such cases a prior spurious operation had been observed. No cases were explicitly noted where voltage decay appears to have prevented a spurious operation from occurring. The differences between these two programs cannot be fully explained, and this may be an area that is worthy of further investigation."

Follow-up testing was also included as a part of the DESIREE-Fire project (Ref. 10) using even lower output CPTs than those used in CAROLFIRE in a further attempt to reproduce the voltage collapse effect. As in CAROLFIRE, the tests failed to reproduce the voltage collapse effect observed in the NEI/EPRI tests. Some cases of voltage degradation were observed, but in no case was a spurious operation avoided because voltage collapsed to below the end device pick-up voltage.

Figure 6-3 (Ref. 20, Figure 2-22), along with Tables 6.1, presents the EPRI/NEI and NRC/SNL AC test results that were compiled and evaluated comparing circuit failure modes for test trials using CPTs and those test trials without CPTs. Since the CPT size used in EPRI/NEI tests is unknown, the group of data labeled as "Unknown Size" represents the EPRI data set. The first four bar chart sets and part of the last "None" bar chart sets represent NRC/SNL test results between circuits using CPTs of various sizes (i.e., 75VA, 100VA, 150VA, and 200VA).

Comparing the findings for these four sizes does not reveal any variations in spurious operations, each denoting above 50 - 68%, which can be considered statistically as the same. However, the EPRI/NEI test results indicate that the likelihood of spurious operation with a CPT is 18%, while that without one is 50%.

Based on testing with AC circuits, in particular using control power transformers (CPTs), the PIRT panel has concluded that there appears to be no substantial effect on spurious operation likelihood based on the presence or size (i.e., the VA output rating) of the CPT. Therefore, the PIRT panel concluded that the presence or size of the CPT has little or no effect on spurious operation probability. This conclusion is contrary to the conclusions of the first EPRI circuit analysis expert panel. Because of this, the PIRT panel removed the CPT as a subgroup to the time-current characteristics in MICROSOFT® XCEL scoring worksheets. The PIRT panel recommended combining both EPRI/NEI and CAROLFIRE test data for AC circuits when estimating the impact of this parameter on the likelihood of spurious operation.

Table 6-1. CPT size - Global Approach

Global Approach	75VA	100VA	150VA	200VA	Unknown Size (EPRI)	None	Total
Fuse Clear	1	5	10	7	10	12	45
Spurious Operation	1	10	20	9	3	15	58
Hot Short	1	10	21	10	7	18	67
HS/SA Possible	2	15	31	17	17	30	112

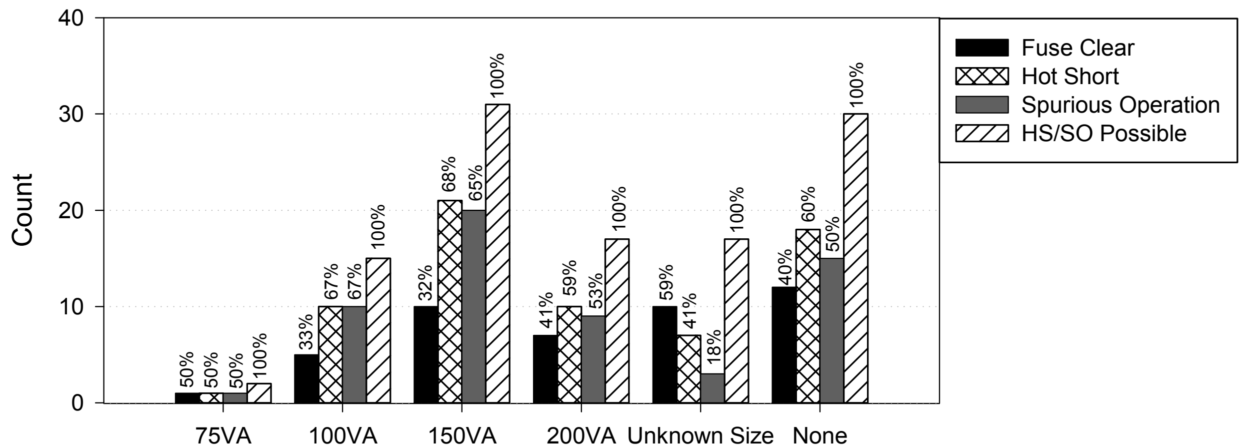


Figure 6-3. CPT size - global approach, AC tests

The PIRT panel spent a substantial amount of time reviewing available test data and other test information in an attempt to identify a rational explanation for the difference in test results given seemingly identical configurations. The panel discussions ultimately lead to an understanding that the phenomenon at work is much more complex than originally thought, and involves the full range of dynamic effects relating to the time-current characteristics of a particular circuit.

The time-current characteristics refer to both electrical power source and circuit protection fuse/breaker (size and timing) characteristics, as well as other system parameters such as cable characteristics and system X/R ratio[13]. In combination, these characteristics determine the

[13] X/R ratio refers the ratio of reactive impedance to resistive impedance. This ratio can have a pronounced effect on the transient magnitude of fault current in AC power systems. X/R ratio is usually

nature and intensity of the available short circuit current and the equipment response to the fault current (e.g., voltage collapse, fuse let-through current and clearing time, and circuit breaker response). These interactions are dynamic and can vary significantly for seemingly identical conditions.

Ultimately, the PIRT panel concluded that CPT size alone, nor indeed the mere presence of a CPT as the powering device, is not a predictable and repeatable circuit design parameter that reliably yields fewer spurious operations. Rather, CPT size is one of many circuit parameters that influence the complex relationship between short circuit current and time. This relationship is a dynamic function with many facets that go well beyond the ability to characterize behavior in such a way to provide simple go-no go practical binning criteria. These concepts are born out in electrical protection theory, which acknowledges the limitations in fully predicting circuit response to faults.

The PIRT panel concluded that the EPRI/NEI test results did not contain an inherent flaw, but instead reflected a particular arrangement of devices, system parameters, and protective device characteristics that produced the observed results. However, as demonstrated by the inability to reproduce in subsequent tests the same results CPT size should not be used as a basis for reducing spurious operation likelihood probabilities. The panel further recommended combining both EPRI/NEI and CAROLFIRE test data for AC circuits when estimating the impact of this parameter on the likelihood of spurious operation.

6.5 Kapton®-insulated Cables

The attributes of the unique construction of Kapton-insulated cable complicate its classification. The insulation material properties partially are thermoset (TS) and partially thermoplastic (TP). The PIRT panel investigated Kapton insulation with the following objectives:

- Assess the arc-tracking phenomenon observed in Kapton-insulated cable under certain conditions to determine if this degradation mode affects the cable's performance under fire conditions, and,
- Determine how Kapton-insulated cable should be treated for "classification" regarding temperature-damage thresholds.

6.5.1 Background

The NRC expressed concern that Kapton-insulated conductors might pose a unique susceptibility to fire-induced failures based on a degradation mechanism called "Arc Tracking." NRC Regulatory Guide 1.189, Revision 2 (Ref. 16), Section 5.5.2 briefly discusses Kapton-insulated cables. Arc Tracking is a degradation mode observed in Kapton-insulated conductors wherein the insulation either was mechanically damaged (nicked or cut) or degraded by wear, and is applied such that the insulation then exposed on a recurring basis to an electrically conductive solution. Arc Tracking degradation appears to be limited to Kapton-insulated conductors; the mode was discovered in aircraft wiring. The majority of aircraft having

only considered for AC power systems; however, reactive elements in DC circuits can significantly influence fault current rise time, which can affect the performance of protective devices.

experienced the Arc Tracking failure mode are naval/marine planes flying from aircraft carriers at sea.

Kapton-wire insulation typically is created by winding multiple layers of plastic film in a continuous spiral around the conductor (wrapped-tape type construction). The main dielectric element in Kapton® is polyimide film (the thermoset material). Du Pont™ uses Teflon® (thermoplastic material) as an adhesive sintering agent to bind the polyimide to the conductor and successive layers of film to each other. A typical system of Kapton wire insulation consists of a layer of Kapton film, typically ~1.0 mil thick, which is coated on both sides with a layer of 0.1 mil Teflon. This multiple layer is wound around the conductor with a ~50% overlap. . A second multilayer Kapton/Teflon film is spirally wound in the opposite direction, again with a ~50% overlap. The wire/insulation assembly then is heated to melt the Teflon so bonding the Kapton to the conductor; this process also is called "sintering" the insulation. The unique construction process for Kapton, employing both thermoset and thermoplastic materials, create ambiguity about the cable's classification since it has attributes and characteristics of both materials. Seemingly, there have been no tests of Kapton-insulated cables in the specific context of fire-induced electrical failure/damage.

Kapton wiring is popular for use in aircraft due to its low weight and very thin insulation. Kapton has very high physical strength, high dielectric capabilities, and some products, at least, are available with very good thermal properties (high temperature tolerance). Hence, it is light and strong. Due to its superior thermal properties, aircraft electrical conductors are designed to operate at much higher temperatures and higher ampacities than in other applications. This results in wire bundles that are much hotter than typically observed in nuclear plant applications. Although Kapton has very good physical strength, aircraft wiring in many applications is more susceptible to physical damage due to the tight confines of the wire's routing (tight bends) and the demands of maintenance (wire bundles having to be moved frequently to gain access to nearby components).

Kapton insulation used in nuclear power plants typically is associated with containment electrical penetrations or component connection wires (pigtails) where the component must meet Equipment Qualification (EQ) requirements. Unlike its use in aircraft, Kapton insulation is not typically used as insulation for electrical conductors in single- or multi-conductor cables, but at the same time, nothing precludes such use.

6.5.2 Arc-Tracking Degradation Mode

The descriptions provided here principally are based on information in EPRI NP-7189 (Ref. 33); although there are numerous other references, the EPRI report focuses on nuclear power plants, and therefore is the most appropriate one.

Arc tracking occurs when two conductors have some type of damage to their electrical insulation, and a conductive fluid film is present (for naval aircraft, this could be salt water, or high pH fluids used to clean the salt deposits off the aircraft), allowing leakage current to flow through the conductive fluid. As the electrical current flows, it heats the fluid, causing it to evaporate, resulting in a narrowing band of moisture, with a resultant smaller cross-sectional area for the current to flow through. The temperature of this narrowing band increases due to the higher current density. As the fluid begins to dry out, the temperature of the local Kapton insulation becomes high enough to char the insulation. If this wetting cycle is repeated constantly, the charred layer eventually will become thick enough to allow conduction through the carbon, resulting in an arc. Once created, the arc causes localized damage to other cables in the area, resulting in additional charring, so allowing more electrical current to flow. Some Arc Tracking events observed in aircraft resulted in significant burning of wire bundles. Research also indicates that physical strain on the wire/insulation also may significantly increase the tendency to produce Arc Tracks.

As documented in EPRI NP-7189 (Ref. 33), research performed by the Naval Research Laboratories identified five conditions that must be present for Arc Tracking to occur:

- There must be a fault or radial crack in the conductor on an energized wire,
- A conductive solution must be present and dripping directly on to the fault,
- There must be a completed circuit to ground,
- Substantial voltage and current must be available, and,
- A specific geometry of wires in relation to ground must exist (e.g., a distance of less than 3/16 of an inch from a ground electrode).

An alternative to dripping conductive fluid on the fault is periodic wetting of the two conductors with such a fluid. Kapton insulation also is susceptible to degradation by hydrolytic degradation, as occurs when the insulation is under significant strain, is at high temperature, and is exposed to water for long periods.

The PIRT panel examined available information to determine if there is any technical rationale upon which the arc-tracking phenomenon can be expected to appreciably change the characteristics of fire-induced cable failure, as documented in hundreds of fire tests performed by industry and NRC. They reached the following conclusions:

- Arc-tracking is a unique failure-mode not likely to exist for NPP applications.
- The arc-tracking mechanism should have no impact on the characteristics of cable failure with regard to MHIF effects. Once fire has severely damaged the cable's insulation, it will undergo full failure quickly. That is, arc-tracking degradation will not cause the cable to establish a long-term high impedance fault under fire conditions.
- It cannot be ruled out that arc-tracking will reduce the cable's temperature-damage threshold (a similar concern as that observed for Kerite-FR material). The reduced integrity of the insulation could hasten the cable's functional failure.

6.5.3 Application and Operating Experience at Nuclear Power Plants

As with the previous section, the information here principally is based on information contained in EPRI NP-7189 (Ref. 33). However, this section also includes elements of general industrial knowledge.

As noted above, Kapton insulation used in nuclear power plants typically is associated with the containment's electrical penetrations or component connection wires (pigtails) where the component must meet Environmental Qualification (EQ) requirements for 10 CFR 50.49 (Ref. 38). Unlike its use in aircraft, Kapton insulation is not typically used as electrical conductor insulation in single- or multi-conductor field-routed cables.

Kapton insulation has experienced electrical failures in nuclear applications. NRC Information Notice 88-89 (Ref. 34) reported several failures of Kapton insulation; however, none of them appear to have involved Arc Tracking. Experience with EQ testing of Kapton indicates that the insulation is susceptible to electrical failure if it is in direct contact with sprays of high pH fluids, such as ammonia hydroxide. However, these chemically induced failures have no correlation to fire-induced failure.

Several performance characteristics of Kapton under fire conditions are known:

- Kapton insulation has demonstrated excellence in flame propagation tests. Kapton passed the IEEE STD-383 (Ref. 35) flame propagation test, also passing a 2.4 kVAC dielectric withstand test afterwards. Flame propagation testing performed by Du Pont on MIL STD W-81381 (Ref. 36) electrical wiring also revealed no problems.

- Cables insulated with Kapton have not been tested in a fire environment to determine the probabilities of attaining electrical failure temperature or of hot short/spurious operation. However, based on the usage of Teflon as a bonding agent, it is believed that Kapton-insulated wire might exhibit a fire-exposure performance similar to either thermoplastic- or thermoset-cable insulation depending on whether failure is driven more by the content of the former (e.g., the Teflon sintering agent) or by that of the latter (the polyimide film).

- It is noted that some Kapton products were specifically designed for high-temperature use and were qualified for up to 400°C (752°F).

Unfortunately, there is very little fire test data to help with classifying Kapton®. Classification from an academic perspective is not all that important. The fundamental consideration is the material's exhibited properties, in this case, the threshold for temperature damage. It is known that some Kapton materials have very good high-temperature characteristics; however, it is not clear whether this is valid for all Kapton materials.

6.5.4 Temperature Damage Thresholds

Given the uncertainty about the limits of Kapton fire-induced thermal damage, the recommended practice relative to its damage thresholds is provided in three parts:

- If the analyst can establish that the cables in question were certified for use under the EQ program, then it is recommended that the cables be assumed to fail consistent with other thermosetting cable insulations. Typical EQ qualification would, for example, include certification in accordance with the *full* IEEE STD-383 severe accident-exposure testing standard. We note that compliance with just the flame-spread element of the IEEE STD-383 standard is *not* sufficient for this case.

- If the analyst can establish and alternate basis for a product/case specific failure threshold (e.g., manufacturer or utility testing of the product in question) then the case-specific damage threshold may be assumed. If the failure threshold established is below that typical for thermoset cables (i.e., less than 330°C) then it is recommended that the cable be treated as a thermoplastic in the spurious operation analysis. If the failure threshold established is consistent with typical thermoset insulations (i.e., greater than or equal to 330°C) then it is recommended that the cable be treated as a thermoset in the spurious operation analysis.

- If the analyst cannot establish a qualification basis for the cables in question, then it is recommended that they be assumed to fail consistent with thermoplastic-insulated cable materials.

6.5.5 Conclusions

The PIRT panel reached the following conclusions on Kapton-insulated cables:

<u>Arc-Tracking Effect:</u>

- The arc-tracking mechanism should have no impact on the characteristics of cable failure with regard to MHIF effects. Once fire has severely damaged the cable's insulation, it will undergo full failure quickly, just like thermoset- and thermoplastic-cable. That is, arc-tracking degradation will not cause the cable to establish a long-term high impedance fault under fire conditions.

- It cannot be ruled out that arc-tracking will reduce the cable's threshold for temperature damage (a similar concern as that observed for Kerite-FR material). The reduced integrity of insulation could hasten the cable's functional failure.

<u>Temperature-Damage Threshold:</u>

Kapton's failure thresholds should be assumed consistent with those of thermoplastic (TP)-insulated cables unless the cable in question was certified for use under the EQ program for severe accident-exposure conditions or an alternate basis for a product/case specific thermal damage threshold can be established. Cables with EQ-based severe accident certification should be assumed to fail consistent with a thermoset (TS) cable-insulation material. Cables using an alternate product/case specific basis for the damage threshold should be assumed to fail consistent with either a TP or TS material depending on the actual damage threshold established (i.e.: if the threshold is less than 330°C treat as TP; if greater than or equal to 330°C treat as TS).

6.6 Panel Wiring

6.6.1 Background

The wiring used within an electrical cabinet (panel wiring) is unique compared to the cables used in general field-routing applications. Field-routing is dominated by multi-conductor cables. In contrast, panel wiring is comprised of both multi-conductor cables, and single conductor cables. In a typical configuration, multi-conductor field routing cables enter/exit the cabinet, usually through either its top or bottom , and each conductor (possibly excepting spare conductors) is terminated either directly onto a specific end device, to ground, or, quite commonly, to a terminal strip mounted within the cabinet. For the conductor termination, a section of the multi-conductor cable jacket will be removed (stripped). Single conductor wires are commonly used within a cabinet to connect field-wire terminations at a terminal strip to their end devices, and for inter-device connections within the cabinet. The configurations used in single conductor-panel wiring are expected to be wide ranging and may include individual conductors routed somewhat loosely through a panel, conductor bundles routed in metal or plastic wire-ways (e.g., Panduit®), bundles of conductors secured with nylon wire ties (zip-ties), and bundles secured with rigid metal- or plastic-retaining loop clamps. Figure 6-4 illustrates typical panel-wiring configurations.

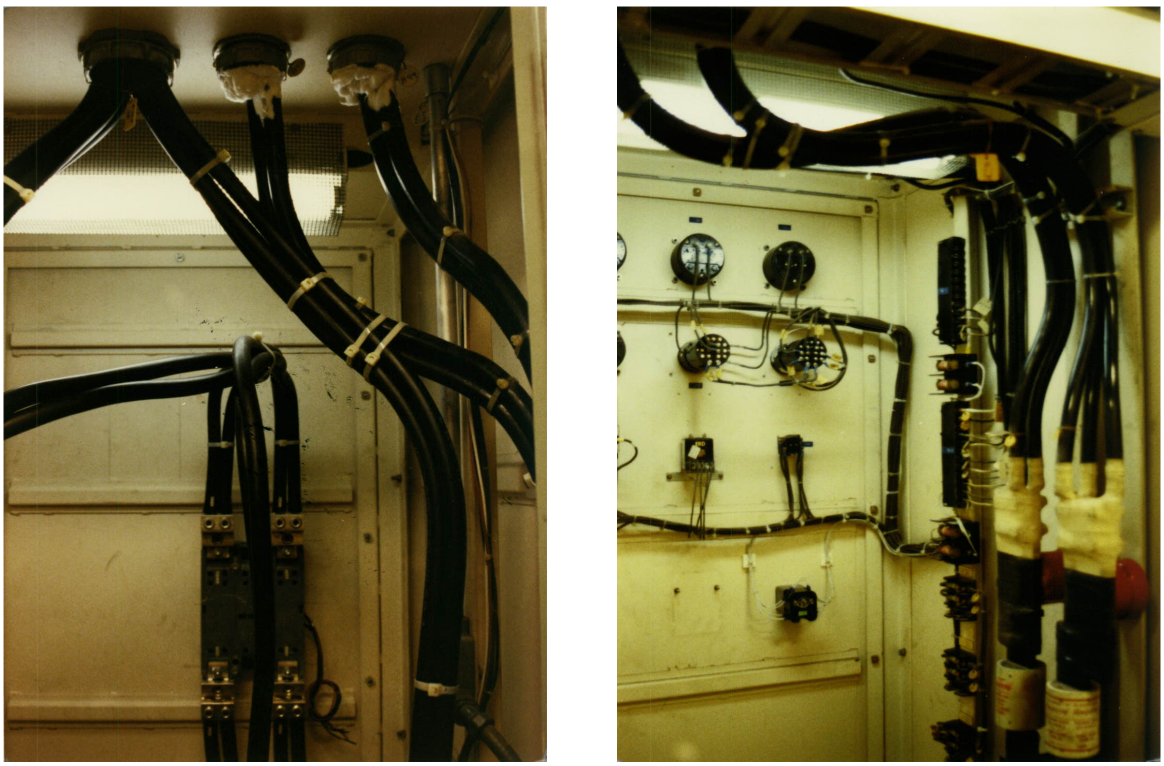


Figure 6-4. Typical Panel Wiring Configurations

6.6.2 Discussion

For those portions of the in-cabinet panel wiring that involve intact multi-conductor cables (e.g., field routing cables where the jacket has not been stripped), the PIRT panel concluded that spurious operation likelihoods should be calculated in the same manner as for control circuit multi-conductor cables in general field-routing applications (e.g., cable tray routing). That is, there is no basis for unique treatment just because a multi-conductor cable has entered an electrical cabinet so long as the individual conductors have not been stripped out of their cable jacket. However, for those portions of the in-cabinet panel wiring that involve single conductor cables (including a multi-conductor cable whose jacket has been stripped), a unique treatment is needed.

To understand the PIRT panel's reasoning, it is important to understand typical practice in manufacturing multi-conductor cables. Depending on the total conductor count, the individual conductors in a typical multi-conductor cable are arranged in one or more concentric layers. A cable with a small conductor count (2-6 conductors) generally has only a single layer. As the count increases, the conductors are arranged in layers in the form of a concentric ring. For example, a typical 7-conductor cable has a single central conductor and a second layer of 6 conductors in a ring around the central one. A 12-conductor cable typically has a central core layer of three conductors and a second ring/layer of 9 conductors. A 19-conductor cable is much like a 7-conductor cable with a third ring/layer of 12 conductors; a 37-conductor cable adds a fourth ring/layer with 18 conductors in it. This practice yields finished cables that are roughly round. This also means that, while special order products are available in effectively any conductor count, most control cables will have one of the more common total conductor counts; namely, 2, 3, 5, 7, 9, 12, 19, 37, or 61 conductors.

One key factor associated with this manufacturing practice is thought to impact the failure behavior of multi-conductor cables, and will be absent from single conductor panel wiring. Manufacturers lay the conductor rings/layers in an alternating helical spiral pattern. That is, each conductor layer is laid as a helical spiral in a geometric pattern, with alternately reversed lay direction between the layers. Conductors in each layer maintain their positions relative to each other, but spiral (rotate) as a group along the length of the cable, with alternate layers spiraling in opposite directions.

Accordingly, manufacturing leaves some degree of residual tension left in the conductors. It is thought that this residual tension may be one factor contributing to the relatively high likelihood of intra-cable shorts given electrical failure of the cable. That is, the residual tension may draw the individual conductors within the cable together as the insulation begins to degrade and lose physical integrity (e.g., melt or burn). Once the conductors are stripped out of the cable jacket, this residual tension is absent so that there may be less impetus for the conductors to short to each other on failure. Similarly, single conductor panel wiring would lack the residual tension associated with multi-conductor cables. A counter-acting effect would be the practice of bundling single conductor cables together as they are routed within the cabinet. That is, while the residual tension associated with multi-conductor cables is absent, the insulated conductors may be routed in relatively tight bundles as noted above.

6.6.3 Recommendation

Overall, shorting of conductors in panel wiring conductor bundles could behave similarly to either intra-cable or inter-cable shorting depending upon the proximity of the conductors and the tightness of their bundles. The PIRT panel believes that the probability of inter-conductor shorting within a bundle lies somewhere between the probabilities of an intra-cable and an inter-cable hot short. This probability is most likely affected by the configuration and tightness of the conductor bundles. The lack of test data for panels clearly is problematic when determining the true behavior of conductors or components in a panel. Hence, it is important to determine bounding characteristics for panel configuration. With this in mind, the PIRT panel strongly recommended further testing in this area. Based on the lack of applicable test data and the potential risk importance of panel wiring, the PIRT panel recommends hot short probabilities equivalent to those of an intra-cable hot short be assumed for panel wiring.

6.7 High Conductor Count Trunk Cables

6.7.1 Background

Multi-conductor cables containing more that 12 conductors typically are classified as “trunk cables.” The large number of conductors within one cable allow for multiple circuits to be contained within one cable and routed to common points within the NPP. Trunk cables are typically have with 19/C, 25/C, 37/C and higher conductor-count configurations. Figure 6-5 shows a photo and illustration of a 37/C trunk cable. The exact number of conductors within a trunk cable depends on the geometrical configuration that ensures the cable’s roundness to ease installing cables.

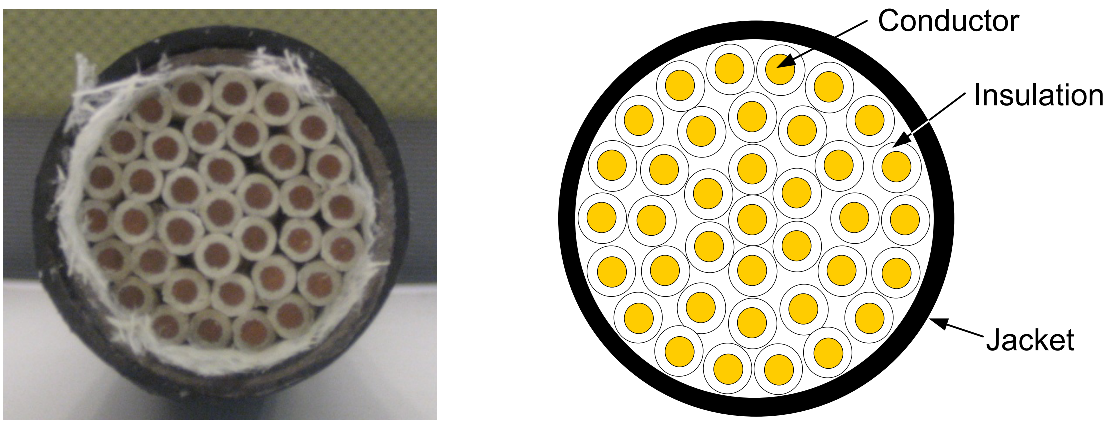


Figure 6-5. Photo and Illustration of 37/C Trunk Cable

6.7.2 Discussion

The number of conductors in a multi-conductor cable may influence the likelihood that a specific pair (or set) of conductors within a cable might short together. That is, the more conductors within a cable, the more opportunities for the conductors to short together under severe thermal conditions. The proximity of source and target conductors may influence the likelihood of this failure mode.

Fire effects on trunk-cable failure modes were explored by a limited set of experiments conducted by Duke Power (Refs. 17 and 18). These results are proprietary to the utility but a publically available power-point presentation made at an Institute of Electrical and Electronic Engineer (IEEE), Insulated Conductors Committee meeting summarizes the results (Ref. 17). In addition, Duke submitted their preliminary test plan to the NRC for review and comment. Information from this also gives an understanding of what they proposed to test (Ref. 37).

From this information, the following was noted. The Duke Power cable tests included a 37/C armored trunk-control cable enclosing 12 AWG conductors with a flame-retardant XLPE 45 mils-thick insulation. Each trunk cable tested included 4 monitored circuits. The findings demonstrated that "the speed and temperature intensity of the fire damage to the armored cables was not significantly affected, but there was a notable increase in spurious-operation activity." More details of the results of the armored cable test results are not available publically.

6.7.3 Conclusions

Because of the large number of conductors in a trunk cable, the electrical expert PIRT panel speculated that the greater availability of target and source conductors could have resulted in the increase in spurious operations seen in the testing. While this may be plausible, there is no way of knowing for certain because the testing did not specifically explore this possibility. Other differences of note between the Duke testing and the testing evaluated by the PIRT panel was that the former testing was conducted on armored cables and the majority of the latter testing was conducted on an ungrounded AC CPT configuration. Because of this lack of understanding, future research in this area is warranted. However, since trunk cables are only used in a limited set of applications within NPPs, this research would be ranked as medium- to low-priority.

7 PIRT PANEL RESEARCH RECOMMENDATIONS

The electrical expert PIRT panel discussed and evaluated an exhaustive number of technical issues on hot short-induced spurious operations and other fire damage-related concerns. For many of these issues, the PIRT panel made final determinations on the credibility and/or importance of the issue. However, for certain technical issues, the PIRT panel could not draw a final conclusion, or they formulated a consensus position, but presented it with the caveat that more research should be conducted to support that position. In certain cases, there was so little information, and the failure modes were so uncertain, that the PIRT panel concluded that more research was needed.

Section 3 discusses the ranking factors that were assigned to influencing parameters for control circuitry. In some cases, the PIRT panel assigned an influencing factor of High, and the associate parameter “State of Knowledge” was ranked as Low. In these cases, the PIRT panel concluded that if there is a lack of knowledge of a parameter that highly influences the likelihood or duration of spurious operations, then research should be conducted to find out how much effect the parameter truly has.

Although the PIRT panel recommends additional research, these recommendations do not imply that the NRC or EPRI will pursue such efforts. The specific research and associated prioritization of that research depends on the internal research planning and budgetary constraints of these two organizations.

This section discusses the research recommendations of the PIRT panel, and then it prioritizes those recommendations in terms of their importance.

7.1 Control Circuit Research

Most research and testing have been undertaken in the area of control circuitry. Because of the availability of data, the PIRT panel was able to evaluate specific control circuit cable parameters using test results. However, for certain influencing parameters, testing data did not exist. In these cases, the PIRT panel used its expertise and experience to provide a ranking of High (H), Medium (M), Low (L), or Uncertain (U) in regard to the influence of that parameter on the likelihood of spurious operations or their duration. Parameters that were assigned either a ranking of ‘High’ or ‘Uncertain’ as an influencing factor along with a ranking of ‘Low’ in regard to the state of knowledge were recommended as candidates for further research. The parameters that met these criteria are listed in Table 7-1. Unless stated otherwise, all parameters apply to both AC- and DC-control circuits.

Of the parameters in Table 7-1, all of them, with the exception of panel wiring and fire suppression, can be performed using similar testing to that done before. Changing the parameters would only require testing of different cable types or circuits. Panel wiring and fire suppression, however, would involve a different, potentially more complicated testing setup. Conceptually, fire suppression could be tested along with the other five parameters by adding in the fire-suppression features for the cables being tested. Therefore, for the purposes of this section, testing of all of these parameters, with the exception of panel wiring, will be cumulatively categorized as “control circuit cable testing.”

Table 7-1. Potential Research Candidates Due to Low State of Knowledge

Parameter	AC	DC	Likelihood Ranking	Duration Ranking
Fire Exposure Condition (Time /Temp)	X	X		H
Panel Wiring	X	X	H	H
Time-Current Characteristics - Fuses/ Breaker Size	X			H
Cable Grounding Configuration (Shield Wrap)	X		H	
Armor Grounded versus Ungrounded Circuit	X		H	
Armored versus Unarmored		X	H	
Fire Suppression (Water Spray and Hose)	X	X		U

The lack of test data for PIRT panels is problematic when attempting to determine the true behavior of conductors or components in a panel. Because panels are installed throughout a NPP, it is important to determine the characteristics of spurious operations for this configuration. The primary concern is the behavior of conductor bundles within a panel. As stated earlier in Section 6, the shorting of conductors in panel wiring conductor bundles could behave similarly to either intra-cable or inter-cable shorting, depending upon the proximity of the conductors and the tightness of the bundles. Therefore, the probability of conductor-to-conductor shorting within a bundle lies somewhere between the probabilities of an intra-cable and an inter-cable hot short. For deterministic analyses, intra-cable hot shorts would be the conservative assumption. Because of this uncertainty about spurious operation behavior in panel wiring configurations, the PIRT panel recommended testing in the area of panel wiring.

7.2 Instrumentation Circuit Research

The PIRT panel was concerned that the low energies involved in instrumentation circuits could cause them to perform and fail differently under fire-induced fault conditions than those of higher energy control circuits. While control circuits progress relatively quickly through fault states due to arcing fault energies, this same progression may not be experienced as readily in lower energy instrumentation circuits. The time required before a fault occurs in the circuit and the duration of the fault state may differ substantially from that of control circuits. In addition, various wiring methods, circuit designs, and the use of shielding (tied to ground or to power supply neutral) may all have dominating influences over the failure modes and effects seen as a fire damages the cable.

Additionally, there is the possibility that instead of an instrument failing in only two functional failure modes, high or low, the instrument could potentially fail in an intermediate mode before its complete failure. This would result in a false reading that could cause an operator to make an incorrect diagnosis, or it could mask an indication of a problem in the plant. Incorrect operator actions due to faulty indication potentially can be more adverse to safety during a fire than the actual fire damage.

Due to the low state of knowledge and potential high consequences of fire-induced failure on instrumentation current loop circuits, the PIRT panel strongly recommended that additional testing be performed. The PIRT panel recommended that the following circuits be included in the testing:

- 10 mA to 50 mA instrumentation circuits
- 4 mA to 20 mA instrumentation circuits
- 1 VDC to 5 VDC instrumentation circuits.

7.3 Surrogate Ground Path Research

The importance of the surrogate-ground-path phenomenon (aka. ground fault equivalent hot short) was discovered during the DESIREE-Fire testing. Based upon the results, the PIRT panel determined that this would have to be considered as a plausible failure mode along with intra-cable and inter-cable shorting. However, with the exception of the DESIREE-Fire results, there is little data available on this phenomenon.

Because of the importance of the surrogate-ground-path phenomenon in DC ungrounded circuits, the PIRT panel strongly recommended further research focusing on the effects and probability of this type of failure mechanism. Also, since the phenomenon depends on the circuitry being ungrounded, ungrounded AC circuits should be included as a sub-set in any such testing.

7.4 Current Transformer Research

The PIRT panel could only definitively concluded that secondary fires were not a credible risk for CTs with turns-ratios 1200:5 and lower. For CTs with higher turns-ratios, the PIRT panel felt that the risk to fire safety was low, but there were no test data to support their position. While there are only a limited population of CTs in NPPs that have these high turns ratios, the PIRT panel felt that testing was warranted for the entire range of turn ratios so that this issue finally can be resolved.

7.5 Conclusions and Prioritization of Future Research

Because there was a lack of knowledge in all of the aforementioned areas, prioritization was based upon the importance of the configurations to plant operations during a fire, and the potential consequences of mal-operation or fire damage. Additionally, consideration was given to the lack of a clear technical consensus on the characteristics of spurious operation. For instance, many of the control circuit parameters could at least be categorized as having a high influence on either the likelihood or duration of spurious operations. This knowledge primarily was based upon the knowledge of cable characteristics during testing. However, in the case of instrumentation, it was difficult to come to any conclusions on spurious operation characteristics because there was so little information.

Prioritization of research is presented below, with highest priority listed first:

1. Instrumentation and Control Circuits [highest priority]
2. Panel Wiring
3. Surrogate Ground Path
4. Control Circuit Cable Testing (Influencing Parameters given in Section 7.1)

5. Current Transformers
6. High Conductor Count Trunk Cables (discussed in Section 6.7) [lowest priority]

Importantly, items 3 and 4 can most likely be accomplished through the same testing program.

Instrumentation was chosen as the number one priority because there is little information about fire-induced failures to instrumentation circuitry and because of the overall importance of instrumentation circuitry to the safe operation of a NPP.

Trunk cables are another special type of multiconductor cables (with 12 or larger number of conductors) often used with multiple identical circuit wiring between the main control room panels and the relay rack room before being routed to the field end devices. It is discussed in detail in Section 6.7 where the PIRT panel ranked the recommended testing to be low or medium.

8
SUMMARY AND CONCLUSIONS

The objective of this PIRT exercise was to identify the phenomena (electrical circuit configurations) that can affect the circuit failure modes from fire-induced cable damage. Using the results from recent fire tests performed by the EPRI/NEI in 2002 and the NRC/SNL (CAROLFIRE in 2008 and DESIREE-Fire in 2010), the electrical expert PIRT panel identified and ranked the parameters that could influence the hot short-induced spurious operations in electrical circuits. Utilizing these parameters, the findings from cable fire tests, expert judgment, and operating experience, the PIRT panel indentified and developed circuit configurations that would be vulnerable to hot short circuit failure modes of concern that can cause certain end devices to operate spuriously.

This PIRT investigated such fire-induced spurious operations of plant components, evaluating both alternating current (ac) and direct current (dc) types of circuits. The PIRT panel's focus encompassed three specific types of electrical circuits, i.e., power, control, and instrument circuits. Their primary emphasis was upon the control circuits (e.g., 120 VAC and 125 Vdc) because fire-induced damage of these types is considered to pose a higher risk to plant safety than does the other types of circuit. Accordingly, the majority of test data from industry, along with the NRC's tests, was related to low-voltage control circuits. Due to the limited test data available for instrument circuits, the PIRT could not undertake a complete parametric treatment of this type. Available failure modes for power circuits are well understood, except for a few unique cases. For certain types of power circuits (for example, three-phase power cables), there were no available findings from specific testing by industry; therefore, the PIRT panel's technical recommendations rested upon their expert judgment involving engineering principles and physical configurations for power cables and power-cable installations. In other instances, such as the PIRT panel's considerations of open circuits in the secondary circuits of current transformers (CTs), their recommendations were based upon available open-circuit test data, manufacturers' input, operating experience (nuclear and non-nuclear), and expert judgment.

The PIRT panel ranked the following parameters "as having a" HIGH impact on the likelihood of hot short-induced spurious operations, and the duration of a spurious operation:

- <u>Spurious Operation</u>
    - Wiring Configuration (number of sources, target, ground/neutral, and their locations) - An increase in the number of source and target conductors was deemed to add to the potential for a spurious operation, whereas an increased number of ground conductors was concluded to lead to an increased potential for a blown fuse that could either prevent a spurious operation or reduce its duration.

    - Conductor Insulation Material Type [for inter-cable hot shorts (thermoset (TS) versus thermoplastic (TP))] - For intra-cable hot shorts/spurious operations, the type of insulation did not contribute to the potential. However, for inter-cable hot shorts/spurious operations, the type of insulation was a contributing factor, since, for example, by the time the char layer on a TS conductor is worn away by the effects of the fire; it will have interacted with an adjacent conductor in the same cable before interacting with a conductor in an adjacent cable.

  - o Grounding Configuration - The ground condition for a specific cable will contribute greatly to that cable's ability to reach grounds, to open the circuit protective device (i.e., fuse, breakers), and remove the voltage potential from the circuit. The latter process eliminates the circuit's ability to hot short with any adjacent conductors. The following parameters could influence the grounding configuration of a circuit:
    - ▪ Cable-grounding configuration (e.g., ground or drain wire, shield wrap)
    - ▪ Armor Grounded versus Ungrounded Circuit (for grounded AC circuits), and, Armored versus Unarmored (for ungrounded DC circuits)
    - ▪ Grounded versus Ungrounded Circuits (for inter-cable hot-shorts).

  - o Cable Routing/Raceway – Panel Wiring (ranked as HIGH due to a lack of available test data, and the belief that testing this parameter is important for assessing its impact on post-fire safe shutdown).

  - o Cable Raceway Fill – Bundles (Note: The PIRT panel considered this important even though they ranked it medium) - The additional cable-to-cable pressure exerted by bundling appeared to make somewhat of a difference (i.e., an increase) in the propensity for spurious operations.

- <u>Duration</u>
  - o Fire Exposure Conditions (flame, plume, hot gas layer) - The slower the progression of fire damage to the cable, the longer will it take fully to erode the insulation from the conductors and thereby ground the cable. The grounding of the cable and the opening of the cable's protective device is the mechanism for stopping the spurious operation. Longer times to reach ground are related directly to longer spurious operations.

  - o Time-Current Characteristics – fuses/breaker size. Larger fuse/breaker sizes are expected to take longer times to clear that, in turn, entail longer durations of spurious operations. Additionally, in some ungrounded DC circuits, larger fuse sizes did not clear immediately. Extended periods of arcing occurred.

  - o Wiring Configuration (number of sources, targets, ground/neutrals and their locations) - The PIRT panel concluded that whilst an increased number of source and target conductors would add to the potential for a spurious operation, more ground conductors would lead to a higher potential for a blown fuse that could either prevent a spurious operation or reduce its duration.

  - o Cable Routing/Raceway – Panel Wiring (ranked as HIGH due to a lack of available test data and the belief that testing of this parameter is important for its impact on post-fire safe shutdown).

  - o Cable Raceway Fill – Bundles (Note: The PIRT panel considered this important even though they ranked it as medium) - The additional cable-to-cable pressure exerted by bundling appeared to make somewhat of a difference (i.e., an increase) in the propensity for spurious operations.

- Latching Circuit Design (e.g., motor operated valves) - This parameter is a specific design-feature of a control circuit that will cause the effects of the hot short to lock-in in a very brief time. This feature in the control circuit design will extend the duration of the spurious operation, but it is not directly related to specific aspects of a cable's fire robustness.

Taking all these factors into consideration and using their expert judgment and experience, the PIRT panel identified thirteen different base cases that represent control circuit cable configurations vulnerable to hot short-induced spurious operations. Based on this assessment, the PIRT panel presented several example cases that currently are used in nuclear power plants and are considered in the safe-shutdown circuit analysis documented in fire protection programs.

In addition to reviewing and evaluating the spurious operation of the control circuits and its duration, the PIRT panel provided technical recommendations on other aspects of fire-induced circuit failures associated with control and power circuits in the analyses of post-fire safe-shutdown circuits. Specifically, the PIRT panel concluded the following:

- The spurious operation of a three-phase AC motor due to proper polarity hot shorts on three-phase power cabling is incredible.

- The spurious operation of DC compound-wound motor due to proper polarity hot shorts in the motive/power cabling is incredible.

- The ignition of a secondary fire from an open circuited CT secondary circuit with a turns-ratio of 1200:5 or less is incredible.

- The guidance given in Nuclear Energy Institute, NEI 00-01, Rev. 2 (Ref. 13), Appendix B.1, can be applied safely to fire safe-shutdown methodologies throughout the plant in resolving concerns associated with Multiple High-Impedance Faults (MHIFs). (Note: Appendix B.1 of NEI 00-01, Rev. 2 offers a basis for concluding that MHIFs need not be considered, provided there exists breaker coordination for any circuits damaged by the fire that previously should have been assessed for the effects of MHIFs and appropriate testing and maintenance is performed).

- The spurious operation likelihood reduction factor of "two" provided in the Fire Probabilistic Risk Assessment (Fire PRA) methods when a control power transformer (CPT) is the derived energy source for a circuit, does not accurately reflect the entirety of the test data; no credit should be taken in the Fire PRA for their use in a CPT-powered control AC circuit. (Note: The revised probability in Volume 2 of this NUREG/CR will be based on a composite of all testing undertaken, and, hence, the probability offered for using with both CPT and non-CPT circuits may be increased by a factor less than 2).

- Kapton® cable, a polyamide stable from -271 to +400 ^{o}C, should be treated as a thermoplastic (TP) material for assessment of circuit failures, including risk-informed applications, unless an alternate basis can be established for the specific cable being analyzed based either on full equipment qualification certification of a cable produce or on other tests (e.g., manufacturer or utility testing of the cable product) that establish a failure threshold. The treatment relative to failure behavior is then assumed consistent with the established failure threshold (see Section 6.5.4 for details).

- Spurious operation caused by shorting conductors through a surrogate ground path in ungrounded circuits as a result of fire induced damage, is a failure mode that occurred during the DESIREE-Fire Testing; it is referred to as “Ground Fault Equivalent Hot Short.” The probability of this failure mechanism for cable-to-cable hot shorts is such that it warrants consideration for including in future testing programs and, subsequently, in analyzing post-fire safe-shutdown conditions.

Additionally, the PIRT panel recommended future research in several areas. The recommendations were based upon a lack of knowledge (and available test data) therein, and the importance of the configurations to plant operations during a fire and the potential consequences of faulty operation to certain electrical devices. The PIRT panel recommended considering the following areas in future research:

1. Instrumentation and Control Circuits (Discussed in Section 5) [highest priority]
2. Panel Wiring (Discussed in Section 6.6)
3. Surrogate Ground Path Hot Short (Discussed in Section 7.3)
4. Control Circuit Cable Testing (Influencing Parameters given in Section 7.1)
5. Current Transformers (Discussed in Section 6.2 & 7.4)
6. High Conductor Count Trunk Cables (Discussed in Section 6.7) [lowest priority]

Finally, based upon the findings of the PIRT panel, BNL will conduct a follow-on expert elicitation via a PRA panel to determine the best-estimate conditional probability (or likelihood) of failure, given fire-induced cable damage. Their findings will be documented in Volume 2 of this NUREG/CR report. These probability estimates represent an advancement of the state-of-the-art for assessing the likelihood of circuit failure and could be used for revising, directly replacing, or creating new probabilities for Table 10-1 through Table 10-5 of NUREG/CR-6850 for conducting Fire PRAs.

9 REFERENCES

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APPENDIX A
PANELIST AND FACILITATOR RESUMES

Harold Barrett, NRC

TITLE/POSITION: Senior Fire Protection Engineer Years of Experience: 37

SUMMARY

Mr. Barrett has provided a wide range of engineering and management services for the nuclear industry. His experience includes nuclear plant regulation, engineering, maintenance and operations, plant technical support, procedure development, site emergency plan participation and direction, shift supervision, training, start-up testing and design reviews. Mr. Barrett has extensive expertise in the day-to-day operation of various U.S. nuclear power plants. In addition, he has provided extensive engineering support in the areas of fire protection, safe-shutdown analysis, valve engineering, motor operated valves (MOVs) and air operated valves (AOVs).

Mr. Barrett is currently the lead technical reviewer for NFPA 805 License Amendment Requests in the U. S. Nuclear Regulatory Commission's Office of Nuclear Reactor Regulation (NRR).

EDUCATION/TRAINING

BS, Marine Nuclear Science, State University of New York Maritime College at Fort Schuyler, 1975

PROFESSIONAL AFFILIATIONS/CERTIFICATIONS

U. S. NRC Qualified Technical Reviewer
Society of Fire Protection Engineers (SFPE) – Member Grade
NEI Fire Protection Working Group NFPA 805 Task Force
NEI Fire Protection Working Group
NEI Fire Protection Rule Making Task Force
Senior Reactor Operator (SRO), U.S. Nuclear Regulatory Commission (NRC)
Second Assistant Engineer, Steam Vessels of Any Horsepower, U.S. Coast Guard
Third Assistant Engineer, Motor Vessels of Any Horsepower, U.S. Coast Guard

EXPERIENCE
Senior Fire Protection Engineer
U. S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Division of Risk Assessment
Washington, DC 20555-0001
4/07 to present

Lead technical reviewer of NFPA 805 License Amendment Requests for the Fire Protection Branch (AFPB) in the Division of Risk Assessment. Responsible for reviewing fire protection, nuclear safety assessment (post-fire safe-shutdown including circuit analysis), fire modeling, non-power operations, radioactive release, monitoring program, programmatic, and performance-based, risk-informed, changes.

Worked closely with the Office of Nuclear Regulatory Research (RES) on fire testing of Direct Current (DC) electrical circuits performed as part of the DESIREE-Fire testing program.

Technical Project Manager and lead reviewer for the first NFPA 805 pilot plant, Shearon Harris. Provided technical oversight of the technical review and development of the first NFPA 805 safety evaluation.

Provided significant technical input to NRC's NFPA 805 infrastructure (Regulatory Guide 1.205, Standard Review Plan Chapter 9.5.1.2, Safety Evaluation Template) and interfaced with industry through the NFPA 805 Frequently Asked Question (FAQ) process.

Principal Engineer
Duke Power Company
Oconee Nuclear Station
Seneca, SC
Dates: 4/99 to 4/07

Project Manager and corporate lead engineer for the NFPA 805 Transition Project. Responsible for program cost, schedule and quality. This program transitioned the fire protection program for all three Duke nuclear sites from deterministic requirements to a Risk-Informed, Performance-Based Program under 10CFR50.48(c) and NFPA 805. Oconee was granted Pilot Plant status during the transition. This required significant coordination and interface with both internal and external groups, including NRC regulators.

Lead engineer for the development and performance of fire testing of armored cable in simulated, representative circuits in both AC and DC configurations.

Responsible for the Appendix R Reconstitution Project at Oconee. This project is reconstituting the post-fire safe-shutdown analysis, including component selection, cable selection and analysis, fire zone/area analysis and compliance assessments.

Engineering Support Program (application, performance, problem resolution and maintenance) for Power Operated Valves (AOVs or MOVs). Responsibilities included program management, maintenance of design basis calculations, diagnostic testing and analysis, performance trending, troubleshooting and root cause analysis, problem resolution as well as equipment failure analysis (root cause analysis processes); component monitoring and trending; valve specification, selection, application; Minor Modification development and support; procedure development; generation and review of calculations.

Senior Engineer
Duke Engineering & Services, Inc.
Charlotte, NC
Dates: 11/97-4/99

Lead Systems Engineer on an Appendix R reanalysis project to reduce the overall reliance on electrical raceway fire barrier wrap for the Salem Nuclear Generating Station. Responsible for development of System and Component Logic, development and population of the Safe-shutdown Equipment List, circuit selection and analysis and resolution of safe-shutdown compliance issues and safe-shutdown procedures development. Responsible for update of licensee configuration documents and generation of the Appendix R Safe-shutdown Analysis Report.

Senior Consultant
HGP, Inc.
Greenville, SC 29615
Dates: 10/94-10/97

Provided engineering, technical and management consulting services to a variety of clients ranging from nuclear utilities to law firms. Performed a Probabilistic Risk Assessment (PRA) of a petrochemical production plant and performed due diligence reviews of nuclear utilities in support of merger and acquisitions. In support of expert testimony in a major litigation case, analyzed management effectiveness and schedule delays related to an extended outage at a large, late model dual unit pressurized water reactor (PWR) in the southwest. Analyzed heat loads to support several real-time temperature transient analyses of nuclear power plant heating, ventilating and air conditioning (HVAC) systems, including loss of ventilation during station blackout and loss of coolant accident (LOCA).

Mechanical Engineer IV, Nine Mile Point Unit 1
Niagara Mohawk Power Corporation
Nine Mile Point Nuclear Station
Lycoming, NY 13093
Dates: 10/92-10/94

Managed the technical aspects of the Generic Letter 89-10 Motor Operated Valve (MOV) Program for Nine Mile Point Unit 1. Defined the MOV program scope, developed maximum expected operating conditions and MOV sizing calculations for all GL 89-10 MOVs. Performed cable voltage drop and DC MOV stroke time calculations. Served as Design System Engineer for numerous systems at the plant, including nuclear instrumentation and automatic depressurization system. Appendix R program design engineer responsible for maintenance of safe-shutdown analysis, transient analysis, inventory loss boundaries, and high and low pressure interface maintenance. Provided direct support to operations during fire and control room evacuation special operating procedure flow chart development.

Program Coordinator, Operations Oversight Operations Support
Nine Mile Point Unit 1
Niagara Mohawk Power (same address as above)
Dates: 04/92-10/92

Provided operations and technical support to the operations branch. Served as a member of the Station Operations Review Committee (SORC). Served as procedure owner for all operations department procedures.

<u>General Supervisor</u>, Shift Operations, Nine Mile Point Unit 1
Niagara Mohawk Power (Same address as above)
Dates: 10/90-04/92

Served as SRO providing day-to-day supervision of shift operations. Supervised a staff of 65 licensed and unlicensed operators, including eight shift supervisors. Responsible for compliance to NRC license, as well as protection of public health and safety and maximum power generation at the lowest cost. Performed the duties of control room advisor and/or site emergency director as part of the Emergency Response Organization. Acted as procedure owner for operations department procedures. Served as a member of the Station Operations Review Committee (SORC).

<u>Associate Senior Engineer</u>, Plant Productivity Group 05/90-10/90
Nine Mile Point Units 1 & 2
Niagara Mohawk Power (Same address as above)
Dates: 05/90-10/90

Served as task manager for resolving reactor feedwater pump testing problems. Managed troubleshooting, disassembly, repair, re-assembly and successful testing of reactor feedwater pumps at Nine Mile Point Unit 1. Discovered pump impellers were installed backwards on pump shafts.

<u>Consulting Engineer</u>
Compis Services
Liverpool, NY 13088
Dates: 11/89-05/90

Developed safety classification basis documents in accordance with 10CFR50 Appendix B for numerous electronic and electrical circuits including 125 VDC ground detector circuits, emergency diesel generator voltage regulator and emergency diesel generator governor control circuits.

<u>Senior Engineer/Training Instructor</u>
General Physics Corporation
Columbia, MD 21046
Dates: 02/89-11/89

Implemented systematic approach to training (SAT) -based programs. Developed training material on symptom-based emergency operating procedures for Savannah River Site.

<u>Level III Test Engineer</u>
Newport News Shipbuilding
Newport News, VA 23607
Dates: 07/88-02/89

Performed naval nuclear propulsion plant testing to support new construction. Directly supervised new system flushes, hydrostatic testing, and reactor plant system start-up testing. Developed, implemented and cleared electrical and mechanical tagouts to support nuclear plant testing and construction.

Assistant Operations Superintendent
Shift Operations, Nine Mile Point Unit 1
Niagara Mohawk Power (Same address as above)
Dates: 07/85-06/88

Provided technical and management support of day-to-day operations of a commercial nuclear station. Directly responsible for symptom-based Emergency Operating Procedure (EOP) development and implementation. Represented NMPC on the boiling water reactor (BWR) Owner's Group Emergency Procedures Committee. Performed QR reviews of all Instrument and Control (I&C) and Maintenance (both Mechanical and Electrical) procedure revisions and temporary procedure changes. Reviewed all new design changes and plant modifications for Operations.

Assistant Supervisor, Technical Support
Nine Mile Point Unit 1
Niagara Mohawk Power (Same)
Dates: 10/83-07/85

Supervised engineers performing plant engineering, operations experience assessment (OEA), modifications, pre-operational testing, LERs and inspection report responses. Reviewed operational occurrences for reportability and acted as a site operations review committee alternate member. Provided technical and operations input into the Limited Scope Probabilistic Safety Assessment (PSA) of Nine Mile Point Unit 1. Provided technical and operations input into a component level safety classification database or Q-List.

Senior Technical Assistant, Technical Support Group
Nine Mile Point Unit 1
Niagara Mohawk Power (Same)
Dates: 08/81-10/83

Performed Operations Experience Assessment (OEA). Performed design review of numerous electrical and electronic control systems such as failure modes and effects analysis of feedwater control system and 125 VDC control power distribution system. Proposed and performed conceptual design, as well as supervised the installation and final pre-operational testing on several control system design improvement modifications. Obtained SRO License. Acted as a key member of the Appendix R Safe-shutdown Analysis team. Established safe-shutdown equipment list, inventory loss paths, and hi/low pressure interfaces. Performed electrical circuit analysis for spurious operation as well as developed confirmatory and redundant relay logic schemes for protection of safe-shutdown components. Performed conceptual design, intermediate design, field installation and final pre-operational testing of electrical design modifications implemented to meet 10CFR50 Appendix R. Supervised the installation of two Shutdown Supervisory Control Cabinets, two Shutdown Supervisory Distribution Cabinets, approximately 60 auxiliary relays, and several thousand feet of control cable. Performed circuit analysis of reactor recirculation pump motor generator set tachometer/voltage regulator circuit. Designed and developed temporary modifications to substitute a solid state power supply to replace the volts/hertz voltage regulator input from the tachometer to prevent premature pump trip and prevent loss of electric generation and subsequent risk of reactor scram.

<u>Nuclear Engineer</u>, GS-11, Code 2340, Test Engineering Group
Norfolk Naval Shipyard
Portsmouth, VA
Dates: 09/80-07/81

Performed reactor plant testing on naval nuclear propulsion plants. Performed work control, technical and operations management activities. Received and provided training on submarine PWR reactor plants.

<u>U.S. Coast Guard Licensed Marine Engineer</u>
Department of the Navy
Military Sealift Command, Atlantic
Bayonne, NJ
Dates: 12/76-05/77 and 08/78-08/80

Served as a U.S. Coast Guard licensed marine engineer and a third, second and first assistant engineer. Operated, maintained and supervised an engineering department on a 16,000 SHP Steam Geared Turbine Powered Refrigerated Stores Ship.

<u>Associate Mechanical Engineer</u>, Haddam Neck Plant
Connecticut Yankee Atomic Power Company
East Haddam, CT
Dates: 06/77-08/78

Performed plant engineering and supervised the installation and testing of modifications on a 580 MW 4 Loop Westinghouse PWR. Coordinated and managed the installation of replacement pressurizer power operated relief valves (PORVs) including installation of new motor operated PORV blocking valves and the associated electrical design, installation and testing. Installed: 1. An instrument air system inside primary containment including the associated electrical design, installation and testing; 2. Added a new mixed bed demineralizer including the associated automated control logic testing; and 3. Installed main turbine moisture separator reheater scavenging steam vent chambers. Served as plant engineering group representative on backshifts during the plant outage. Represented the plant on a team to alleviate spent fuel rack bulging and assisted in developing a spent fuel rack poison cavity venting tool.

<u>Nuclear Engineer</u>, GS-7, 9, Code 2370, Nuclear Refueling Engineering
Mare Island Naval Shipyard
Vallejo, CA 94590
Dates: 09/75-12/76

Revised procedures to support reactor refueling activities on Naval Nuclear Propulsion Plants. Performed reactor plant shield surveys. Received training on submarine reactor plant refueling procedures, equipment, support systems and design.

David Crane, Pyrolico

TITLE/POSITION: Vice President

EXPERIENCE

- Mr. Crane has over 25 years of industrial experience in the commercial nuclear, semiconductor, pharmaceutical and automotive industries.
- Mr. Crane has held engineering and engineering management positions in fire protection, life-safety systems, environmental health and safety, instrumentation and controls, electrical and bulk gas system distribution systems.
- Mr. Crane has held technical advisor and/or supervisor roles on three 10CFR50 Appendix R program enhancements, including Reg. Guide 1.189, as well as one NFPA 805 project.
- Mr. Crane has extensive experience representing industry to regulatory agencies: US NRC, US EPA, state and local authorities having jurisdiction.
- Mr. Crane has led multinational engineering teams for the semiconductor industry in the areas of life-safety and industrial control systems.
- Mr. Crane is skilled in performing OSHA PSM and EPA RMP analysis as well as establishing and managing RCRA / Hazardous Waste and SPCC programs.
- Mr. Crane has designed, installed and maintained life-safety and industrial control systems with a combined I/O in excess of 20,000 points.

EDUCATION

- Bachelor of Science degree in Electrical Engineering from Western Michigan University
- Completed coursework in Environmental Management at the University of Maryland University Campus
- Certification in Industrial Firefighting from Lambton College, Sarnia, Ontario, Canada
- Microsoft Certified System Engineer certificate from Colorado Technical University

PUBLISHED WORK

Mr. Crane has published numerous semiconductor white papers on plant industrial controls integration, and advanced process control.

Robert Daley, NRC

Engineering Branch Chief – United States Nuclear Regulatory Commission

PROFESSIONAL HIGHLIGHTS

- Manages electrical, I&C, and fire protection engineers
- Specialist in the area of 10 CFR 50.59 evaluations
- Skilled and proficient in the area of fire protection safe-shutdown analysis
- Certified as an NRC Operator Licensing Examiner for BWR and PWR nuclear plants
- Manages, plans, and directs present and future efforts in the growing areas of digital systems and cyber security
- Design Electrical Engineer at Grand Gulf Nuclear Plant
- Technical Specification Coordinator and member of the Technical Specification Task Force while at River Bend Station
- Member of the BWROG Fire-induced Fire-induced Circuit Failures Task Force
- BWR-6 Senior Reactor Operator Certification

PROFESSIONAL EXPERIENCE

United States Nuclear Regulatory Commission 2000 - Present
Engineering Branch Chief
Supervises engineering inspectors in the implementation of the NRC's Reactor Oversight Program to assure the safety of licensed activities and compliance with requirements. Provides administrative oversight of engineering inspectors.

- Manages technical issues and inspection in the areas of electrical engineering, instrumentation and controls, digital systems, fire protection, cyber security, and 10 CFR 50.59.
- Manages and schedules all regional team Fire Protection inspections and Modification and 10 CFR 50.59 inspections.
- Member of the IMC 0612 (Power Reactor Inspection Reports) and IMC 0620 (Inspection Documents and Records) working groups.
- Organized, led, and facilitated a two day agency-wide Modifications and 10 CFR 50.59 workshop.
- Member of the Office of Research PIRT Electrical Expert Panel for fire-induced cable failure modes.
- Led an agency-wide self-assessment of inspection report quality. The assessment team consisted of staff from all four regions and NRC headquarters.

Senior Reactor Engineer
Led and participated in engineering team inspections at nuclear power plants including the Component Design Basis Inspections, Modification and 50.59 Inspections, Fire Protection Inspections, and In-service Inspections.

- Certified as an Operator Licensing Examiner. Qualified to write, review, and administer NRC exams for the qualification of Senior Reactor Operators and Reactor Operators for BWR and PWR nuclear plants.

- Regional contact for engineering modification and 10 CFR 50.59 issues and inspections.
- Provided significant technical and inspection support during the Davis-Besse extended shutdown for reactor vessel head corrosion and for the Point Beach 95003 supplemental inspection.
  - Led an electrical issues inspection at Davis-Besse during their extended shutdown.
  - Led the Point Beach CDBI that that was used as a basis for their exit from the 95003 process.
- Regional Power Uprate point of contact.
- Expertise and specialty areas include:
  - Fire Protection Safe-shutdown Circuitry Analysis
  - 10 CFR 50.59
  - Technical Specifications
  - Electrical and I&C Design
  - Station Blackout
  - Equipment Qualification (EQ)
  - 10 CFR 50, Appendix J

Entergy Operations, Inc. **1991-2000**
Senior Engineer – Grand Gulf Nuclear Power Station
Evaluated and resolved electrical system and component design and performance problems. Developed electrical engineering specifications/standards, design drawings, and design changes. Proficient in protective relaying and fuse/breaker coordination. Design changes have included complex control circuitry modifications.

- Performed electrical system design including fuse/breaker replacement, electrical coordination calculations, transformer replacement, and re-design of the airlock door control circuitry.
- Fire Protection Safe-shutdown Engineer.
- Technical lead for the license basis reconstitution project for Fire Protection, Electrical Engineering, and I&C.
- Member of the fire protection (Appendix R) Safe-shutdown Analysis Owner's Group (BWROG) committee.
- Entergy's representative on the BWROG circuit failures task force.
- Operations Test Coordinator for surveillances and equipment testing during plant outage activities.

Senior Engineer – River Bend Station
Performed a variety of assignments in the areas of electrical engineering, nuclear licensing, nuclear safety assessment, and operations.

- Served as Technical Specification Coordinator for four years. Coordinated plant activities and resolved issues regarding Technical Specifications and the Technical Requirements Manual.
- River Bend representative on the Technical Specifications Task Force (TSTF).
- Senior Reactor Operator certified.
- Root Cause Team Leader. Led root cause evaluations for significant plant events. Trained and proficient in:
  - Kepner-Tregoe
  - TapRoot

  - Management Oversight and Risk Tree (MORT)
- Developed and implemented License Amendment Requests (LAR) and Licensee Event Reports (LER). Developed and submitted the first 10 CFR 50, Appendix J, Option B, License Amendment in the nuclear industry.
- Directed and assisted in assessments and analyses of plant processes and adverse trends/issues.

RCA (Thomson Consumer Electronics) **1990 - 1991**
Shift Supervisor
Supervised two production lines and 43 personnel in the manufacturing of high optical quality glass for television screens. Coordinated the technical efforts involved in keeping a high-speed, fully automated production line in constant operation. Responsibilities included the maintenance and repair of robotics and complex machinery as well as the adjustment of equipment to maintain maximum productivity.

United States Navy Nuclear Officer **1984 - 1989**
Served as a naval officer assigned to the USS Long Beach.

- Supervised 25 personnel in the daily maintenance of all shipboard electrical distribution equipment, electrical machinery and electronic hardware.
- Supervised and coordinated the operational staff in 2 nuclear power plants as a fully qualified Nuclear Reactor Watch Officer and Engineering Duty Officer.

EDUCATION AND CERTIFICATIONS

US NRC
- Operator Licensing Examiner Certification for BWR and PWR nuclear plant designs
- GE BWR Technology Series
- Westinghouse PWR Technology Series
- Reactor Inspector qualification

Entergy Operations, Inc.
- Senior Reactor Operator Certification – River Bend Station
- Successfully passed the Engineer in Training (EIT) exam

US Navy
- Engineering Duty Officer and Engineering Officer of the Watch (USS Long Beach)
- Surface Warfare Officer Qualification
- Naval Nuclear Power School and Naval Nuclear Power Prototype School.

College Level Coursework
Northwestern University – Bachelor of Science in Electrical Engineering (1984)
Ohio State University – Finished 1/3 of Master's Degree in Electrical Engineering (1990)

Other Pertinent Training
Team and Meeting Facilitator
ANSI/ISA-S67.04-2006: Set points for Nuclear Safety-Related Instrumentation
Protection of Industrial and Commercial Electric Power Distribution Systems – Univ. of Wisconsin
Understanding Power Cable Characteristics - Univ. of Wisconsin
Ultrasonic Testing, Level I and II

PANELIST AND FACILITATOR RESUMES

ASME Section XI In-Service Inspection
Fire Protection SDP
Software Verification and Validation
ETAP Power System Engineering Workshop
GE EHC and Turbine Trip and Monitoring System
RCIC System and Control Circuitry
GE Neutron Monitoring Systems

Daniel Funk, Kleinsorg Group Risk Services

SUMMARY

Mr. Funk is the Manager of Risk Analysis for Kleinsorg Group Risk Services (KGRS). In this capacity he directs technical and business operations for the group. The KGRS Risk Analysis Group provides consulting services to the nuclear power industry, specializing in all aspects of analysis relating plant response to fire and safe shutdown capability. Mr. Funk maintains an active technical role in his specific area of expertise – electrical power and control. He has 30 years of engineering, testing, and management experience, and has held positions as engineering manager, principal engineer, engineering supervisor, and project manager.

Mr. Funk is highly proficient at completing complex, multi-discipline projects on time, within budget, and to high quality standards. He is an accomplished project manager and has established expertise in the design, analysis, evaluation, testing, maintenance, modification, and operation of electrical power systems, instrumentation & control systems, and complex industrial equipment. Mr. Funk has extensive experience with nuclear power plants, Department of Defense facilities, electrical power distribution systems, industrial power and control systems, electrical and fire safety, and codes and standards.

EDUCATION/CERTIFICATIONS

Registered Professional Engineer:

Oregon No. 13734	Electrical and Control Systems
Washington No. 30516	Electrical
California No. E17744	Electrical

Bachelor of Science Degree, Electrical & Computer Engineering, Oregon State University, 1981
Naval Nuclear Power School

PROFESSIONAL AFFILIATIONS

Institute of Electrical and Electronic Engineers (IEEE)
National Fire Protection Association (NFPA)
IEEE Standards Coordinating Committee 29 (1995 – 2003)

EXPERIENCE

Senior Technical Consultant *November 2011 – Present*
Kleinsorg Group Risk Services
A Hughes Associates Company

Mr. Funk joined KGRS in November 2011 as a Senior Technical Consultant and Manager of the Risk Analysis Group. He oversees the group's activities and maintains an active technical role in projects and nuclear industry research activities. Mr. Funk continues his efforts to advance and promote state-of-the-art methods, techniques, and tools for addressing fire risk at nuclear plants. Mr. Funk's primary areas of expertise and recent accomplishments are summarized below:

Fire Protection – Extensive experience with fire protection requirements and issues for electrical systems and equipment at nuclear power plants and hazardous industrial facilities:

- Specific expertise in the evaluation and analysis of fire-induced circuit failures, spurious operations, and associated circuits.
- Fully versed in all aspects of fire safe shutdown analysis for Appendix R and NFPA 805. Serving as project manager and/or lead electrical for numerous Appendix R, NFPA 805, Fire PRA, and Multiple Spurious Operation projects.
- Industry representative for joint NRC/EPRI expert panel for assessment of fire-induced circuit failures (Electrical PIRT Panel). Active participant in industry and NRC fire-induced circuit failure tests, including EPRI/NEI, CAROL-FIRE, and DESIREE-FIRE.
- Providing direction and technical consulting to utilities for major projects involving NFPA 805 transition, multiple spurious operation analysis, and fire-induced circuit failure issues.
- Co-author of NUREG 6850, with primary responsibility for development of advanced analytical methods for the analysis of fire-induced circuit failures.
- Principal author for report of EPRI/NEI fire-induced cable failure test program (EPRI 1003326).
- Member of industry-wide Expert Panel to assess spurious operation likelihood (EPRI 1006961).
- Expertise in the use of ARCPlus® and CAFTA software as applied to safe shutdown analysis, nuclear safety capability assessment, and multiple spurious operations. Developer of the Fire Data Manager (FDM®) module of ARCPlus.
- Member of project team to develop optimization techniques for fire protection equipment maintenance programs at nuclear plants (EPRI 1006756). The performance-based techniques developed by the project are being introduced into NFPA codes and standards.
- Conduct fire risk assessments for electrical process equipment as part of U.S. and European Union equipment safety certifications.

Electrical Power Systems – Extensive engineering design and analysis expertise with electrical power systems for nuclear power plants, DoD facilities, DoE facilities, and hazardous industrial facilities:

- Conducted numerous full-scope electrical engineering studies, including short circuit, power flow, electrical protection and coordination, arc flash, motor starting, and power quality.
- Familiar with design requirements, equipment specifications, codes/standards, and construction support for electrical power distribution systems, including medium voltage, low-voltage, overhead, and underground distribution.
- Extensive experience with and knowledge of electrical analysis software, including EasyPower®, Etap®, SKM PowerTools, and ArcView/ArcMap® (Geobase software)
- Directed managed comprehensive master planning studies of electrical distribution systems at DoD facilities. Projects typically involve: 100% field walkdown of equipment ♦ regeneration of one-line and layout drawings ♦ Geobase satellite coordinate

determination ♦ characterization of all equipment and development of Geobase-compliant equipment databases ♦ development of electrical software models ♦ full-scope electrical analysis ♦ reliability and vulnerability assessment ♦ 10-year system plan.

- Managed all aspects electrical design projects requiring professional engineer certification. Prepared designs for projects with construction value up to $50M.
- Developed operation, maintenance, and training manuals for electrical distribution systems.
- Provide electrical analysis, electrical design, and electrical safety training to engineers and electrical linemen.
- Experienced in the design, analysis, maintenance, and testing of batteries and critical DC power systems. Received national recognition for accomplishments in advancing techniques for battery performance testing.

Codes and Standards – Broad knowledge of electrical and fire safety codes and standards, including IEEE, ANSI, NFPA, UL, NEMA, NETA, SEMI, IEC, UFC, MIL, and European Directives.

PREVIOUS EXPERIENCE

Principal Engineer *1990 – November 2012*
Edan Engineering Corporation

Prior to joining KGRS, Mr. Funk was a founder and co-owner of Edan Engineering Corporation. As a principal of the company, he directed Edan's technical and business operations for over 20 years. Mr. Funk helped build Edan into a solid engineering and test firm with nationally recognized expertise in several fields. Edan Engineering recently joined Hughes Associates and KGRS, and now operates as a division of Hughes providing specialized electrical engineering services to critical government facilities.

Project Manager *1989 – 1990*
Precision Interconnect

Mr. Funk joined Precision Interconnect as a project manager in charge of product development for customized electrical connection systems used in military and aerospace guidance and navigation systems. He led a team of engineers and technicians through the development and qualification cycle for several unique products. Mr. Funk was instrumental in obtaining government approval to allow Precision Interconnect to supply military components under a certified quality assurance program. Mr. Funk gained extensive knowledge of military specifications and standards, and developed the qualification test plan and procedures for component certification.

Electrical Engineering Manager *1986 – 1989*
Portland General Electric Company

Mr. Funk joined Portland General Electric Company as an Engineer II working for the Trojan Nuclear Plant. Within a 2-year period he was promoted to senior engineer and then to supervising engineer. As a supervising engineer, Mr. Funk managed a group of 10 to 14 electrical engineers. He was accountable for budget, schedule, and technical adequacy of engineering design and analysis activities under his control. Mr. Funk ultimately advanced to become the Electrical Engineering Manager, where he managed over 80 engineers, designers, and drafters. He managed an annual budget in excess of $20M and was responsible for electrical, instrumentation & control, fire protection, and environmental qualification engineering activities.

Navy Submarine Officer *1981 – 1986*
US Navy

Mr. Funk started his career as a naval submarine officer. He rapidly qualified as Officer of the Deck and Engineering Officer of the Watch. His assigned duties included Assistant Weapons Officer, Damage Control Assistant, Reactor Controls Assistant, and Quality Assurance Officer. He received numerous commendations while serving in the Navy and was consistently rated as the top junior officer on board.

PUBLICATIONS

- Air Force Manual 32-1181, *Design Standards for Facilities Interior Electrical Systems*
- *Advanced Circuit Analysis Methods Development for Fire-Risk Analyses*, presented at 2005 ANS Conference
- NUREG/CR-6850, *Fire PRA Methodology for Nuclear Power Facilities*, September 2005
- EPRI Report 1003326, *Characterization of Fire-Induced Circuit Faults: Results of Cable Fire Testing*, December 2002
- EPRI Report 1006756, *Fire Protection Equipment Surveillance Optimization and Maintenance Guide*, July 2003
- EPRI Report 1969001, *Spurious Actuation of Electrical Circuits Due to Cable Failures: Results of an Expert Elicitation*, May 2002
- EPRI Report 1006522, *Stationary Battery Monitoring by Internal Ohmic Measurements*
- EPRI Report 106154, *Instrument Monitoring and Calibration Product Guide*, October 2000
- EPRI Report 106752-R2, *Instrument Performance Analysis Software System*, July 1999
- Air Force Pamphlet 32-1186, *Valve Regulated Lead Acid Batteries for Stationary Applications*, January 1999
- EPRI Report 100249-R1, *Emergency Battery Lighting Unit Maintenance and Application Guide*, June 1997

Thomas Gorman, PPL

EDUCATION:

Rensselaer Polytechnic Institute
Bachelor of Science in Civil Engineering

Syracuse University
Masters in Business Administration

PPL Susquehanna, LLC
Plant Operations Certification Program

PROFESSIONAL AFFILIATIONS:

Registered Professional Engineer – Pennsylvania

Society of Fire Protection Engineers – Member Grade

BWROG – Chairman of the Appendix R Committee & Fire Protection Sub-Committee of the IRIR Committee

NEI Circuit Failures - Issue Task Force Member

PROFESSIONAL EXPERIENCE:

Chicago Bridge & Iron Company – 1974 to 1976 – Engineer

Niagara Mohawk Power Corporation – 1976 to 1982 – Civil Group Supervising Engineer

PPL Susquehanna, LLC – 1982 to Present – Sr. Staff Engineer

Mr. Gorman has 38 years of design engineering experience with 35 of the years in the Electric Power Industry and 34 in the Nuclear Power Industry. He has specialized in Appendix R post-fire safe-shutdown analysis for 28 years. He has been a contributing author to the development of the following industry documents:

- GE-NE-T43-00002-00-03 R01, BWROG Position on the Use of SRVs and Low Pressure Systems as Redundant Safe-shutdown Paths, dated August 1999.
- GE-NE-T43-00002-00-02 R0, Generic Guidance for BWR Post-Fire Safe-shutdown Analysis, dated November of 1999.
- NEI 00-01 Revision 2, Guidance for Post-Fire Safe-shutdown Circuit Analysis, dated June of 2009.
- NEDO 33638, BWROG Assessment of Generic Multiple Spurious Operations (MSOs) in Post-Fire Safe-shutdown Circuit Analysis, dated June of 2011.

James Higgins, BNL

TITLE: Group Leader

FIELD OF EXPERTISE: Nuclear Facility Operations, Fire/Electrical, Human Factors, PRA

EDUCATION:

1969 - BS, Naval Engineering, Mathematics, U.S. Naval Academy
1970 - MS, Mathematics, Naval Postgraduate School
1971 - U.S. Naval Nuclear Propulsion Training

EXPERIENCE:

1983-Present
Brookhaven National Laboratory - Provided various types of onsite reviews, analysis and research, and technical assistance to the NRC and DOE on various programs including: advanced/new reactor reviews, updating of NRC standard review plan, fire protection/safe-shutdown, review of soviet reactors, inspection of specific technical issues & allegations at NPPs, aging of components and systems, PRA-based inspection prioritization, PRA sensitivity analyses on the effect of variation in human performance, value-impact analyses, influence of organizational factors, safety policy, upgrades to annunciators and local control stations, and control room human factors reviews. Performed safe-shutdown inspection onsite. Group leader responsible for review of many triennial fire protection inspections including electrical separation, associated circuits, and safe-shutdown. Participated in aging study of motors, nuclear grade battery testing, and diesel generator reliability. Performed inspections at vendor sites for all US nuclear grade EDG vendors. Knowledgeable in new reactor designs, AP1000, ABWR, EPR and ESBWR. Program manager at BNL for the review of university reactor license renewal for the NRC, including review of 8 reactor submittals. Performed onsite reviews of research reactors at BNL, ORNL/HFIR, and NIST. Developed, administered, and taught training courses and programs for NRC and DOE, including work for NRC Regional Offices, HQ, TTC and for DOE. Participated in DOE ORRs for HFIR at ORNL and two at Savannah River (for DWPF and CIF). Assisted in the development/teaching of DOE Conduct of Ops course, engineering fundamentals course, performance based inspection course, and fire protection courses for Russian personnel and NRC inspectors. Participated with the International Atomic Energy Agency (IAEA) in missions to RBMK reactor sites in Russia and Lithuania. Performed root cause analysis of various failures at these sites and provided recommendations for improvements in their operations. Served as Principle Investigator, Group Leader and Assoc. Division Head.

1976-83
U.S. Nuclear Regulatory Commission - Region-based reactor inspector at operating and preoperational BWR and PWR commercial nuclear power plants. Inspected approximately 20 to 25 different reactor plants. Served as lead inspector for containment testing, pipe supports and snubbers, refueling, and in-service testing of pumps and valves. Also inspected plants to review responses to major incidents and accidents. Reviewed safe-shutdown facility and procedures. Senior Resident Inspector at Shoreham Nuclear Power Station (BWR). Inspected the construction and preoperational test phases of the plant and initial reactor fuel delivery. Participated as an expert witness during licensing hearings. Reviewed numerous allegations regarding improper practices. Section Chief, Region I, responsible for all resident inspectors and the inspection program at four operating reactors (PWRs). Author of over 100 NRC inspection reports.

1971-76
U.S. Navy - Division Officer in the Engineering Department of the USS Nathan Hale (SSBN - 623) a nuclear powered polaris submarine. Served as the Sonar Officer, Electrical Officer, Reactor Controls Officer, and Auxiliary Division Officer. Qualified as Submarine Officer, Engineering Officer of the Watch, and as Engineer Officer. Trained in various aspects of handling, repairing, and use of nuclear weapons. Served as Division Director and Instructor at the U.S. Naval Nuclear Power School. Responsible for course curriculum, exams, and instruction techniques, while teaching reactor plant systems and electrical theory courses. Wrote a new course text for the Electrical Theory Course. Served as Department Head of the Weapons Department of the USS Billfish (SSN - 676), a fast attack nuclear-powered submarine. Responsible for the sonar systems, fire control systems, torpedo and missile systems (including a nuclear weapons capability), and deck systems.

SELECTED PUBLICATIONS LIST

- Review of the IEEE Standard for Computerized Operating Procedure Systems, BNL Technical Report No. BNL-91087-2010, February 26, 2010, J. O’Hara and J. Higgins
- SER on Review of the Initial Test Program for the US-APWR, DCD Chapter 14.2. October, 2008 and August 2009, J. Higgins, W. Gunther and R. Belles
- Guidance for the Review of Changes to Human Actions, NUREG-1764, Rev. 1, J. Higgins, J. O'Hara, et al. September 2007
- SER on Review of Containment Leak Rate Testing for the US-APWR, Chapter 6.2.6, June, 08, J. Higgins and R. Deem
- Evaluation of the WCAP-16555, AP1000 Identification of Critical Human Actions, and Risk Important Tasks (TR59), BNL Technical Evaluation Report No. Q4060, J. Higgins & J. O’Hara, 2007
- Evaluation of the ESBWR Operating Experience Review (OER) Plan, BNL TER No. 11094-2-3/06, James Higgins and John O’Hara, 2007
- Technical Specification for the Control Room Upgrade for the NBS Reactor at the NIST Center for Neutron Research (NCNR), March 4, 2004, D. Danseglio, J. Higgins, and J. O’Hara
- Adaptation of the NRC Risk-Informed Inspection Notebooks for the Evaluation of Electrical Circuit Inspection Findings during Fire Protection Inspections, March 18, 2003, J. Higgins
- Nine Summary Reports on Risk-Informed Benchmarking Trips for nine (9) nuclear power plants’ Significance Determination Process (SDP) 2003
- Technical Evaluation Report, Human Factors Engineering Review of the Oskarshamn Unit 1 Modernization Program, prepared for Statens Kärnkraftinspektion (SKI), the Swedish Nuclear Power Inspectorate, John O’Hara and James Higgins, October 9, 2002
- Human Factors Engineering Program Review Model, NUREG-0711, O’Hara, Higgins, et al., 2002
- Maintainability of Digital Systems, Technical Basis and Human Factors Review Guidance, NUREG/CR-6636, W. Stubler, and J. Higgins, March, 2000
- Safety Significance of Inadvertent Operation of Motor Operated Valves in Safety-Related Piping Systems in Pressurized Water Reactors, BNL report E-2071-T1-12-93, Rev. 1, March, 1995, C. Ruger, J. Carbonaro, J. Higgins, and W. He
- Risk Sensitivity to Human Error, NUREG/CR-5319, P. Samanta, J.C. Higgins, et al., April 1989
- Reliability Program to Improve and Maintain Emergency Diesel Generator Performance, BNL Technical Report A-3817-4-87, S. Karimian, J.C. Higgins, & J.H. Taylor, April 1987
- PRA Applications, NUREG/CR-4372, J.C. Higgins, January 1986
- A Review of Emergency Diesel Generator Performance at Nuclear Power Plants, NUREG/CR-4440, J.C. Higgins and M. Subudhi, November 1985

- Authored over 100 NRC inspection reports for nuclear safety reviews at commercial nuclear power plants. Plants included: Beaver Valley 1, Calvert Cliffs 1 & 2, Fitzpatrick, Ginna, Haddam Neck, Indian Pt. 2 & 3, Limerick 1 & 2, Maine Yankee, Millstone 1 & 2, Nine Mile Pt. 1, Oyster Creek, Peach Bottom 2 & 3, Pilgrim, Salem 1 & 2, Shoreham, Susquehanna 1, Three Mile Island 1 & 2, Vermont Yankee, Yankee Atomic.
- Course Text for US Naval Nuclear Power School Electrical Theory for Mechanical Operators, 1976

Steven Nowlen, SNL

CURRENT EMPLOYMENT:

Employer:	Sandia National Laboratories Risk and Reliability Analysis Department 6231
Title/Position:	Distinguished Member of the Technical Staff
Employed Since:	October 17, 1983
Business Address:	Mail Stop 0748 Albuquerque, New Mexico, USA 87185-0748
Phone:	(505)845-9850 Facsimile: (505)844-2829 e-mail: spnowle@sandia.gov

EDUCATION AND HONORS:

Appointed to the rank of Distinguished Member of the Technical Staff at Sandia National Laboratories, October 2001, an honor reserved for no more than 10% of the SNL engineering/science staff.

Master of Science, Mechanical Engineering, Michigan State University, East Lansing Michigan, March 1984.

DuPont Research Fellow, Department of Mechanical Engineering, Michigan State University, 1981-1983.

Bachelor of Science with High Honor, Mechanical Engineering, Michigan State University, East Lansing Michigan, December 1980, Graduated Phi Beta Kappa.

PROFESSIONAL EXPERIENCE:

Since joining Sandia in 1983, I have been active in both experimental and analytical research in the fields of nuclear power plant safety with a focus on fire safety and quantitative fire risk analysis. I have been Sandia's technical and programmatic lead for the nuclear power fire research programs since 1987. My responsibilities include direct technical contributions, technical team leadership, sponsor interactions, program planning and program management.

The most important application of my research has been in the development and application of probabilistic risk assessment (PRA) methods for fires in nuclear power plants; that is, quantitative assessments of the impact of fires on nuclear power plant safety and operations. I also have experience in harsh environment equipment qualification testing and accelerated thermal and radiation aging of materials.

My experimental work has included the planning, execution, evaluation, and reporting of fire safety experiments, as well as the interpretation, evaluation, and application of experimental results generated by other researchers. Specifically, I have experience in the testing of fire growth behavior, large-scale room fires, enclosure ventilation and smoke purging, cable and electrical equipment fire-induced damage, smoke particulate characterization, fire barriers, smoke damage effects on digital equipment, and cable ampacity and ampacity derating.

As a secondary aspect of my experimental experience, I have also participated in Equipment Qualification tests assessing the performance of electrical equipment in the harsh steam and radiation environments associated with nuclear power plant severe accidents. This work has included both accelerated thermal and radiation aging of electrical cables and the evaluation of equipment performance during harsh environmental exposures such as loss of coolant accidents.

Related analytical efforts in the area of fire safety have included the evaluation and validation of computer fire simulation models, the review and analysis of actual fire events in nuclear power plants, fire risk assessment analytical support work, the development and evaluation of fire risk assessment methods, and the development and evaluation of analytical methods for cable ampacity and fire barrier ampacity derating assessments. I have also participated as an expert consultant in various inspection activities for U.S. Nuclear Regulatory Commission (NRC).

I have performed training for the NRC staff in the application of the NRC Significance Determination Process (SDP) for fire protection inspection findings. I am currently participating in an effort to develop and deploy inspector training for application to those NRC licensees transitioning to the new risk-informed, performance-based fire protection requirements. I also act as technical coordinator and classroom instructor for the annual Fire PRA training course offered as a part the NRC Office of Nuclear Reactor Research (RES) and Electric Power Research Institute (EPRI) collaboration on fire research. This training course has been conducted annually since 2005 and routinely attracts well over 100 participants per year.

I was a member of the U.S. NRC Senior Review Board for the review of Individual Plant Examination for External Events (IPEEE). I am currently a member of the ASME/ANS Joint Committee on Nuclear Risk Management Subcommittee on Standard Maintenance. I also co-chair the associated working group on fire risk.

My publication list is available on request and includes 10 journal articles, approximately 30 formal SNL technical reports, five invited conference papers and over 20 other general conference papers. I also co-authored a section of the SFPE *Handbook of Fire Protection Engineering* entitled “Risk Assessment for Nuclear Power Plants.”

NOTABLE ROLES AND ACCOMPLISHMENTS:

SNL technical area lead and program manager for nuclear power plant related fire research (1987-present)

Voting member of the American Society of Mechanical Engineers (ASME) American Nuclear Society (ANS) Joint Committee for Nuclear Risk Management (JCNRM) Subcommittee on Standards Maintenance

Co-Chair of the ASME/JCNRM *Standard for Level 1 / Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications* Fire Working Group (RA-Sa-2009)

Leading member of the core writing team for the American Nuclear Society (ANS) Standard on Fire PRA methodology (ANSI/ANS-58.23-2007)

Lead author and NRC technical team lead for the consensus Fire PRA methodology NUREG/CR-6850 which as developed as a collaboration between the NRC and the Electric Power Research Institute (EPRI))

Technical Coordinator for development of the U.S. NRC Significance Determination Process (SDP) for risk-informed fire inspections (2003-2004)

Technical coordinator and instructor for the annual NRC/EPRI Fire PRA methodology training sessions (2004-present)

Member of the Nuclear Regulatory Commission (NRC's) Senior Review Board for the review and evaluation of licensee submittals under the Individual Plant Evaluation of External Events Program (1995-2001)

Technical advisor to the U.S. NRC staff during development of the National Fire Protection Association (NFPA) *Performance-Standard for Fire Protection for Light Water Nuclear Reactor Electric Generating Plants* (NFPA 805) (1995-2001).

Qualified as an expert witness in nuclear power plant fire safety in U.S. Federal Criminal District Court (1995).

Andy Ratchford, RDS

SUMMARY

Mr. Ratchford is the President of Ratchford Diversified Services, LLC, an engineering services consulting firm providing fire protection and risk management consulting services. Mr. Ratchford has more than 27 years of experience in the nuclear field, including 22 years in nuclear power plant fire protection. He has provided fire protection and post-fire safe-shutdown technical support to more than one half of the nuclear power plants in the United States. He is actively involved in industry activities, such as development of risk-informed guidance for fire protection (NFPA 805), the implementation guidance for NFPA 805 (development of NEI 04-02), NFPA 805 transition pilot plant activities, and resolution of major nuclear plant fire protection issues such as multiple spurious operations and operator manual actions.

EDUCATION/TRAINING

B.S., Civil Engineering, Clemson University, 1984
U.S. Navy Nuclear Power Program
Cooperative Education Program, Savannah River Site, Aiken, SC, 1981 - 1983

PROFESSIONAL AFFILIATIONS/CERTIFICATIONS

Registered Professional Mechanical Engineer, State of California
Member, American Nuclear Society
Member, Society of Fire Protection Engineers
Member, National Fire Protection Association (NFPA)
Member, NFPA Technical Committee on Fire Protection for Nuclear Facilities (alternate)
Member, NEI NFPA 805 Task Force
Member, NEI Circuit Failures Task Force

EXPERIENCE

Principal — ***09/99-Present***
Ratchford Diversified Services/KGRS Strategic Alliance

Principal of Ratchford Diversified Services, an engineering consulting firm that provides technical services to the nuclear industry. He has provided consulting services to a number of clients as a subcontractor to a number of engineering consulting firms. He is a leading technical contributor to the Strategic Alliance for NFPA 805 Transition, led by Kleinsorg Group Risk Services, LLC (KGRS), an alliance of companies involved in the technical direction and support of licensees transition their fire protection programs to 10 CFR 50.48(c).

He is an active participant in the nuclear fire protection community, including participation in numerous NRC and NEI workshops and meetings as a member of the KGRS Strategic Alliance. He is a member of the NFPA Technical Committee on Fire Protection for Nuclear Facilities and has been actively involved in the development of NFPA 805 and its implementing guidance for transition to a risk-informed, performance-based fire protection program (NEI 04-02). He has served as an NEI representative in the NFPA 805 pilot plant process and is actively involved in the NFPA 805 Task Force meetings, Pilot Observation Meetings, and other pilot activities. He has been involved in all aspects of NFPA 805 transition, including lead roles in the resolution of industry issues related to multiple spurious operations and operator manual actions. He has developed a number of NFPA 805 Frequently Asked Questions (FAQs) in support of pilot plant activities.

He has worked closely with the Fire PRA community in the integration of Fire PRA into the NFPA 805 application and resolution of industry issues. This includes technical support and reviews of Fire PRA Component and Cable Selection, modeling of spurious operations, and use of the Fire PRA in support of change evaluations. He has also participated in Fire PRA Peer Reviews, with an emphasis on the Fire PRA Component Selection, Fire PRA Model Development, Cable Selection, and Circuit Analysis tasks. He is a participant on the Phenomena Identification and Ranking Table (PIRT) panel for fire-induced circuit failures as applied to Nuclear Power Plant applications, an activity sponsored by the NRC Fire Research Branch.

He serves in technical oversight and consultant roles on a number of NFPA 805 transition projects, including both pilot plants (Harris Nuclear Plant and Oconee Nuclear Station) and fleet transition projects for Florida Power and Light and Southern Nuclear Corporation. He was instrumental in the development of the pilot plant NFPA 805 License Amendment Requests, having worked extensively with Progress Energy, Duke Energy, and NEI on the format, content, and level of detail in the submittals.

He has also been very active in industry efforts in the resolution of fire-induced circuit failures using the processes in NEI 00-01. He was an active participant in the NEI Circuit Failures Task Force group that developed NEI 00-01, Revision 2. He also a led or participated in 15 Expert Panels addressing fire-induced multiple spurious operations and their impact on plant safety.

In addition to primary roles in the NFPA 805 transition, he also has supported licensees during NRC Triennial Fire Protection Inspections and performed and led self assessments addressing fire protection, post-fire safe-shutdown, and fire-induced circuit failure issues.

Fire Protection Manager ***08/96-09/99***
Duke Engineering & Services
Managed the Western Region Fire Protection and Hazards Analysis group. Responsible for project quality and business performance, including nuclear and commercial and industrial business areas. This included managing fire protection and Appendix R program validation projects, self assessments, and resolution of complex technical issues for numerous clients.

Supervisor ***06/94-08/96***
VECTRA Technologies
Supported American Electric Power with an Appendix R Revalidation Project for Cook Nuclear Plant (CNP). Was the primary author and project manager for an Appendix R Topical Design Basis Document and a Fire Protection Topical Design Basis Document for CNP. Project Engineer for a comprehensive Thermo-Lag Fire Barrier Resolution Project for Entergy at River Bend Station.

Lead Senior Engineer ***02/90-06/94***
ABB Impell
Assigned to the Mechanical Engineering Group responsible for support of Diablo Canyon Power Plant (DCPP) for Pacific Gas and Electric. He was the project engineer of the comprehensive DCPP Fire Protection/ Appendix R Upgrades Project, which included responsibility for all technical and financial aspects of this multi-disciplined project.
Commissioned Officer 02/85-1/90

U.S. Navy Submarine Force
He served 5 years in the U.S. Navy as a submarine officer in the Nuclear Propulsion Program. This included training and education, as well as a tour of duty as a Submarine Officer. Certified as Engineer Officer of Naval Nuclear Power Plants by the Department of Energy and the U.S. Navy.

PUBLICATIONS

Mr. Ratchford has been a principal contributor to many nuclear industry fire protection documents. A listing of documents and his level of participation in the development of the document is provided below:

NFPA 805, Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001, Code Committee Member, Contributing Author

NEI 04-02, Guidance for Implementing a Risk-Informed, Performance-Based Fire Protection Program Under 10 CFR 50.48(c), Principal Contributor

NEI 00-01, Guidance for Post-Fire Safe-shutdown Circuit Analysis, Task Force Member, Reviewer

EPRI Technical Report 1010981, Transition Process Pilot Report – NEI 04-02 Guidance for Implementing a Risk-Informed, Performance-Based Fire Protection Program Under 10 CFR 50.48(c), Principal Contributor

EPRI Technical Report 1001442, A Pilot Plant Evaluation NFPA 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," Principal Contributor

NRC. NUREG/CR-6850, EPRI Technical Report 1011989, Fire PRA Methodology for Nuclear Power Facilities, September 2005, Independent Reviewer (selected sections)

Farley Units 1 and 2, 10 CFR 50 Approved Appendix R Exemption, August 16, 2005 (RI-PB approaches using NEI 04-02 methods), Principal Contributor

EPRI Technical Report 1006756, Fire Protection Equipment Surveillance Optimization and Maintenance Guide, July 2003, Principal Contributor

Mano Subudhi, BNL

CLASSIFICATION: Engineer (Scientific Staff)

FIELD OF EXPERTISE: Mechanical Engineering: Codes and Standards; Piping and Equipment Design and Analysis; Equipment Qualification; Electrical Equipment Aging; Materials Science; Structural Engineering; Seismic Analysis

EDUCATION:

1969 - B.S., Mechanical Engineering, Banaras Hindu University, India
1970 - M.S., Mechanical Engineering, Massachusetts Institute of Technology
1974 - Ph.D., Mechanical Engineering, Polytechnic Institute of New York

EXPERIENCE:

1976-Present
Brookhaven National Laboratory, Currently performing piping design certification reviews for ESBWR, APWR and EPR and revising design-specific review standards (DSRSs) for small modular reactors. Conducted workshops and classes on various topics associated with NRC regulations in FSU countries.

Developed SER templates for the new reactor licensing. Moderator and Technical lead for expert panel for material degradation PIRT. Served as lead engineer, principal investigator, and group leader. Completed engineering projects for NRC, DOE, and other federal agencies. Developed qualification guidelines for the dynamic and seismic evaluation of Class 1E equipment. Studied alternate procedures for calculating the inertia and pseudo-static responses for multiple supported piping systems. Developed the EPIPE finite element computer code for benchmarking and confirmatory analyses of several as-built piping systems. Principal Investigator for the NRC's equipment aging research program to develop maintenance practices including ISI/IST to mitigate equipment failures. Conducted tests on equipment performance. Studied impact of aging on seismic capacity in the event of an earthquake. Evaluating environmental qualification procedures for cables. Completed studies and issued reports on: NPP EDG performance, reliability, and inspection techniques; snubber performance and inspection; risk-based inspection; system performance and aging; and component performance and aging. Reviewed relief requests for ISI requirements and applications for license renewal. The LR review primarily included reactor coolant system in PWR plants (e.g., ANO1, North Anna and Surry, and Catawba and McGuire). Performed LRA audits of reactor coolant system at BWR sites (e.g., Brown's ferry, Brunswick, Oyster Creek and FitzPatrick).

1975-1976
Bechtel Power Corp., Mechanical Engineer. Involved in the stress analysis of nuclear power plant components subjected to thermal, dead weight, seismic, thermal transients, pressure and fatigue loads; special problems including water hammer, flow-induced vibrations, and sudden valve closures; and preparation of Nuclear Class I Reports for licensing purpose. Represented Bechtel in the interfacing with manufacturers, clients and vendors.

1974-1975
Nuclear Power Service, Sr. Stress Analyst. Performed stress analysis of mechanical and piping systems according to the requirements of ASME B&PVC, Section III, and ANSI B31.1

Code. Applied finite element techniques in the analysis and certification of components, which did not meet the code requirements. Have written computer programs for incorporating the ASME standards for solving complex stress problems.

1971-1974
PINY, Teaching Fellow. Research was based on investigation of a stability criterion to study the dynamic response of some complex nonlinear systems. Carried out experiments to introduce damping into the materials used in the sporting goods fields.

1969-1971
M.I.T., Research Assistant. Developed a yield criterion and an associated flow rule for a porous material with the eventual goal of predicting ductile fracture.

SELECTED PUBLICATIONS:

"Seismic Evaluation of the Brookhaven High Flux Beam Research Reactor," BNL *Technical Report*, December 1979.

"Seismic Analysis of Piping Systems Subjected to Independent Support Excitations by Using Response Spectrum and Time History Methods," *BNL Technical Report No. BNL-NUREG-31296,* April 1982. Also, *Presented at the ASME Summer PVP Conference,* Portland, Oregon, PVP-Vol. 73, June 1983.

"The Assessment of Alternate Procedures for the Seismic Analysis of Multiply Supported Piping Systems," *Proceedings of the 1985 ASME PVP Conference, New Orleans, PVP-Vol. 98.3,* June 1985.

"Seismic Upgrading of the Brookhaven High Flux Beam Research Reactor," *Proceedings of DOE Natural Phenomena Hazards Mitigation Conference, Las Vegas,* October 1985.

"Improving Motor Reliability in Nuclear Power Plants," *NUREG/CR-4939, BNL-NUREG-52031, Vols. 1,2,3,* November 1987. Also, *Proceeding of the 15th WRSM,* October 1987.

"Age-Related Degradation of Westinghouse 480-Volt Circuit Breaker," *NUREG/CR-5280, BNL-NUREG-52178, Vols. 1&2,* November 1990.

"Degradation Modeling with Application to Aging and Maintenance Effectiveness Evaluations," (Co-author), *NUREG/CR-5612, BNL-NUREG-52252,* March 1991.

"Life Testing of a Low Voltage Air Circuit Breaker to Assess Age-Related Degradation", *Nuclear Technology, Vol. 97, pp.362-370,* March 1992.

“Managing Aging in Nuclear Power Plants: Insights from NRC’s Maintenance Team Inspection Reports,” *Nuclear Safety, Vol. 35, No. 1,* January-June 1994.

“Literature Review of Environmental Qualification of Safety-Related Electric Cables,” *NUREG/CR-6384, BNL-NUREG-52480, Vols. 1&2,* April 1996.

“RAPTOR Gas Gun Testing Experiment,” (Co-author) Proprietary, CRADA BNL-C-96-01, June 1998.

"IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant," (Co-author), BNL-65714, September 1998.

"Review of Industry Responses to NRC Generic Letter 97-06 on Degradation of Steam Generator Internals," NUREG/CR-6754, BNL-NUREG-52646, December 2001.

"A Reliability Physics Model for Aging of Cable Insulation Materials," NUREG/CR-6869, BNL-NUREG-73676-2005, March 2005.

"Application of laser generated ultrasonic pulses in diagnostics of residual stresses in welds," Proc. of SPIE, 2005.

"Expert Panel Report on Proactive Material Degradation Assessment," NUREG/CR-6923, BNL-NUREG-77111-2006, February 2007.

Gabriel Taylor, NRC

EDUCATION

The University of Maryland – College Park, MD
Masters of Science in Fire Protection Engineering
Graduated: May 2012
Thesis: *Evaluation of critical nuclear power plant electrical cable response to severe thermal fire conditions*, 2012
Engineer-in-training (EIT) / Fundamentals of Engineering (FE) certificate
(Maryland Reg. No. 38236 – Oct 2009)

The Pennsylvania State University – University Park, PA
Bachelor of Science in Electrical Engineering
Graduated: December 2004

EXPERIENCE

U.S. Nuclear Regulatory Commission – Rockville, MD **11/2007–Present**
Fire Protection Engineer *Office of Nuclear Regulatory Research (RES)*

- Authored NUREG-2128, *Electrical Cable Test Results and Analysis during Fire Exposure (ELECTRA-FIRE)*
- Authored NUREG-1924, *Electric Raceway Fire Barrier Systems in US Nuclear Power Plants*
- Instruct NRC-RES/EPRI fire PRA electrical circuit analysis training
- Witnessed fire testing, analyzed results and wrote test reports
    - Duke Armored cable testing
    - Navy Digital I&C testing
    - Progress Penetration Seal Testing
- International OECD Fire-Events Database and High Energy Arching Fault Task Group
- International OECD Digital Instrumentation and Control Failure Modes Task Group
- Managed DOE work on fire-induced failure circuit testing and conducted supplementary data analysis
- Supported NRR and RES meetings and activities and presentations at numerous conferences
- Presented CAROLFIRE research to Advisory Committee on Reactor Safeguards (ACRS) 2/2008

U.S. Nuclear Regulatory Commission – Rockville, MD **4/2005–10/2007**
NSPDP General Engineer *Office of Nuclear Reactor Regulation*

- Graduate of Nuclear Safety Professional Development Program (NSPDP) Class of 2007
- DORL: Evaluated proposed changes to license amendments in regards to their effect to public safety
- ACRS: Prepared summary report for committee members and assisted with meeting preparations
- RII/Watts Bar Resident Office: Basic inspector qualified IMC 1245 Appendix A

The Pennsylvania State University – University Park, PA 8/2003–2/2004
Undergraduate Research Assistant Semiconductor Spectroscopy Lab Dr. P. M. Lenahan

- Modified magnet power supply to operate correctly using U.S. power system
- Designed data acquisition system to signal average ESR and SDR signals using LabVIEW 7
- Reviewed, ordered, and installed SDR spectroscopy system

OSRAM Sylvania Inc. – St. Marys, PA 1–3/2005 & 1– 8/2003
Process Engineer & Engineering Co-Op (R&D, Process, EH&S, Electrical Departments)

- Developed and conducted tests to examine customer complaints and analyzed the safety of products
- Developed a recycling program to reduce net residual waste and increase gain from recyclable goods
- PLC programming using VersaPro for GE PLC's (Latter-logic)
- Designed and constructed electrical cabinet using AutoCAD (ergonomic layout for operator and maintenance)

ACHIEVEMENT, SKILLS, AND AREAS OF PERSONAL STUDY

Eagle Scout – Troup #95, Bucktail Council
Dean's List – The Pennsylvania State University (Fall 03, Fall04)
Eta Kappa Nu (HKN)-Epsilon Chapter–National Electrical/Computer Engineering Honors Society
Dale Carnegie Program Graduate
Penn State Conservation Leadership School Graduate
Rivers Conservation Leadership School Graduate
Member of IEEE, SFPE, HKN

APPENDIX B
MICROSOFT® EXCEL PIRT PANEL SCORING SHEETS

The PIRT panel scored the influence parameter rankings using numerical scheme consistent with the alphabetical scores presented in Tables 3.1 and 3.2 of this report, as described below:

Score	Letter Scheme		Number Scheme
High	H	=	3
Medium	M	=	2
Low	L	=	1
Uncertain	U	=	0

Two MICROSOFT® EXCEL worksheets represent AC and DC control circuits are presented in the following pages.

AC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 1.1 SPURIOUS ACTUATION of AC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 1.2 SPURIOUS ACTUATION of AC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 1.5 DURATION of Spurious Actuations	Parameter Importance	State of Knowledge
				1.1			1.2			1.3		
1	Conductor Count			1.1.1	**1.00**		1.2.1	**1.00**		1.3.1	**1.00**	
	a. 1	2	N/A		N/A	N/A		1	2		1	2
	b. 2-6	3	3		1	2		1	2		1	2
	c. 7-9	3	3		1	3		1	3		1	3
	d. 10 - 15	3	3		1	2		1	2		1	2
	e. >15	3	3		1	1		1	1		1	1
2	Exposure Condition			1.1.2	**2.00**		1.2.2	**2.00**		1.3.2	**3.00**	
	a. Flame	3	3		2	3		2	3		3	3
	b. Plume	3	3		2	3		2	3		3	3
	c. Hot Gas Layer	2	3		2	3		2	3		3	3
	d. Time/temperature	1	3		2	1		2	1		3	1

AC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 1.1 SPURIOUS ACTUATION of AC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 1.2 SPURIOUS ACTUATION of AC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 1.5 DURATION of Spurious Actuations	Parameter Importance	State of Knowledge
3	Routing / Raceway **(Excluding g. Panel Wiring)**			1.1.3	**1.00**		1.2.3	**1.00**		1.3.3	**1.00**	
	a. Cable Tray Vertical	3	3		1	2		1	2		1	2
	b. Cable Tray Horizontal	3	3		1	3		1	3		1	3
	c. Cables in Horiz. Conduits	3	3		1	3		1	3		1	3
	d. Cables in Vert. Conduits	3	3		1	2		1	2		1	2
	e. Cables in Air Drop Configuration	2	3		1	2		1	2		1	2
	f. Tray type	3	3		1	1		1	1		1	1
	g. Panel wiring	3	2		**3.00**	1		**3.00**	1		**3.00**	1

AC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 1.1 SPURIOUS ACTUATION of AC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 1.2 SPURIOUS ACTUATION of AC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 1.5 DURATION of Spurious Actuations	Parameter Importance	State of Knowledge
4	Raceway Fill **(Excluding d. Bundles)**			1.1.4	**1.00**		1.2.4	**2.00**		1.3.4	**2.00**	
	a. Maximum Loading	3	3		1	2		2	2		2	1
	b. Intermediate Loading	3	3		1	3		2	3		2	2
	c. Minimum Loading (1 or 2 cables)	3	3		1	3		2	3		2	3
	d. Bundles	3	3		**2.00**	3		**2.00**	3		**2.00**	3
5	Insulation Type			1.1.5	**1.00**		1.2.5	**3.00**		1.3.5	**1.00**	
	Insulation Material	3	3		1	3		3	3		1	3
6	Aging	3	3	1.1.6	**1.00**	1	1.2.6	**1.00**	1	1.3.6	**1.00**	1
7	Jacket			1.1.7			1.2.7			1.3.7		
	a. Material	3	3		**1.00**	3		**2.00**	3		**1.00**	3
	b. Coatings	3	3		**1.00**	1		**1.00**	1		**1.00**	1

AC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 1.1 SPURIOUS ACTUATION of AC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 1.2 SPURIOUS ACTUATION of AC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 1.5 DURATION of Spurious Actuations	Parameter Importance	State of Knowledge
8	Time-Current Characteristics:			1.1.8	**1.00**		1.2.8	**1.00**		1.3.8	**3.00**	
	Fuse/breaker size and type	3	2		1	1		1	1		3	1
9	Grounding Cable Configuration			1.1.9	**3.00**		1.2.9	**3.00**		1.3.9	**2.00**	
	a. Drain Wire	1	3		3	2		3	2		2	1
	b. Shield wrap	2	3		3	1		3	1		2	1
10	Voltage level			1.1.10	**1.00**		1.2.10	**1.00**		1.3.10	**1.00**	
	a. < 100vac	1	2		1	1		1	1		1	1
	b. 120vac	3	3		1	3		1	3		1	3
	c. > 150vac	1	2		1	1		1	1		1	1
11	Armor Grounded vs Ungrounded Circuit	3	3	1.1.11	**3.00**	1	1.2.11	**3.00**	1	1.3.11	**2.00**	1

AC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 1.1 SPURIOUS ACTUATION of AC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 1.2 SPURIOUS ACTUATION of AC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 1.5 DURATION of Spurious Actuations	Parameter Importance	State of Knowledge
12	Wiring Configuration			1.1.12	**3.00**		1.2.12	**3.00**		1.3.12	**3.00**	
	a. # of Sources	3	3		3	2		3	2		3	2
	b. # of Targets	3	3		3	2		3	2		3	2
	c. Locations of S & T	3	3		3	2		3	2		3	2
	d. # of Grounds/neutrals	3	3		3	2		3	2		3	2
13	Conductor Size	3	3	1.1.13	**1.00**	2	1.2.13	**1.00**	2	1.3.13	**1.00**	1
14	Suppression			1.1.14	**1.50**		1.2.14	**1.50**		1.3.14	**U**	
	a. Water Spray	3	3		1.5	1		1.5	1		U	1
	b. Hose	3	3		1.5	1		1.5	1		U	1
15	Latching vs Nonlatching Device			1.1.15	**1.00**		1.2.15	**1.00**		1.3.15	**3.00**	
	a. Latching MOV	3	3		1	1		1	1		3	3
	b. Non-Latching MOV	3	3		1	3		1	3		3	3

AC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)												
Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 1.1 SPURIOUS ACTUATION of AC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 1.2 SPURIOUS ACTUATION of AC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 1.5 DURATION of Spurious Actuations	Parameter Importance	State of Knowledge
16	Circuit Grounded vs. Ungrounded	2	3	1.1.16	**1.00**	2	1.2.16	**3.00**	2	1.3.16	**2.00**	1

DC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 2.1 SPURIOUS ACTUATION of DC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.2 SPURIOUS ACTUATION of DC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.3 INTER-CABLE GROUND FAULT EQUIVALENT SPURIOUS ACTUATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 2.4 DURATION OF SPURIOUS ACTUATION	Parameter Importance	State of Knowledge
				2.1			2.2			2.3			2.4		
1	Conductor Count			2.1.1	**1.00**		2.2.1	**1.00**		2.3.1	**1.00**		2.4.1	**1.00**	
	a. 1	2	N/A		N/A	N/A		1	2		1	2		1	2
	b. 2-6	3	3		1	2		1	2		1	2		1	2
	c. 7-9	3	3		1	3		1	3		1	3		1	3
	d. 10 - 15	3	3		1	2		1	2		1	2		1	2
	e. >15	3	3		1	1		1	1		1	1		1	1
2	Exposure Condition			2.1.2	**2.00**		2.2.2	**2.00**		2.3.2	**2.00**		2.4.2	**3.00**	
	a. Flame	3	3		2	3		2	3		2	3		3	3
	b. Plume	3	3		2	3		2	3		2	3		3	3
	c. Hot Gas Layer	2	3		2	3		2	3		2	3		3	3
	d. Time/temperature	1	3		2	1		2	1		2	1		3	1

DC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 2.1 SPURIOUS ACTUATION of DC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.2 SPURIOUS ACTUATION of DC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.3 INTER-CABLE GROUND FAULT EQUIVALENT SPURIOUS ACTUATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 2.4 DURATION OF SPURIOUS ACTUATION	Parameter Importance	State of Knowledge
3	Routing / Raceway **(excluding f. Panel Wiring)**			2.1.3	**1.00**		2.2.3	**1.00**		2.3.3	**1.00**		2.4.3	**1.00**	
	a. Cable Tray Vertical	3	3		1	2		1	1		1	1		1	1
	b. Cable Tray Horizontal	3	3		1	3		1	3		1	3		1	3
	c. Cables in Horiz. Conduits	3	3		1	3		1	2		1	2		1	2
	d. Cables in Vert. Conduits	3	3		1	2		1	1		1	1		1	1
	e. Cables in Air Drop Configuration	2	3		1	2		N/A	N/A		N/A	N/A		1	1
	f. Tray type	3	3		1	1		1	1		1	1		1	1
	g. Panel Wiring	3	2		**3.00**	1		**3.00**	1		**2.00**	1		**3.00**	1
4	Raceway Fill **(Excluding d. Bundles)**			2.1.4	**1.00**		2.2.4	**2.00**		2.3.4	**1.00**		2.4.4	**1.00**	
	a. Maximum Loading	3	3		1	2		2	1		1	1		1	1
	b. Intermediate Loading	3	3		1	3		2	3		1	3		1	3
	c. Minimum Loading (1 or 2 cables)	3	3		1	3		2	3		2	3		2	3
	d. Bundles	3	3		**1.00**	3		**2.00**	2		**2.00**	2		**2.00**	2

DC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 2.1 SPURIOUS ACTUATION of DC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.2 SPURIOUS ACTUATION of DC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.3 INTER-CABLE GROUND FAULT EQUIVALENT SPURIOUS ACTUATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 2.4 DURATION OF SPURIOUS ACTUATION	Parameter Importance	State of Knowledge
5	Insulation Type			2.1.5	1.00		2.2.5	3.00		2.3.5	1.00		2.4.5	2.00	
	Insulation Material	3	3		1	3		3	3		1	2		2	3
6	Aging	3	3	2.1.6	1.00	1	2.2.6	1.00	1	2.3.6	1.00	1	2.4.6	1.00	1
7	Jacket			2.1.7	1.00		2.2.7	2.00		2.3.7	1.00		2.4.7	1.00	
	a. Material	3	3		1	3		2	3		1	3		1	3
	b. Coatings	3	3		1	1		1	1		1	1		1	1
8	Time-Current Characteristics:			2.1.8	1.00		2.2.8	1.00		2.3.8	1.00		2.4.8	3.00	
	Fuse/breaker size and type	3	3		1	1		1	1		1	2		3	3
9	Grounding Cable Configuration			NOT APPLICABLE			NOT APPLICABLE			NOT APPLICABLE			NOT APPLICABLE		
10	Voltage level			NOT APPLICABLE			NOT APPLICABLE			NOT APPLICABLE			NOT APPLICABLE		
11	Armor vs. Unarmored	2	3	2.1.11	1.00	1	2.2.11	3.00	1	2.3.11	3.00	1	2.4.11	2.00	1

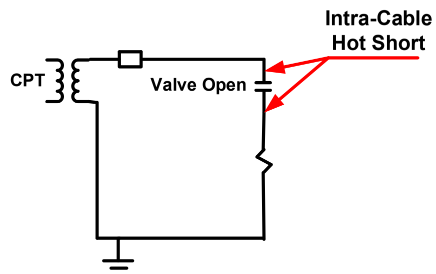
DC CONTROL CIRCUITS PANEL MEMBER: Panel Consensus (Cont'd.)

Identification	INFLUENCING PARAMETERS	Parameter Applicability	Research Ease Ranking	Effect of Parameters on the Likelihood -- 2.1 SPURIOUS ACTUATION of DC control circuit - INTRA-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.2 SPURIOUS ACTUATION of DC control circuit - INTER-CABLE short	Parameter Importance	State of Knowledge	Effect of Parameters on the Likelihood -- 2.3 INTER-CABLE GROUND FAULT EQUIVALENT SPURIOUS ACTUATION	Parameter Importance	State of Knowledge	Effect of Parameters on the Plant Cable Configuration -- 2.4 DURATION OF SPURIOUS ACTUATION	Parameter Importance	State of Knowledge
12	Wiring Configuration			2.1.12	3.00		2.2.12	3.00		2.3.12	3.00		2.4.12	3.00	
	a. # of Sources	3	3		3	2		3	2		3	2		3	2
	b. # of Targets	3	3		3	2		3	2		3	2		3	2
	c. Locations of S & T	3	3		3	2		3	2		3	2		3	2
	d. # of Grounds/neutrals	3	3		3	2		3	2		3	2		3	2
13	Conductor Size	3	3	2.1.13	1.00	2	2.2.13	1.00	2	2.3.13	1.00	2	2.4.13	1.00	1
14	Suppression			2.1.14	1.50		2.2.14	1.50		2.3.14	2.00		2.4.14	U	
	a. Water Spray	3	3		1.5	1		1.5	1		2	1		U	1
	b. Hose	3	3		1.5	1		1.5	1		2	1		U	1
15	Latching vs Nonlatching Device			2.1.15	1.00		2.2.15	1.00		2.3.15	1.00		2.4.15	3.00	
	a. Latching MOV	3	3		1	1		1	1		1	1		3	3
	b. Non-Latching MOV	3	3		1	3		1	3		1	1		3	3

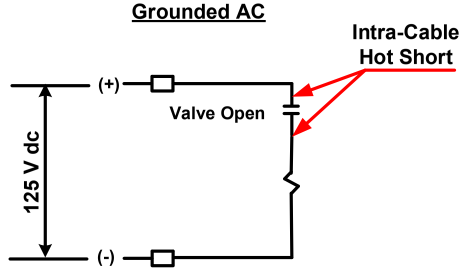
APPENDIX C
CONTROL CIRCUIT CONFIGURATIONS FOR SINGLE AND DOUBLE BREAK DESIGNS

During the PIRT panel meetings, the use of circuit diagrams and physical circuit configuration layouts became more common to be drawn on white boards to assist with the discussion of numerous issues and to assist in understanding how various parameters affect the likelihood of hot short-induced spurious operations. Furthermore, the PIRT panel determined that providing these circuit diagrams and physical layout illustrations to be valuable for the reader of the report and the follow-on expert elicitation by the PRA panel. Thus, the following pages provide simplified schematic configuration and physical configuration illustrations, along with specific notes on the configuration to assists the reader of this report. The list is meant to represent the pool of circuit designs that the PIRT panel determined to be important for discussions and development of conditional spurious operation probabilities, but is not meant to be exhaustive or representative of detailed circuit diagrams common to US NPPs. The diagrams for the eight specific cases are presented in the following order:

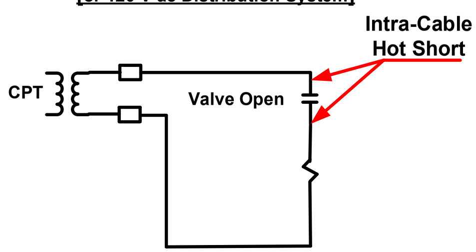
Case 1: Single contact Intra-cable hot short-induced spurious operation
Case 2: Single contact Inter-cable hot short-induced spurious operation
Case 3: Single contact Inter-cable hot short-induced spurious operation via a ground plane interaction from cables in the same or different raceway
Case 4: Double contact – one Intra-cable and one Inter-cable hot short-induced spurious operation
Case 5: Double contact – two Inter-cable hot short-induced spurious operations
Case 6: Double contact – two Intra-cable hot short-induced spurious operations
Case 7: Double contact – Intra (+) and ground fault hot short (-) – induced spurious operation
Case 8: Double contact – Inter (+) and ground fault hot short (-) – induced spurious operation



Grounded AC

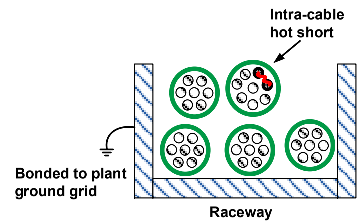


Ungrounded DC
[or 120 V ac Distribution System]



Ungrounded AC

Simplified Schematic Configuration – Single Break Control Circuit

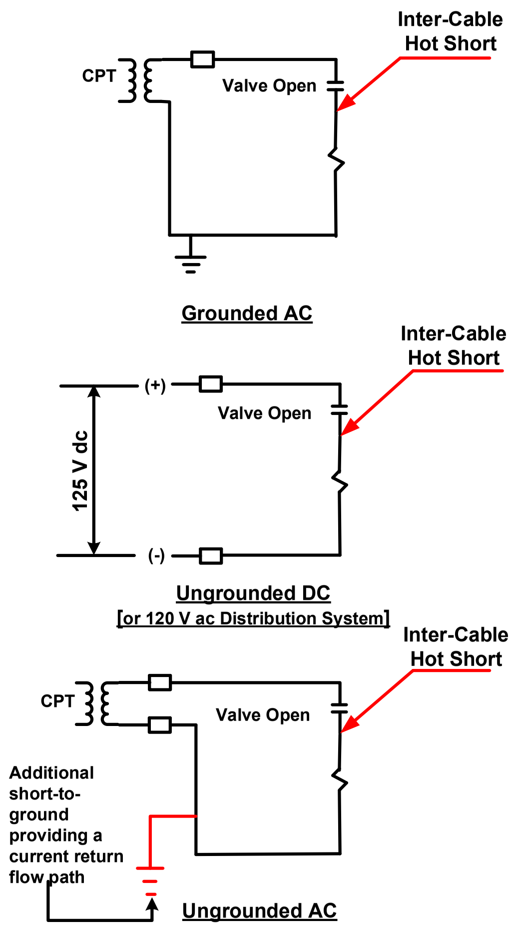


Physical Configuration

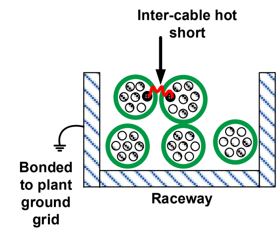
Notes:

1. Component is energize to open.
2. A fire-induced intra-cable hot short will open the component.
   a. If the component is a latching circuit, the component will remain open even if the intra-cable hot short is eliminated, e.g., goes to ground.
   b. If the component is a non-latching circuit, the component will close when the intra-cable hot short is eliminated, e.g., goes to ground.
   c. If power is lost to the control circuit by blowing the control power fuses or by a failure of the power supply to the fuses, the component will close regardless of whether or not it is a latching or non-latching circuit.
3. The behavior described on this drawing is typical of an intra-cable hot short from a conductor within the same circuit. If the intra-cable hot short is from a conductor in the same cable, but from a different circuit, the behavior will be governed more by the characteristics described for the inter-cable hot short in Case 2.

Case 1 – Single Contact Intra-Cable Hot Short – Induced Spurious Operation



Simplified Schematic Configuration – Single Break Control Circuit

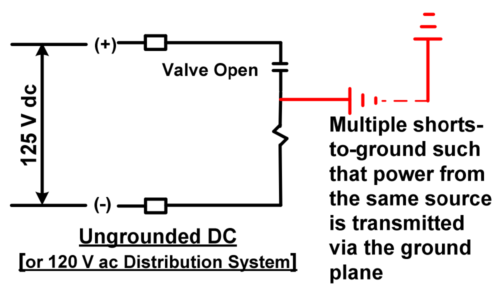


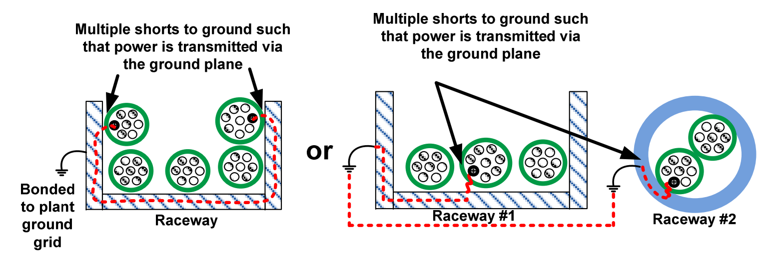
Physical Configuration

Notes:

1. Component is energize to open.
2. A fire-induced inter-cable hot short will open the component.
   a. If the component is a latching circuit, the component will remain open even if the inter-cable hot short is eliminated, e.g., goes to ground.
   b. If the component is a non-latching circuit, the component will close when the inter-cable hot short is eliminated, e.g., goes to ground.
   c. If power is lost to the control circuit by blowing the control power fuses on the aggressor circuit or by a failure of the power supply to the fuses in either the primary or aggressor circuit, the component will close regardless of whether or not it is a latching or non-latching circuit.
3. For the case of the ungrounded DC or ungrounded distributed AC circuit, the inter-cable hot short must come from the same battery source. This is required since an inter-cable hot short from a different battery source will not have a current return flow path.
4. For the case of the ungrounded AC circuit power from a CPT, the inter-cable hot short must be accompanied by a short to ground on the negative leg of the circuit providing a current return flow path to the power source of the aggressor circuit. If the aggressor circuit is an ungrounded AC source off of a CPT, the aggressor circuit will also require a ground on the negative leg to complete the circuit and cause the spurious operation.
5. For the case of the grounded AC circuit powered from a CPT, if the aggressor circuit is an ungrounded AC source off of a CPT, the aggressor circuit will also require a ground on the negative leg to complete the circuit and cause the spurious operation.

Case 2 – Single Contact Inter-Cable Hot Short – Induced Spurious Operation





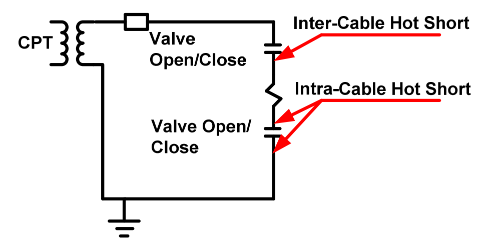
Simplified Schematic Configuration – Single Break Control Circuit

Physical Configuration

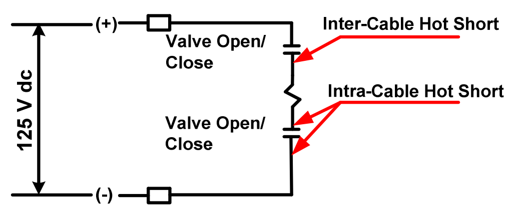
Notes:

1. Component is energize to open.
2. A fire-induced hot short can open the component.
   a. If the component is a latching circuit, the component can remain open even if the hot short is eliminated.
   b. If the component is a non-latching circuit, the component will close when the hot short is eliminated.
   c. If power is lost to the control circuit by blowing the control power fuses or by a failure of the power supply to the fuses, the component will close regardless of whether or not it is a latching or non-latching circuit.
3. For the case of the ungrounded DC or an ungrounded AC distribution system circuit, the ground equivalent hot short hot short must come from the same battery source. This is required since a ground fault equivalent hot short from a different battery source will not have a current return flow path.

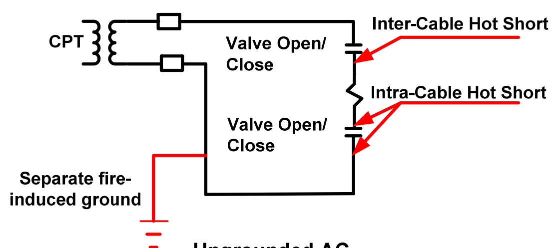
Case 3 – Single Contact Inter-Cable Hot Short – Induced Spurious Operation via a ground plane interaction from cables in the same or different raceway



Grounded AC

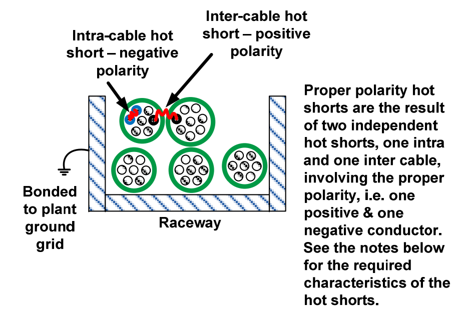


Ungrounded DC
[or 120 V ac Distribution System]



Ungrounded AC

Schematic Configuration – Double Break Control Circuit

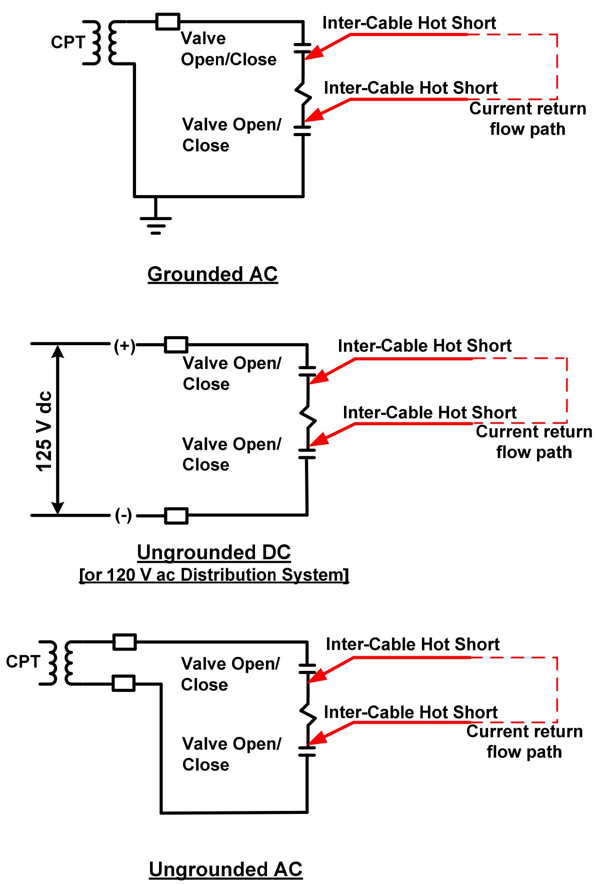


Physical Configuration

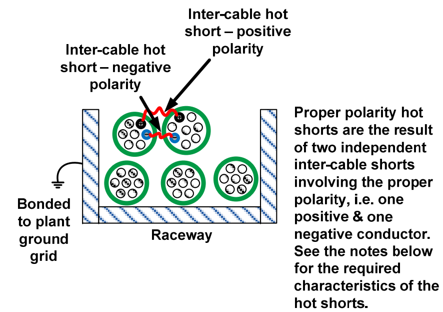
Notes:

1. The component is energized to either open or close a respective valve.
2. The double break design requires two hot shorts to energize the component.
3. A fire-induced inter-cable + an intra-cable hot short will energize the component.
   a. If either hot short is eliminated, the component will de-energize and the affected component will return to its original position.
   b. If power is lost to the control circuit by blowing the control power fuses or by a failure of the power supply to the fuses, the component will de-energize and the affected component will return to its original position.
3. For the case of the ungrounded DC or the ungrounded AC distribution system circuit, the inter-cable hot short must come from the same battery source. This is required since an inter-cable hot short from a different battery source will not have a current return flow path.
4. For the case of the ungrounded AC circuit powered from a CPT, the inter-cable hot short must come from a separate and compatible ac source. If the aggressor circuit is an ungrounded AC circuit powered from a CPT, the aggressor circuit must also experience a fire-induced ground on its negative leg to provide a ground path for the return current. Additionally the target circuit must also be accompanied by a fire-induced short to ground on its negative leg providing a current return flow path. In summary, for the case of an ungrounded AC circuit powered from a CPT attacked by another ungrounded AC circuit powered from a CPT, for the spurious operation to occur, a third hot short, i.e., a ground equivalent hot short, must occur.
5. For the case of the grounded AC circuit powered from a CPT, the inter-cable hot short must come from a separate and compatible ac source. If the aggressor circuit is an ungrounded AC circuit powered from a CPT, the aggressor circuit must experience a fire-induced ground on its negative leg to provide a flow path through the ground plane for the return current.
6. The behavior described on this drawing for the intra-cable hot short is typical of an intra-cable hot short from a conductor within the same circuit. If the intra-cable hot short is from a conductor in the same cable, but from a different circuit, the behavior will be governed more by the characteristics described for the inter-cable hot short in Case 5.

Case 4 – Double Break - One Intra and One Inter-Cable Hot Short – Induced Spurious Operation.



Schematic Configuration – Double Break Control Circuit



Physical Configuration

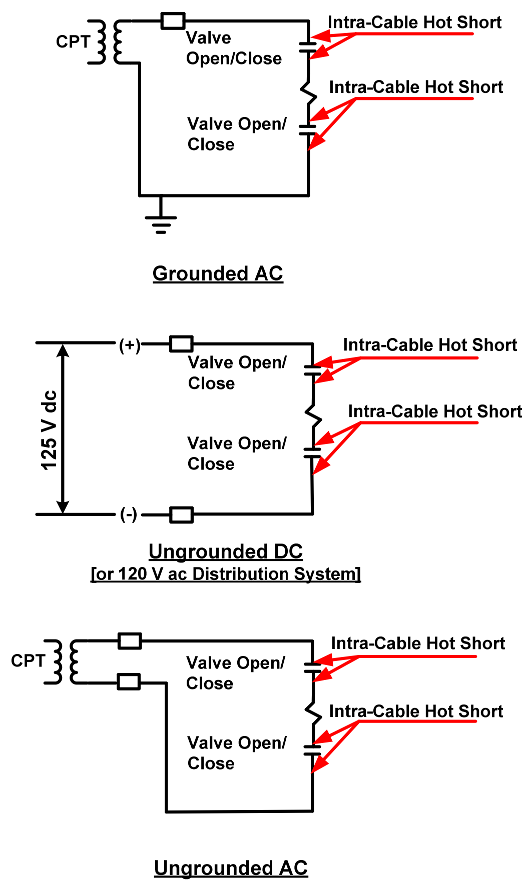
Notes:

1. The component is energized to either open or close a respective valve.
2. The double break design requires two hot shorts to energize the component.
3. Two fire-induced inter-cable hot shorts will energize the component.
   a. If either hot short is eliminated, the solenoid will de-energize and the affected component will return to its original position.
   b. If power is lost to the control circuit by blowing the control power fuses or by a failure of the power supply to the fuses, the component will remain energized since the hot shorts are powered from a separate circuit.
   c. If power is lost to the circuit for the aggressor cables, the component will de-energize and the affected component will return to its original position.

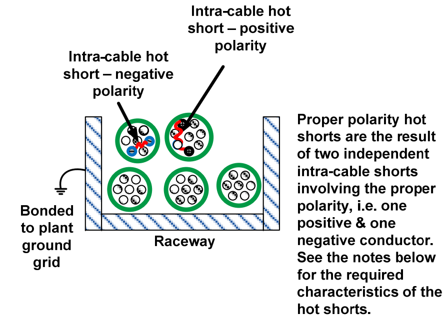
3. For all cases aggressor cables must be from a compatible ungrounded source, i.e., a common source providing both the positive and negative legs so that the current will have a flow path to the same power source.

4. For the grounded or ungrounded AC case, if the aggressor circuit is a grounded AC circuit, then a single ground on the underside of the coil is sufficient to cause a spurious operation.

Case 5 – Double Break - Two Inter-Cable Hot Shorts – Induced Spurious Operation.



Schematic Configuration – Double Break Control Circuit

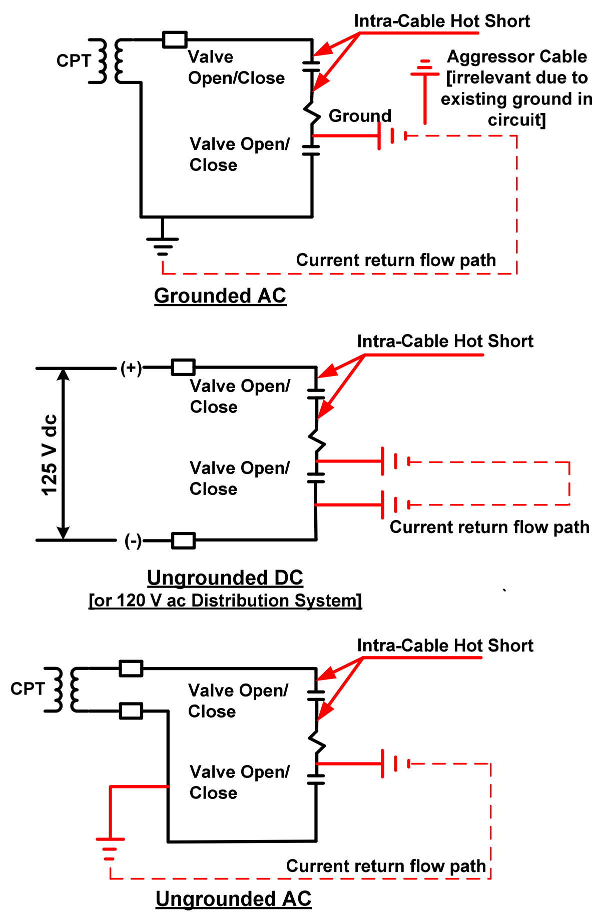


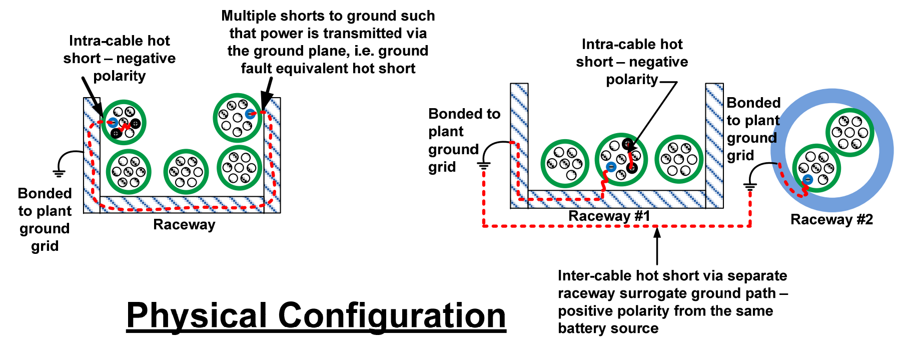
Physical Configuration

Notes:

1. The component is energized to either open or close a respective valve.
2. The double break design requires two hot shorts to energize the component.
3. Two fire-induced intra-cable hot shorts will energize the component.
   a. If either hot short is eliminated, the component will de-energize and the affected component will return to its original position.
   b. If power is lost to the control circuit by blowing the control power fuses or by a failure of the power supply to the fuses, the component will de-energize and the affected component will return to its original position.
4. The behavior described on this drawing is typical of intra-cable hot shorts from conductors within the same circuit. If the intra-cable hot shorts are from conductors in the same cable, but from a different circuit, the behavior will be governed more by the characteristics described for the inter-cable hot short in Case 5.

Case 6 – Double Break - Two Intra-Cable Hot Shorts – Induced Spurious Operation.





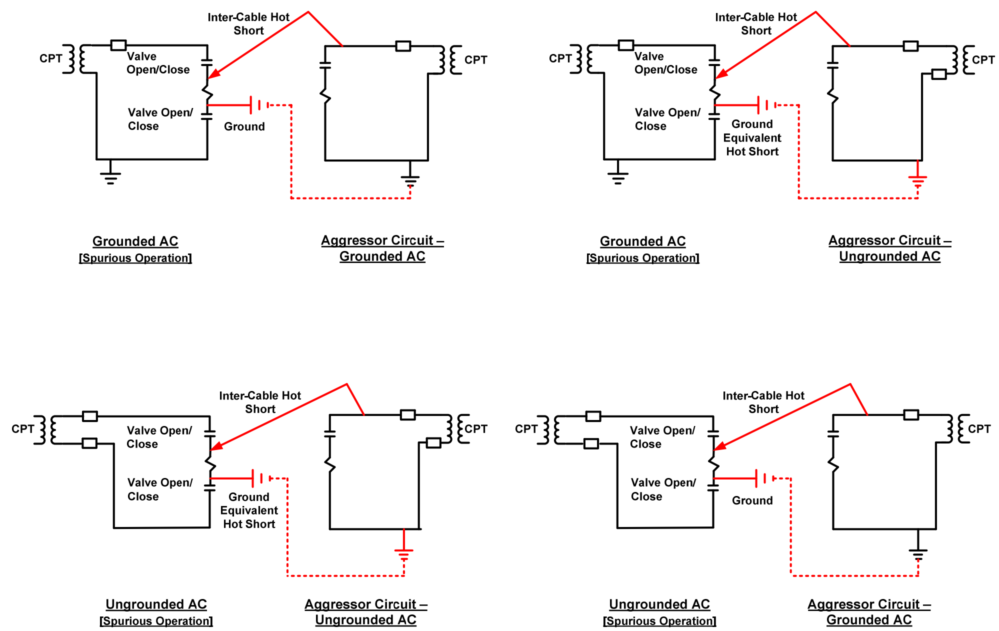
Physical Configuration

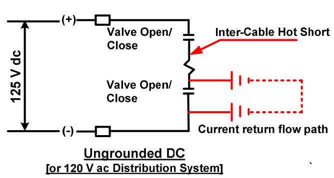
Notes:

1. The component is energized to either open or close a respective valve.
2. The double break design requires two hot shorts to energize the component.
3. A fire-induced intra-cable + a ground equivalent hot short will energize the component.
   a. If either hot short is eliminated, the component will de-energize and the affected component will return to its original position.
   b. If power is lost to the control circuit by blowing the control power fuses or by a failure of the power supply to the fuses, the component will de-energize and the affected component will return to its original position.
3. For the case of the ungrounded DC or an AC ungrounded distribution system circuit, the ground equivalent hot short must include a ground on the negative leg of a circuit from the same battery source. This is required since a ground equivalent hot short from a different battery source will not have a current return flow path. The orientation of the two types of hot shorts, i.e., either above or below the coil, has no impact on the spurious operation of this circuit.
4. For the case of the ungrounded AC circuit powered from a CPT, the ground equivalent hot short must include a short to ground on the negative leg of the ungrounded AC circuit providing a current return flow path. The orientation of the two types of hot shorts, i.e., either above or below the coil, has no impact on the spurious operation of this circuit.
5. For the case of the grounded AC circuit powered from a CPT, only an intra-cable hot short and a ground is required for the spurious operation to occur. The aggressor cable for the ground equivalent hot short is irrelevant due to the ground that already exists within the grounded circuit. The existing circuit ground on the negative leg of the circuit provides a current return flow path. The orientation of the two types of hot shorts, i.e., either above or below the coil, does have an impact on the spurious operation of this circuit. With the ground fault hot short above the coil, the positive leg of the ground equivalent hot short will blow a fuse and no spurious operation will occur.
6 The behavior described on this drawing is typical of an intra-cable hot short from a conductor within the same circuit. If the intra-cable hot short is from a conductor in the same cable, but from a different circuit, the behavior will be governed more by the characteristics described for the inter-cable hot short in Case 8.

Schematic Configuration – Double Break Control Circuit

Case 7 – Double Break - Intra (+) and Ground Fault Equivalent Hot Short (-) – Induced Spurious Operation.

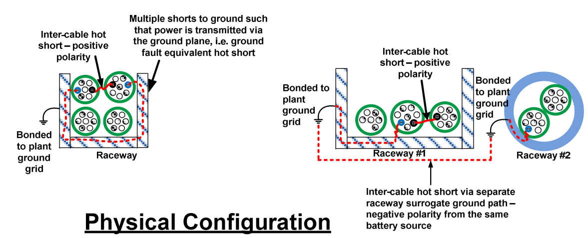




Schematic Configuration – Double Break Control Circuit

Notes:

1. The component is energized to either open or close a respective valve.
2. Except as noted below, the double break design requires two hot shorts to energize the component.
3. Except as noted below, a fire-induced inter-cable + a ground equivalent hot short will energize the component.
   a. If either hot short is eliminated, the component will de-energize and the affected component will return to its original position.
   b. If power is lost to the control circuit by blowing the control power fuses on the aggressor circuit or by a failure of the power supply to the fuses on the aggressor circuit, the component will de-energize and the affected component will return to its original position.
3. For the case of the ungrounded DC or an ungrounded AC distribution system circuit, the inter-cable hot short and the negative leg of the ground equivalent hot short must come from the same battery source. This is required since hot shorts from a different battery source will not have a current flow path. The orientation of the two types of hot shorts, i.e., either above or below the coil, has no impact on the spurious operation of this circuit.
4. For the case of the ungrounded AC circuit powered from a CPT, the aggressor circuit can be either a grounded or an ungrounded AC circuit. In either case, the inter-cable and negative leg of the ground equivalent hot short must be from the same AC circuit powered from the same CPT. This assures the availability of a current flow path through the aggressor circuit. If the aggressor circuit is a grounded AC circuit, then all that is required is a ground below the solenoid, since the ground in the aggressor circuit will provide the current flow path. The orientation of the two types of hot shorts, i.e., either above or below the coil, does have an impact on the spurious operation of this circuit, if the aggressor circuit is an grounded AC circuit. With the ground fault hot short above the coil, the positive leg of the ground equivalent hot short in the aggressor circuit will blow the fuse in the aggressor circuit and no spurious operation will occur.
5. For the case of the grounded AC circuit powered from a CPT, the aggressor circuit can be either a grounded or an ungrounded AC circuit. In either case, the inter-cable and negative leg of the ground equivalent hot short must be from the same AC circuit powered from the same CPT. This assures the availability of a current flow path through the aggressor circuit. If the aggressor circuit is a grounded AC circuit, then all that is required is a ground below the solenoid, since the ground in the aggressor circuit will provide the current flow path. The orientation of the two types of hot shorts, i.e., either above or below the coil, does have an impact on the spurious operation of this circuit, if the aggressor circuit is a grounded AC circuit. With the ground fault hot short above the coil, the positive leg of the ground equivalent hot short in the aggressor circuit will blow the fuse in the aggressor circuit and no spurious operation will occur.



Physical Configuration

Case 8 – Double Break - Inter (+) and Ground Fault Equivalent Hot Short (-) – Induced Spurious Operation.

CONTROL CIRCUIT CONFIGURATIONS FOR SINGLE AND DOUBLE BREAK DESIGNS

APPENDIX D
SELECTED PRESENTATION VIEWGRAPHS

During the first PIRT meeting held during November 2010, BNL presented to the PIRT panel the results of the EPRI/NEI and the NRC/SNL cable testing programs. In addition, BNL presented the project's overall objectives, and an approach to achieve these objectives in order to start the discussion among the PIRT panel members. This appendix includes a selected number of these presentations.

EPRI/NEI OMEGA POINT CABLE FIRE TESTS (EPRI Test Report 1003326 and Expert Elicitation Report 1006961)

SPURIOUS ACTUATION OF ELECTRICAL CIRCUITS DUE TO CABLE FIRES

Mano Subudhi
Brookhaven National Laboratory
November 2010

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

EPRI/NEI OMEGA POINT CABLE FIRE TESTS

- A total of 18 tests - all followed a common pattern
- Test rig with test cables located several feet above the floor – distance was varied
- Test cables (control cables only) in cable trays (including two in vertical configuration and one in air-drop configuration) or conduits
- Both single- and multiple-conductor cables energized with 120 VAC
- SCDU – MOV motor starter control circuit and IRMS – insulation resistance monitored
- Thermocouples located adjacent to the electrically monitored cables, in cable trays, and in test room
- Measurements included voltage, current, electrical impedance of selected cables
- Fire HRR (70 – 450 kW) through fuel flow rate approximation

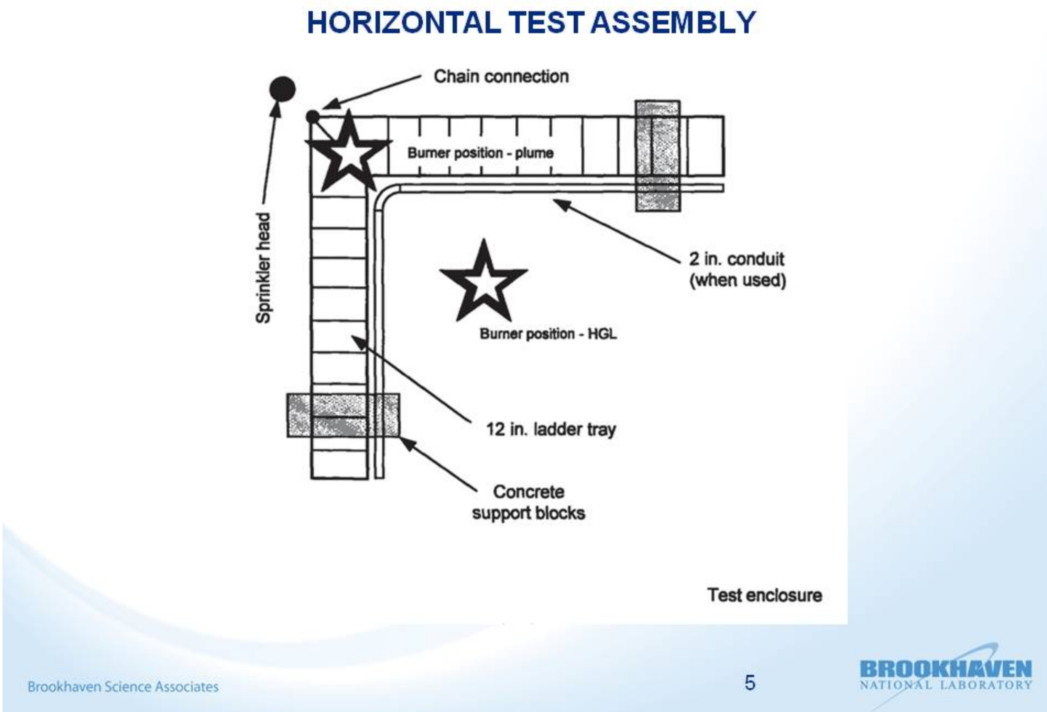
Brookhaven Science Associates 2 BROOKHAVEN NATIONAL LABORATORY

OMEGA POINT TEST SET-UP CAPABILITY

- To ascertain fire-induced cable failures
  - Short to ground
  - Short to another cable (inter-cable)
  - Short to another conductor (intra-cable)
  - Open circuit
- Circuit measurements to ascertain failure mode (i.e., a spurious actuation of the circuit and/or blown protective fuses)
- Each test ran for a predetermined time, some extended until cable damage was observed
- Over half of the 18 tests with cables directly in the fire plume and for a half-dozen tests with cables in hot gas but out of the plume
- Water spray used at the end of the test

OMEGA POINT CABLE FIRE TEST OBJECTIVES

- Cable failures
  - TS cables versus TP cables
  - Effect of armored cable
  - Cable trays versus conduits
  - Plume versus hot gas layer effect
  - Cable tray fill and location within the tray
  - Horizontal and vertical cable trays, air drop configuration
  - Water spray impact
- Spurious actuations
  - Hot shorts in multi-conductor control cables (intra-cable shorts)
  - Hot shorts in cable-to-cable (inter-cable)
  - Multiple spurious actuations
  - Shorts to ground versus hot shorts
  - Influence of CPT
  - Influence of cable/circuit electrical configuration
- Cable Monitoring
  - Open circuits
  - IR in damaged cable
  - V and I values in damaged cable


HORIZONTAL TEST ASSEMBLY
Chain connection
Sprinkler head
Burner position - plume
2 in. conduit (when used)
Burner position - HGL
12 in. ladder tray
Concrete support blocks
Test enclosure
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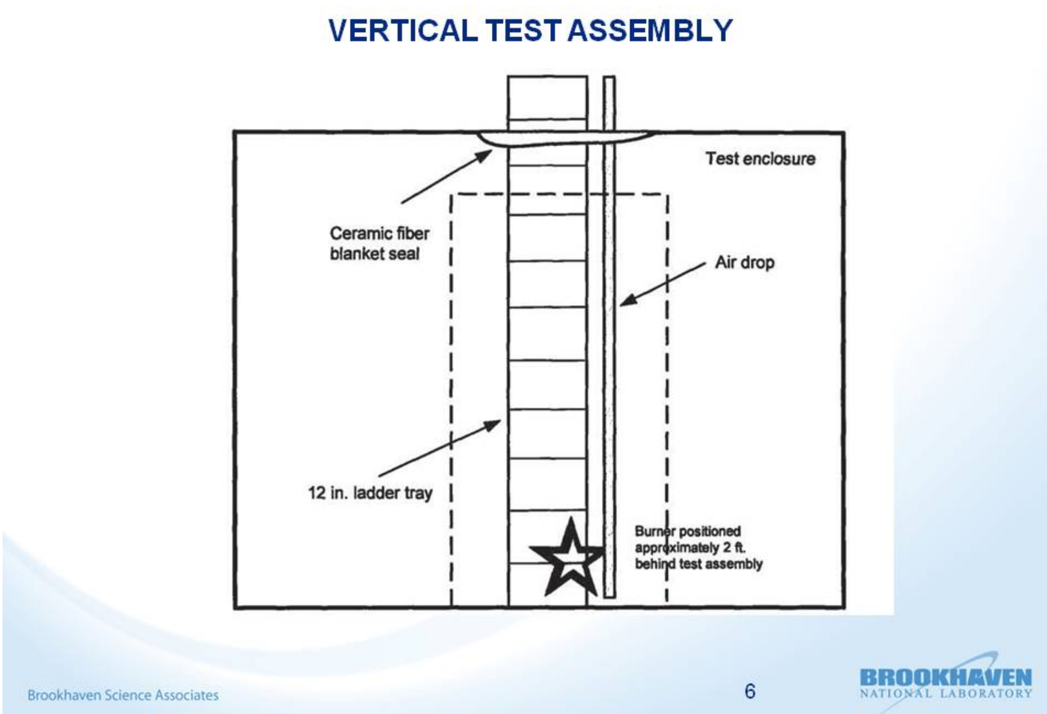
VERTICAL TEST ASSEMBLY
Test enclosure
Ceramic fiber blanket seal
Air drop
12 in. ladder tray
Burner positioned approximately 2 ft. behind test assembly
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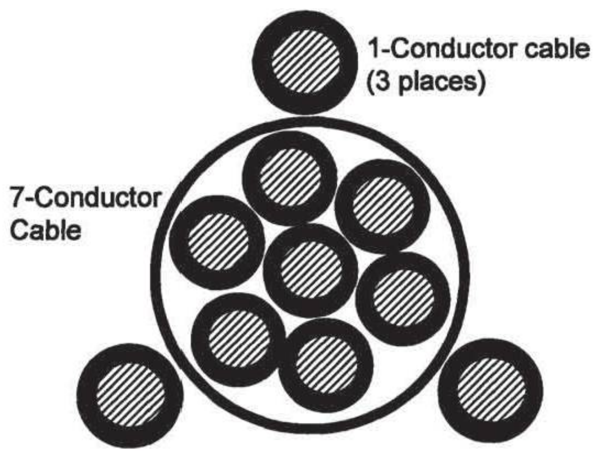
CABLE BUNDLE CONFIGURATION



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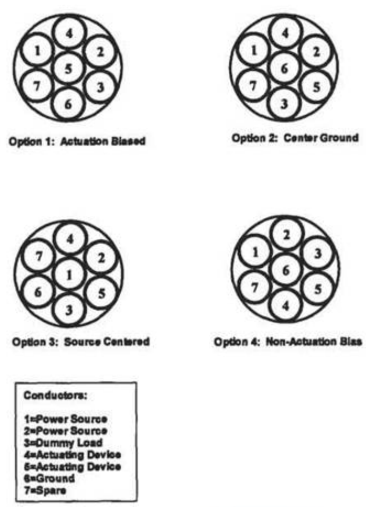
CONDUCTOR CONNECTION PATTERNS



AB – Actuation Biased

CG – Center Ground

SC – Source Centered

NAB – Non-Actuation Biased

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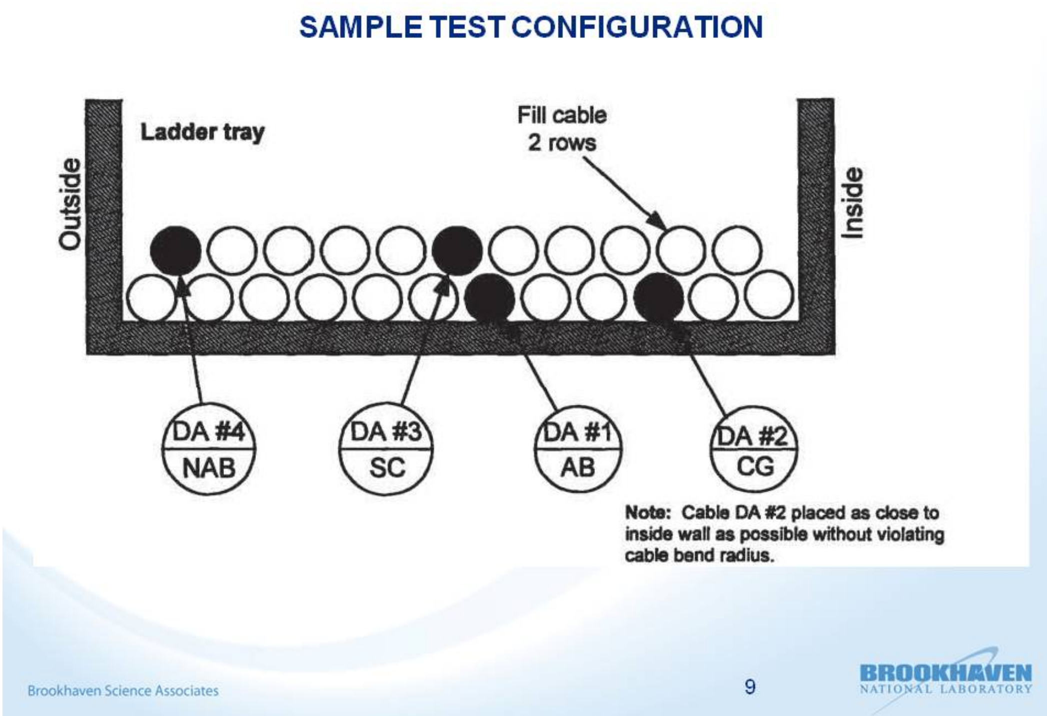
SAMPLE TEST CONFIGURATION
Ladder tray
Fill cable
2 rows
Outside
Inside
DA #4
NAB
DA #3
SC
DA #1
AB
DA #2
CG
Note: Cable DA #2 placed as close to inside wall as possible without violating cable bend radius.
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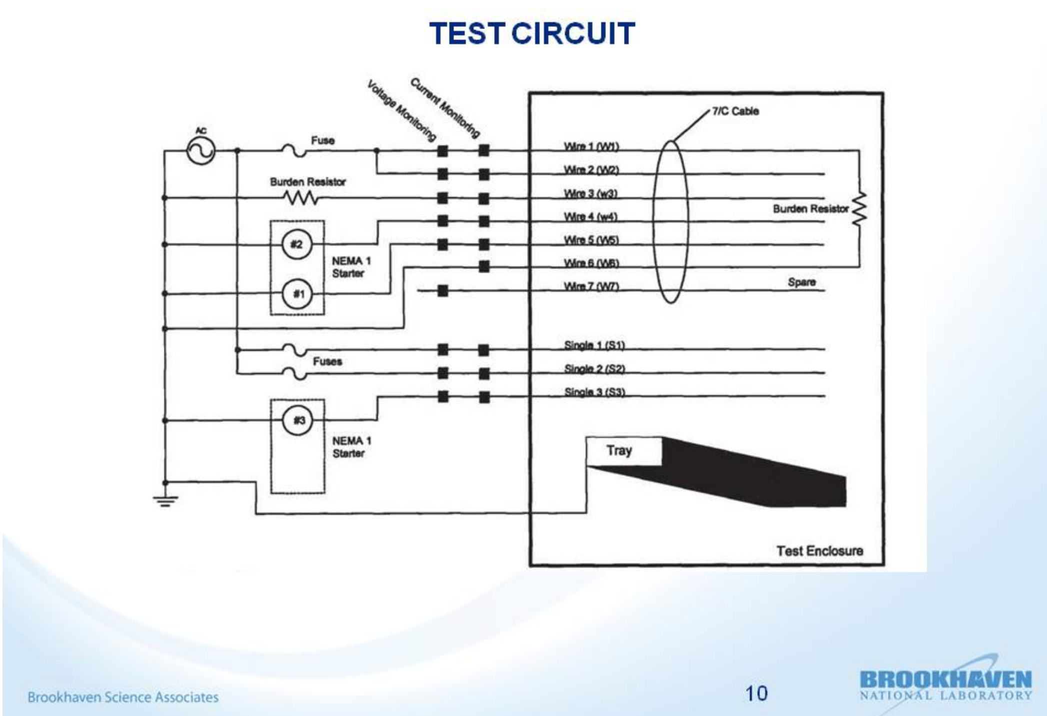
TEST CIRCUIT
AC
Fuse
Voltage Monitoring
Current Monitoring
7/C Cable
Burden Resistor
Wire 1 (W1)
Wire 2 (W2)
Wire 3 (w3)
Wire 4 (w4)
Wire 5 (W5)
Wire 6 (W6)
Wire 7 (W7)
Burden Resistor
Spare
#2
#1
NEMA 1
Starter
Fuses
Single 1 (S1)
Single 2 (S2)
Single 3 (S3)
#3
NEMA 1
Starter
Tray
Test Enclosure
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OMEGA POINT CABLE FIRE TEST GROUPS

- **Group 0:** Test Numbers 1 and 13; Four 8/C armored XLPE cables placed among two rows of filler cable within a 12-inch horizontal ladder tray
- **Group 1:** Test Numbers 2, 3, 5, 7 and 15; TS cables, HRR and type of exposure varied and the horizontally mounted ladder tray with two rows of fill cables held constant
- **Group 2:** Test Numbers 8, 9, 11 and 12; Same as Group 1 with constant HRR at 145 kW and test configuration varied
- **Group 3:** Test Numbers 4, 6 and 16; TP cables with HRR and test configuration varied
- **Group 4:** Test Numbers 10 and 17; TS and TS/TP cables mounted in a vertical (including air-drop) orientation
- **Group 5:** Test Numbers 14 and 18; Cable-to-cable interaction tests, No SCDU used, instead 3 specific monitoring circuits are used

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OMEGA POINT CABLE FIRE TEST MATRIX

Test Number	Cable Type	No of Conductors	Raceway Type	Tray Fill Rows	Fire Intensity (kW)	Exposure Mode	CPTs Used?	Cable Failure Leading to Spurious Device Actuations
1	Armored TS	8	Horizontal tray	2	350	Hot Gas	No	At least one device actuation
2	TS	7	Horizontal tray	2	70	Plume	No	No Failure
3	TS	7	Horizontal tray	2	145	Plume	No	At least one device actuation
4	TP	7	Horizontal tray	2	145	Plume	No	At least one device actuation
5	TS	7	Horizontal tray	2	200	Hot Gas	No	No Failure
6	TP	7	Horizontal tray	2	200	Hot Gas	No	At least one device actuation
7	TS	7	Horizontal tray	2	350	Hot Gas	No	At least one device actuation
8	TS	7	Horizontal tray & conduit	3	145	Plume	No	At least one device actuation
9	TS	7	Horizontal tray	1	145	Plume	No	At least one device actuation
10	TS	7	Vertical tray & Air Drop	1	200	Hot Gas/ Radiation	No	At least one device actuation
11	TS	7	Horizontal tray	4	145	Plume	No	Failed but no device actuation
12	TS	7	Horizontal tray & Conduit	1	145	Plume	Yes	At least one device actuation
13	Armored TS	8	Horizontal tray	2	350	Hot Gas	Yes	Failed but no device actuation
14	TS	7	Horizontal tray	Partial	145/150	Plume	No	Internal shorts before C-to-C short. No device connection
15	TS	7	Horizontal tray & conduit	1	350/200/450	Hot Gas	Yes	At least one device actuation
16	TP	9	Horizontal tray & conduit	2	145	Plume	Yes	At least one device actuation
17	TS & TP	9	Vertical tray	1	200	Hot Gas/ Radiation	Yes	At least one device actuation
18	TS	7	Horizontal tray	Partial	250	Hot Gas	No	Internal shorts before C-to-C short. No device connection

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OMEGA POINT CABLE FIRE TEST RESULTS

- **Cable failure stages:** First – IR and electrical properties degrade without affecting the cable function; Second – Rapid degradation of IR and electrical properties causing short duration (minutes to tens of minutes) cable failures; and Third – IR and electrical properties drop to too low (IR less than 1000 ohms) leading to cable failure
- **Hot short:** A transient phenomenon associated with a cable damage between an energized conductor and another conductor within the same cable (intra-cable) or in another co-located cable (inter-cable), rather than a short to ground or an open circuit. Sooner or later (and usually sooner), either a high electrical current will cause a fuse blow or breaker trip, or there will be high-current burn-out causing a short to ground.
- **Spurious Actuation:** An undesired electric connection between one energized conductor (aka. Source) and a second conductor (aka. Target) that may or may not be energized.

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

- An energized 7/C TS un-armored cable on a horizontal tray along with a single layer of 1/C and 7/C cables, with electrical circuit connection through a CPT and exposed to hot gas layer of a gradual heat-up fire
  - Cable failures
    - Small cables are more likely to fail at slightly lower temperatures than larger cables
    - Cables in loaded tray fail at slightly different temperatures depending on their location
    - Cables fail more quickly in lightly-loaded trays than in more heavily-loaded trays
    - Cables fail more quickly in horizontal rather than vertical trays
    - Cables fail more quickly if they are made out of TP rather than TS material
  - Intra-cable and Inter-cable failures
    - First noted degradation in the cable's/conductor's electrical integrity, manifested by a small leakage current, and/or a small change in its IR.
    - Followed by the cable or conductor ultimately fails to maintain its electrical integrity, manifested by either shorts-to-ground, shorts-to another conductor, or becomes an open circuit
  - Spurious actuations
    - SA can occur not only when the desired conductor is involved by itself, but also when certain other undesired conductors become involved through faults
    - Both the electrical properties and the spatial configuration are important for potential of an SA occurring in an electrical circuit
    - Highly dependent on detailed layout and cable configuration
    - Depends on too many variables and stochastic in nature - which conductor shorts to which other conductor, or shorts to ground, or goes to an open-circuit state

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

- An energized 7/C TS un-armored cable on a horizontal tray along with a single layer of 1/C and 7/C cables, with electrical circuit connection through a CPT and exposed to hot gas layer of a gradual heat-up fire - General Observations
  - Intra-cable shorting is much more likely than inter-cable shorting
  - High likelihood of an intra-cable short given a fire-induced cable failure
  - High likelihood of the source conductor to short to grounded conductor than to a non-grounded conductor
  - Low likelihood of a source conductor in a fire-induced cable damage will short to an adjacent 1/C target cable than to an intra-cable short. Also, an intra-cable short occurs earlier than an inter-cable short
  - Conductor short to another non-grounded conductor is followed by an eventual short-to-ground after a short time interval (Note that this time interval for a TP cable is much shorter than a TS cable)
- An energized 1/C cable on a horizontal tray along with other 1/C and 7/C cables and exposed to hot gas layer of a gradual heat-up fire
  - Short to ground before shorting to another cable (Note that for TP cables the likelihood of this occurring is high)

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

- Multiple spurious actuation
  - Several instances of multiple SAs in the same test, sometimes involving different conductors in the same multi-conductor cable
  - Some tests indicated that several conductors in the same cable or adjacent cables exhibited damage phenomena (i.e., lower IR) which are precursors to an SA
- Effect of cable material type
  - Given a fire-induced cable damage, no significant differences in the likelihood of SAs between TS and TP cables
  - Thermal threshold - TS Cables = 550 °F and TP Cables = 400 °F
  - Fragility curve (5%, 50%, 95%) - TS Cables = 680, 800, and 1200 °F and TP Cables = 400, 450, and 800 °F
  - Time interval between a hot short and a short to ground – TS Cables = several minutes and TP Cables = seconds to tens of seconds
  - Probability of shorting to ground rather than to a non-grounded conductor 1/C conductor – TS = 85-90% and TP = 70-75%
  - Probability of an inter-cable short between a multi-conductor cable and an adjacent 1/C cable – For TP cable it is 1.5 to 2 times greater than TS cable
  - TP cable exhibits IR changes at lower temperature than TS cable

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

- Armored multi-conductor TS cable
  - Cable damage is similar to or somewhat lower than that of unarmored TS cable
  - Fragility curve for TS Cables - for unarmored cable 680, 800, and 1200 °F and for armored cables 570, 750, and 830 °F
  - Short to ground is significantly higher than for unarmored cable
  - Intra-cable shorting is 20-30% compared to 70-80% for unarmored cable
  - Inter-cable shorting is non-existent
  - Typically, if one conductor shorts to ground, then a fuse or breaker trip would de-energize all other conductors within the cable
- Cable tray versus conduit
  - Thermal threshold and thermal fragility for TS cable in conduit is lower than for cables in tray, specifically with multiple layers of fill because of lower thermal capacity
  - Short-to-ground for a conductor is significantly higher in cables in conduit than in tray
  - Intra-cable shorting is 20-30% in conduit compared to 70-80% in trays
  - Inter-cable shorting is lower in conduit than in tray
  - Probability of SA is significantly smaller by a factor of 3-5 for cable in conduit than in tray

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

- Plume effects versus hot gas layer effects
  - For multi-layer cables in tray, the top layer experiences harsher conditions in a hot-gas-layer exposure, while the bottom layer experiences harsher conditions in a plume-exposure scenario
  - Cables in the middle layer would suffer least likely damage from either scenario
  - For slowly-developing fires the local temperature at the cable is the primary determinant of cable failure
- Effects of cable tray fill and location of the tray
  - Both these factors are secondary importance compared to the temperature profile of the cable
  - Cables in less filled tray are more susceptible to damage than a tray with more fill
  - Intra-cable conductor-to-conductor short has little effect, whereas inter-cable shorting increases the probability of SA in a heavily-loaded cable tray
- Horizontal and vertical cable trays and air drops (none exposed to plume)
  - Radiant heat is less damaging than hot-gas-layer exposure
  - No conclusive effect for vertical compared to horizontal tray configuration

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

- Impact of water spray
  - Probability of SA due to water spray could occur in the range of a few percent
- Influence of CPT
  - Absence of a CPT in the circuit increases the probability of SA (given cable damage and intra-cable shorting) by about a factor of 2 or less
- Cable/circuit electrical-configuration influence factors
  - Presence or absence of a source conductor and a target conductor
  - Proximity or absence of a grounded conductor or other ground plane
  - Presence or absence of latching circuitry and/or protection devices
  - Detailed wiring configuration, as the actuation conductor enters the circuit
  - Other circuit failure causing SA (not evaluated here)

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

<u>Summary of Probabilities</u>

Open Circuit	<0.01
TS, M/C, intra-cable short	0.75(0.6-0.9)
short to a non-grounded conductor, w/grounded conductor	0.4 (0.25-0.55)
Armored TS, M/C, intra-cable short	0.25(0.1-0.4)
In conduit, TS, M/C, intra-cable short	0.25(0.2-0.3)
TS, M/C to 1/C, no intra-cable short	0.2 (0.05-0.35)
TP, M/C to 1/C, no intra-cable short	0.4 (0.25-0.55)
Armored TS, M/C to 1/C, no intra-cable short	0
In conduit, TS, M/C to 1/C, no intra-cable short	<0.2
TS, 1/C to 1/C or M/C, hot short before short-to-ground	0.1-0.15
TP, 1/C to 1/C or M/C, hot short before short-to-ground	0.25-0.3
Armored TS,1/C to 1/C or M/C, hot short before short-to-ground	0
In conduit, TS, 1/C to 1/C or M/C, hot short before short-to-ground	<0.1
TS, M/C to M/C, no intra-cable short	<0.2

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OMEGA POINT CABLE FIRE TEST RESULTS (CONTD.)

Summary of P_{SACD} (Spurious actuation given cable damage)

Base case, TS, M/C, intra-cable	0.3 (0.1-0.5)
TP, M/C, intra-cable	0.3 (0.1-0.5)
Armored, TS, M/C, intra-cable	0.075(0.02-0.15)
In conduit, TS, M/C, intra-cable	0.075(0.025-0.125)
w/o CPT, TS, M/C, intra-cable	0.6 (0.2-1.0)
Base case, TS, 1/C, inter-cable	0.2 (0.05-0.3)
TP, 1/C, inter-cable	0.2 (0.05-0.3)
Armored w/fuses, TS, 1/C, inter-cable	0.0075(0.002-0.015)
In conduit, TS, 1/C, inter-cable	0.05(0.0125-0.075)
Base case, TS, M/C with 1/C, inter-cable	0.1 (0.05-0.2)
TP, M/C with 1/C, inter-cable	0.1 (0.05-0.2)
In conduit, TS, M/C with 1/C, inter-cable	0.025(0.0125-0.05)
Base case, TS, M/C with M/C, inter-cable	0.01-0.05
TP, M/C with M/C, inter-cable	0.01-0.05
In conduit, TS, M/C with M/C, inter-cable	0.005-0.01

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OMEGA POINT CABLE FIRE TEST SUMMARY

- Cable Failure defined at IR = 1000 Ω or Lower
- Temperature Thresholds below which no cable failure occurs:
  - TS Cables = 550 °F
  - TP Cables = 400 °F
- Conductor to Conductor Shorts (Likelihood) [Steve Nowlen]
  - Intra-cable shorting in cable trays 0.7 – 0.8
  - Intra-cable shorting in conduits 0.2 – 0.3
  - Intra-cable shorting in armored cable 0.2 – 0.3
  - Inter-cable shorting in cable trays ≤ 0.2
  - Inter-cable shorting in conduits ≤ 0.1
  - Inter-cable shorting in armored cable 0.0

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OMEGA POINT CABLE FIRE TEST SUMMARY

Spurious Actuation Likelihood[Steve Nowlen]	w/o CPT	w/ CPT
• Given intra-cable shorts in cable trays		
- w/ grounded conductor	0.5(0.25-0.6)	0.25(0.1-0.5)
- w/o grounded conductor	0.6(0.4-0.8)	0.4(0.1-0.7)
• Given intra-cable shorts in conduits		
- w/ grounded conductor	0.1(0.05-0.3)	0.05(0.01-0.1)
- w/o grounded conductor	0.4(0.1-0.6)	0.1(0.05-0.2)
• Given inter-cable shorts in cable trays		
- TS cables	0.1(0.05-0.25)	n/a
- TP cables	0.25(0.1-0.4)	n/a
• Given inter-cable shorts in conduits		
- TS cables	0.05(0.01-0.1)	n/a
- TP cables	0.1(0.05-0.2)	n/a
• Given inter-cable shorts in armored cable		
- w/ grounded conductor	0.05(0.01-0.7)	0.01(0.005-0.02)
- w/o grounded conductor	0.05(0.01-0.7)	0.01(0.005-0.02)

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OMEGA POINT CABLE FIRE TEST SUMMARY

Spurious Actuation Likelihood[Mark Salley]	P_{SA}	Cable T (°F)
• Armored Jacket w/TS and w or w/o CPT	0.25	700
• TP w/o CPT	0.88	390-400
• TP w/ CPT	0.38	390-400
• TS w/o CPT	0.45	660-680
• TS w/ CPT	0.17	660-680

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OMEGA POINT CABLE FIRE TEST SUMMARY

Spurious Actuation Duration Expected [Dan Funk]

	Duration (Sec)
• Median	0.7
• Mean	1.59
• Standard Deviation	2.255
• 2 sigma	4.51
• 3 sigma	6.77

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INFLUENCE FACTORS ON FUSE FAILURES AND DEVICE ACTUATIONS IN OMEGA POINT TESTS

- Cable insulation materials: TS (XLPE, EPR) and TP (Tefzel, PE, PVC) – Moderate Factor
- Number of conductors – Strong Factor
- Armoring – Strong Factor
- Power supply (CPT) – Strong Factor
- Cable raceway (trays and conduits) – Moderate Factor
- Cable tray loadings (1, 2, 3, 4 Rows) – Strong Factor
- Cable tray orientation (Horizontal and Vertical) – Weak Factor
- Exposure mode and intensification (Plume at 145 kW, Hot gas layer at 200, 350, and 450 kW) – Moderate Factor
- Cable-to-circuit wiring configuration (Actuation biased, Non-actuation biased, Ground-centered, Source-centered) – Strong Factor
- Water spray – Weak Factor

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‘Bin 2’ Item A: Spurious actuations caused by inter-cable shorting for thermoset cables

- Several spurious actuations caused by intra-cable shorting of both thermoset and thermoplastic cables
- A few spurious actuations caused by inter-cable shorting among thermoplastic cables
- No spurious actuations attributed to inter-cable shorting between thermoset cables

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Bin 2 Item B: Spurious actuations caused by Inter-cable shorting between thermoplastic and thermoset cables

- The Omega Point tests had not included any “mixed” bundles
- Thermoset cables are more robust than thermoplastic cables in terms of vulnerability to fire-induced electrical failure
- Thermoset cables will likely fail only after longer exposure times, perhaps well after any thermoplastic cables had failed
- Thermoset and thermoplastic cables are not likely to interact because of the likely time differences associated with their times to failure

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Bin 2 Item C: Concurrent spurious actuations associated with failures impacting three or more cables

- Omega Point tests showed that multiple spurious operations could occur during a single test, but that timing and hot-short duration issues could play a significant role in such behaviors
- Provided limited variations in the test configuration and were generally limited to cables co-located in a common single raceway
- Hence, initial guidance was to focus on spurious actuations potentially arising from shorts impacting any two cables, and to defer higher order failure combinations pending additional data

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Bin 2 Item D : Multiple spurious operations in control circuits with properly sized control power transformers (CPTs)

- The use of control power transformers (CPTs) is common for many AC control circuits
- Tested both with and without CPTs
- The CPTs appeared to have a substantive impact on the likelihood of spurious actuations
- Only explored one circuit configuration and one CPT size leaving many unanswered questions
- Interim guidance was to consider only single spurious actuations for circuits using "properly sized" CPTs

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Bin 2 Item E : Fire-induced hot shorts lasting more than 20 minutes

- The duration of hot shorts could be a definitive factor in both the likelihood of multiple concurrent spurious actuations and the potential impact of spurious actuations on certain types of devices
- Tests saw a maximum hot short duration of about 11 minutes
- Interim guidance was to consider hot shorts persisting for nominally twice this time (20 minutes)

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Bin 2 Item F : Consideration of spurious actuations for cold shutdown circuits

- Item is related to cold shutdown requirements included in 10CFR50 Appendix R
- Fire PRAs typically consider hot shutdown to be success so risk implications of cold shutdown circuits were unclear
- Fundamentally, the cable behaviors should be no different for a cold shutdown circuit
- Hence, this item was not considered amenable to resolution via testing and new data
- No investigation of Item F was undertaken as a part of CAROLFIRE tests

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OMEGA FIRE TESTS VERSUS CAROLFIRE TESTS

- Raceway loading – neatly packed versus randomly filled cables in cable trays
- Exposure conditions – hot gas layer, plume and radiant directly above the fire versus variation exposure to hot gas layer (within the plume but outside the flame zone), and radiant heating
- Cables tested – a small number of cable types versus a wide range of cable products and configurations
- Bundling arrangement – maximizes inter-cable failure versus bundling with 3/C to 12/C cable co-located in a common raceway
- Cable combinations – a single cable type versus mixed cable types (no armored cable)
- Cable thermal response – a limited thermal measurements versus an extensive measurements
- CPT size – 150% of normal circuit demand versus 150-166%, 227-250% and 300-333% of required circuit power
- Raceway configuration – both horizontal (with radial bend) and vertical raceways versus straight sections without bends and air drop configuration

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SNL CAROLFIRE CABLE FIRE TESTS

SPURIOUS ACTUATION OF AC ELECTRICAL CIRCUITS DUE TO CABLE FIRES

Mano Subudhi
Brookhaven National Laboratory
November 2010

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science U.S. DEPARTMENT OF ENERGY

CAROLFIRE AC TEST OBJECTIVES

- To support the resolution of the Bin 2 Items
  - Item A – Inter-cable shorting between TS cables: Penlight/Intermediate-scale tests
  - Item B – Inter-cable shorting between TS and TP cables: Penlight/Intermediate-scale tests
  - Item C – Spurious actuations arising from failures impacting more than two cables at a time: Intermediate-scale tests
  - Item D – Multiple spurious actuations due to fire-induced cable failures for control circuits powered by a properly sized CPT : Intermediate-scale tests
  - Item E – Fire-induced spurious actuation signals lasting greater than 20 minutes : Intermediate-scale tests
  - Item F – Consideration of cold shutdown circuits : NOT ADDRESSED
- To provide thermal response data to support fire response modeling and damage time predictions
  - Thermal response data correlated to the FMEA data

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CAROLFIRE TESTS

- Small-scale radiant heating tests (*Penlight*)
  - 26 preliminary tests (PP1 through PP26) to explore general failure behavior of cables under varying heat flux conditions
  - 68 additional tests (PT1 through PT68) and 1 special test (Spec1)
    - 17 tests not completed, thus a total of 52 *penlight* tests completed
  - Special test (Spec1) is a thermal-monitoring test (cable bundle versus single cable) for fire modeling data
  - A total of 78 tests completed
  - Used IRMS only
- Intermediate-scale tests representative of in-plant conditions
  - 4 preliminary tests (IP1 through IP4)
  - 14 additional tests (IT1 through IT14)
  - Primary objective to resolve Bin 2 Items
  - A total of 18 tests completed
  - Used IRMS and surrogate MOV – Motor starter SCDU

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CAROLFIRE PENLIGHT SMALL-SCALE TESTS

- Heats target cables via grey-body radiation from a heated shroud – Representative of smoke-filled HGL exposure
- Well controlled, well instrumented tests
- Allows for many experiments in a short time
- Thermal response and failure for single cables and small cable bundles (up to six cables)
- Cable tray, air drop, conduit configurations
- Tested mixed cable types (TS and TP) and manufacturers

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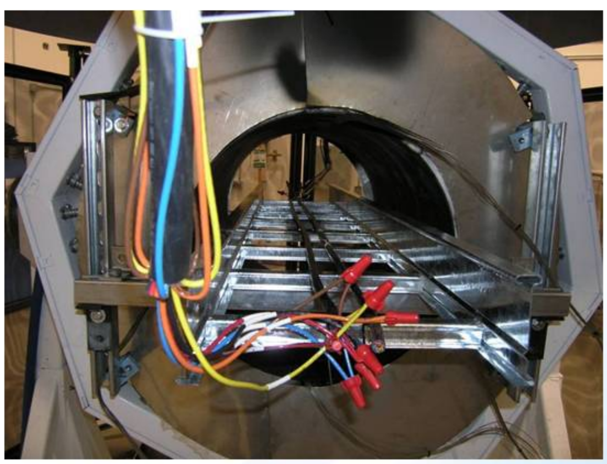
PENLIGHT SMALL-SCALE TESTS (OPEN)



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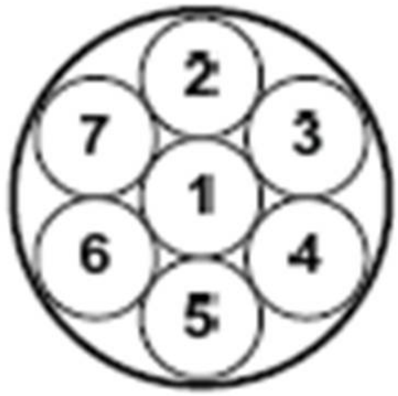
CONDUCTOR NUMBERING SCHEME



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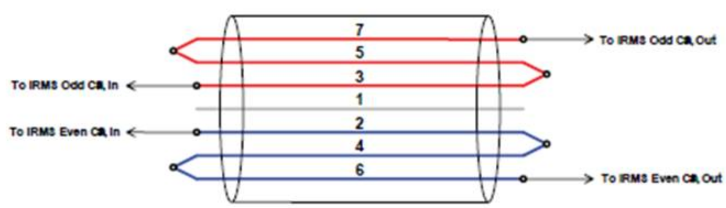
GROUPING OF CONDUCTIORS TO IRMS



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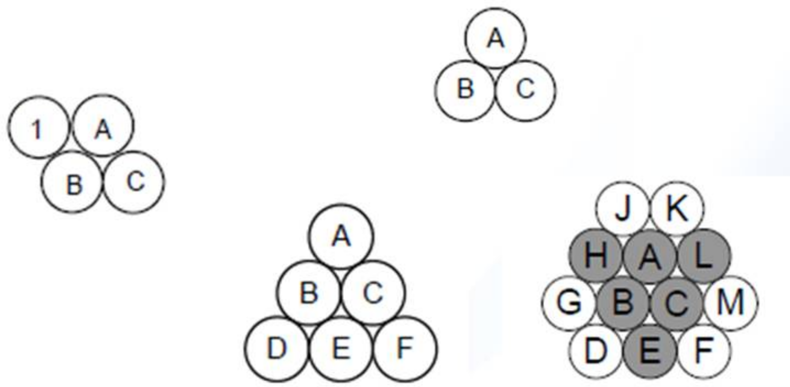
CABLE BUNDLE CONFIGURATIONS



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BROOKHAVEN NATIONAL LABORATORY

CAROLFIRE PENLIGHT SMALL-SCALE TEST GROUPS

- A total of 16 tests applicable to Bin 2, Items A and B
  - Preliminary tests: PP1 – PP26. Not used.
  - Group 1: PT1 - PT31; PT32 and PT33 not performed. Not used (single lengths)
  - Group 2: PT34 - PT37; Effect of a cable bundle against single cable – inter-cable interactions
  - Group 3: PT38 - PT41 not performed. No data available
  - Group 4: PT42 - PT50; Same as Group 2, but varied TS/TP cable type combinations
  - Group 5: PT51 - PT59 not performed. No data available
  - Group 6: PT60 - PT61; Effect of jacket TP material on TS insulation
  - Group 7: PT62 - PT63, Not used (single lengths)
  - Group 8: PT64 - PT65, Not used (single lengths)
  - Group 9: PT68, PT66 and PT67 not performed. Only PT68 data available; mixed TS and TP bundles
  - Special: Spec1. Not used (thermal behavior only)

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PENLIGHT CABLE FIRE TEST MATRIX

Test Group Number	Cable Type	Number of Conductors	Raceway Type	Bundle Size	Shroud Temperature (°C)	Test Observations
1	Single cable lengths used – No data available					
2	TS/TS, TS/TP	7	Horizontal tray/ Conduit	3 (conduit)/ 6 (tray)	525 (18.8 kW/m²)	-Both TS and TP cables indicated intra-cable shorts, followed by ground shorts -TS/TS and TS/TP cable interactions indicated inter-cable shorts as tertiary effect (after intra-cable shorts, followed by grounding) -PT35 indicated TP/TP cable interaction as secondary effect (after one of the cable grounded) -No noticeable effect on raceway types
3	Tests not performed					
4	TS/TS, TS/TP	7	Horizontal tray/ Conduit	3 (conduit)/ 6 (tray)	525 (18.8 kW/m²)	-Included both TS/TS and TS/TP bundles of various types -No significant inter-cable interaction noted and failures are tertiary (after intra-cable and ground shorting) -No specific bias regarding cable location in the bundle (PT42) -SR cables did not fail either internally or externally (PT44, PT45)
5	Tests not performed					
6	TS-insulation /TP-jacket	7	Horizontal tray/ Conduit	3 (conduit)/ 6 (tray)	525 (18.8 kW/m²)	-PT61 indicated intra-cable short, followed by grounding, but no inter-cable interaction -PT60 indicated inter-cable interaction as secondary after an intra-cable shorting
7	Test results not used because it involved testing of single lengths of cables					
8	Test results not used because it involved testing of single lengths of cables					
9	TS/TS, TS/TP, TP/TP	7	Horizontal tray	6	525 (18.8 kW/m²)	-Vita-Link cable did not fail either internally or externally -No substantive inter-cable interactions noted
Spec 1	Special thermal test – No data available					

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SUMMARY OF PENLIGHT TEST RESULTS

- In the context of Bin 2 Items A and B, these tests were performed for spurious actuations arising from inter-cable interactions between TS/TS cables and TS/TP cable bundles (Omega Point Testing studied TP/TP cable bundles as plausible cable failure mode for SA)
- Inter-cable interactions are tertiary effect (after intra-cable and grounding), except two exceptions involving TS/TP and TS/TS shorting
- Generally noted tertiary fault interactions in one cable and the other faults were either secondary or tertiary
- In PT45 the inter-cable fault was tertiary for TP (Tefzel) and primary for TS (XLPO)
- In PT60 the inter-cable fault was secondary (after intra-cable shorting) for one TS(XLPE/PVC) cable and primary for other TS(XLPE/PVC) cable
- TP cables are far less resistance to heating than TS cables
- TP cable would fail earlier than the TS cables

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CAROLFIRE INTERMEDIATE-SCALE TESTS

- Less controlled, but a more realistic testing scale
- Hood is roughly the size of a typical ASTM E603 type room fire test facility (more open to allow for ready access)
- Propene (Propylene) burner fire source (200 kW typical)
- Different exposure conditions (flame region, plume, hot gas layer exposures)
- Cables in trays, conduits and air drop

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CAROLFIRE INTERMEDIATE-SCALE TEST SETS

- One IRMS was used for IP1 through IT5 tests
- Two IRMS units were used for IT6 through IT14 tests
- SDCUs were used for IP3 through IT14 tests; IP3 used one SCDU and all others used four SCDUs
- IP1 through IP4 are single cable tests on cable trays for fire model improvement
- IT4 is a single cable test in support of the fire modeling

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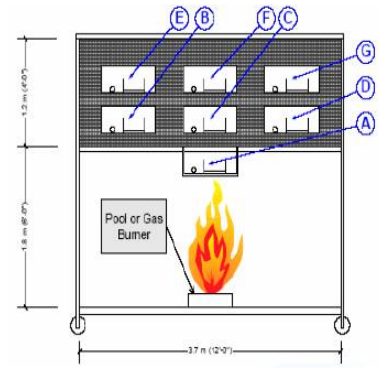
LAYOUT OF INTERMEDIATE-SCALE TEST LOCATIONS



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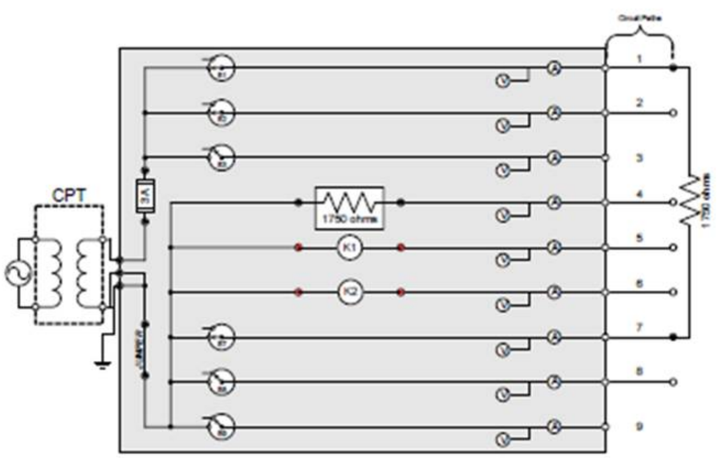
MOV-1 SCDU CIRCUIT CONFIGURATION



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TEST CONFIGURATION

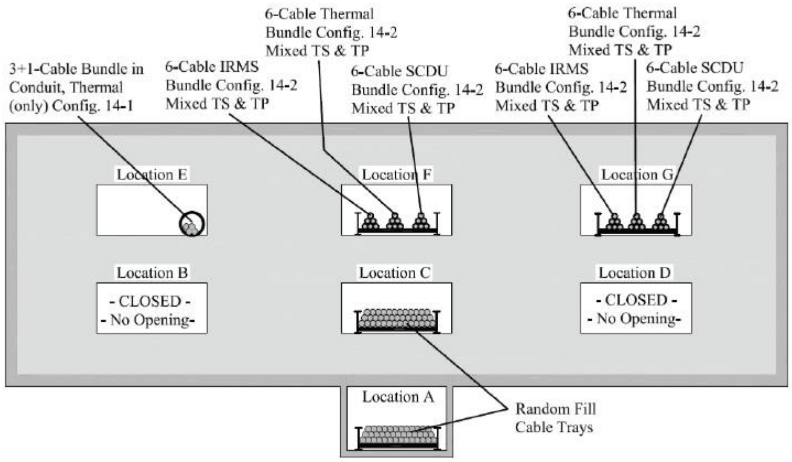

Figure 6.73: Test setup for IT-14.

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INSTRUMENTATION FOR BOTH ELECTRICAL PERFORMANCE AND THERMAL RESPONSE

- Cable thermal response (surface and interior)
  - Direct measurement of the cable temperatures during the tests
  - Can be used to calculate fire-to-cable net heat transfer (i.e., every cable is in effect a target specific slug calorimeter)
- Raceway surface temperatures
  - Conduits and cable trays
- Exposure environment temperatures
  - Air and surface, additional slug calorimeters
- Cable electrical response via two monitoring systems
  - SNL's Insulation Resistance Measurement System (IRMS)
  - Surrogate Circuit Diagnostic Unit (SCDU - circuit simulator)

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INTERMEDIATE-SCALE IRMS TEST RESULTS
INTER-CABLE INTERACTIONS

- Bin 2 Item A
  - One clear case of an inter-cable C-to-C short between two TS cables occurred as primary failure mode for both cables (IT1)
  - Other TS-to-TS interactions were detected as secondary fault for one cable and primary fault for the second (IT7), or as tertiary fault for one cable and primary for the second (IT6 and IT7)
- Bin 2 Item B
  - Two cases of inter-cable interactions between a TS-TP cable
  - No cases of inter-cable shorting as primary mode for both cables
  - One case of inter-cable shorting as secondary mode for one cable and primary for the second (IT9). In the same test, a second inter-cable interaction where tertiary fault in one cable but primary for the second cable

INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX IRMS and SCDU TESTS

Test Number	Cable Type	Number of Conductors	Raceway Type	Bundle Size (Instrumentation)	Cable Location	Number of SCDU tests	Comments
IP1	TS (XLPE/CSPE)	3,7	Horizontal tray	1 (Thermal, IRMS, SCDU)	A	0	SCDU test not performed
IP2	TS (XLPE/CSPE)	3,7	Horizontal tray	1 (Thermal, IRMS, SCDU)	A	0	SCDU test not performed
IP3	TP (PVC/PVC)	3,7	Horizontal tray	1 (Thermal, IRMS,SCDU)	A	1	SCDU connected to a single 7/C TP cable
IP4	TP (PVC/PVC)	3,7	Horizontal tray	1 (Thermal , IRMS); 4 (4SCDUs)	A	4	SCDU connected to a 3+1 Cable 7/C TP cable bundle
IT1	TS(XLPE/CSPE)	2,7,12	Horizontal tray	Random Fill 12 (Thermal, 4 SCDUs) 12 (Thermal, IRMS) 4 (Thermal)	A B G D, E	4	B – All four SCDUs connected to TS bundle
IT2	TS(XLPE/CSPE) /TP(PE/PVC) mix, TP(PVC/PVC)	7	Horizontal tray /Air Drop (single PVC)	12 (Thermal, 2SCDUs) 6 (Thermal, IRMS, 1SCDU) 1 (Thermal) 1 (Thermal, 1SCDU)	A C E G	4	A – SCDUs to 12 bundle TS and TS/TP mix; C – SCDU to TS/TP mix; C-A Air drop for thermal), G-SCDU for single TP cable
IT3	TS(XLPE/CSPE), TS(EPR/CPE), TP(PE/PVC)	7	Horizontal tray	6 (Thermal, 2SCDUs) 6 (Thermal, IRMS, 1SCDU) 1 (Thermal) 1 (Thermal, 1SCDU)	A C E G	4	A – SCDUs to 6 bundles of TS and TS/TP mix; E(single thermal TP) , G(thermal and SCDU for single TP cable)
IT4	TS(XLPE, XLPO,EPR), TP(PE, PVC, TEF)	7	Horizontal tray /Air Drop (single PVC)	6 (Thermal, 2SCDUs) 6 (Thermal, 2SCDUs) 1 (Thermal) 1 (Thermal, IRMS)	A C E G	4	A and C-SCDUs to two 6 -bundle TS/TP mix for intercable config.; C-A Air drop (TP for thermal), E(single thermal TS, 3/C)
IT5	TS(XLPE, XLPO,EPR,SR), TP(PE, PVC, TEF), Vita-Link	7	Horizontal tray /Air Drop (single XLPE)	6 (Thermal, 2SCDUs) 6 (Thermal, IRMS, 1SCDU) 1 (Thermal) 1 (Thermal, 1SCDU)	A C E G	4	E(single thermal TS), A- SCDUs to Intercable and VL; C-SCDU to intercable; G(thermal+SCDU for TS single cable), C-A Air drop (TS for thermal)

INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX IRMS AND SCDU TESTS (CONTD.)

Test Number	Cable Type	Number of Conductors	Raceway Type	Bundle Size (Instrumentation)	Cable Location	Number of SCDU tests	Comments
IT6	TS(XLPE, XLPO,EPR,SR), TP(PE, PVC, TEF)	7	Horizontal tray /Air Drop (XLPE,PE, TEF Bundle)	6 (Thermal, 2SCDUs) 6 (IRMS, 2SCDUs) 3 (Thermal) 1 (Thermal)	A C E G	4	A-SCDUs to PE and XLPO in mix cable bundles; C-SCDUs to SR and EPR in mix bundles; C-A Air drop of 3-cable bundle thermal
IT7	Mixed TS (XLPE,XLPO,EPR)/ TP(PE,TEF,PVC)	7	Horizontal tray Conduit at E	6 (Thermal, IRMS, 2SCDUs) 6 (Thermal, IRMS) 4 (Thermal, 1SCDU) 6 (Thermal, 1SCDU)	A C E G	4	A-SCDUs to XLPE and EPR in mix bundles; E and G-SCDU to PVC 3+1 bundles; Conduit at E
IT8	Mixed TS (XLPE)/ TP(PE,PVC)	7	Horizontal tray Conduit at E	6 (Thermal, IRMS, 2SCDUs) 6 (Thermal, IRMS) 4 (Thermal, 1SCDU) 6 (Thermal, 1SCDU)	A C E G	4	A-SCDUs to XLPE and PE in mix bundles; E and G- SCDU to 3+1 bundles; Conduit at location E
IT9	Mixed TS (XLPE,EPR, SR)/TP(PE,TEF)	7	Horizontal tray Conduit at E	6 (Thermal, IRMS, 2SCDUs) 6 (Thermal, IRMS) 4 (Thermal) 6 (Thermal, 2SCDUs)	A C E G	4	A-SCDUs to EPR and PE in mix bundles; 3+1 Thermal Bundle in conduit at location E; G-SCDUs to EPR and PE in mix bundles
IT10	Mixed TS (XLPE,XLPO,EPR, SR)/TP(PE,TEF,PV C)	7	Horizontal tray Conduit at E	6 (Thermal, IRMS, 2SCDUs) 6 (Thermal, IRMS) 4 (Thermal) 6 (Thermal, 2SCDUs)	A C E G	4	A-SCDUs to SR and TEF in mix bundles; 3+1 Thermal Bundle in conduit at location E; G-SCDUs to EPR and PE in mix bundles
IT11	Mixed TS (XLPE,XLPO,EPR)/ TP(PE,TEF,PVC)	7	Horizontal tray Air drop at E	6 (Thermal, IRMS, 2SCDUs) 6 (Thermal, IRMS) 4 (Thermal, SCDU) 6 (Thermal, SCDU)	A C E G	4	A-SCDUs to PVC and XLPE in mix bundles; E-3+1 Thermal+SCDU air drop bundle to PE cable; G-SCDU to PVC in a mix bundle

Brookhaven Science Associates 20 BROOKHAVEN NATIONAL LABORATORY

INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX TRMS AND SCDU TESTS (CONTD.)

Test Number	Cable Type	Number of Conductors	Raceway Type	Bundle Size (Instrumentation)	Cable Location	Number of SCDU tests	Comments
IT12	Mixed TS (XLPE,XLPO,EPR)/ TP(PE,TEF,PVC)	7	Horizontal tray Air drop at E	6 (Thermal, IRMS, 2SCDUs) 6 (Thermal, IRMS) 4 (Thermal, SCDU) 6 (Thermal, SCDU))	A C E G	4	A-SCDUs to PVC and XLPE in mix bundles; E-3+1 Thermal+SCDU air drop bundle to PE cable; G-SCDU to PVC in a mix bundle
IT13	Mixed TS (XLPE,XLPO,EPR)/ TP(PE,TEF,PVC), V-L	7	Horizontal tray	Random Fill Random Fill 4 (Thermal) 6 (Thermal,IRMS,2 SCDUs) 6 (Thermal,IRMS,2 SCDUs)	A C E F G	4	E-3+1 Thermal Bundle in conduit. F-SCDUs to XLPE and VitaLink in mix bundles; G-SCDUs to XLPE and VitaLink in mix bundles
IT14	Mixed TS (XLPE,XLPO,EPR)/ TP(PE,TEF,PVC)	7	Horizontal tray	Random Fill Random Fill 4 (Thermal) 6 (Thermal,IRMS,2 SCDUs) 6 (Thermal,IRMS,2 SCDUs)	A C E F G	4	E-3+1 Thermal Bundle in conduit. F-SCDUs to XLPE and EPR in mix bundles; G-SCDUs to XLPE and EPR in mix bundles

NOTES: Location A is outside the hood and exposed to plume, while Locations B through G are inside the hood and exposed to hot gas layers.
TS and TP Cables are mixed from various manufacturers.
IT1 and IT2 included 12-cable bundles; IT1, IT13 and IT14 included random fill raceways; most other included 6-cable bundles.
Typically, 6-cable bundles are located in a tray, while 3-cable bundles are in a conduit. 4-cable bundles included three electrical performance and one thermal performance.

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INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX PRELIMINARY TEST RESULTS

Test Number	Cable Type	Number of Cond.	Raceway Type	Bundle Size	CPT in VA (GRND.)	Intra-Cable Short Mode and Duration	Inter-Cable Interaction Detected ?	Test Observations
IP1	TS	3/7	Tray	1	NA	No data available. Only thermal response indicating that cable ignition was concurrent with electrical failure		
IP2	TS	3/7	Tray	1	NA	No data available. Only thermal response indicating that un-insulated drain wire shorted to ground, followed by intra-cable short between conductors. Both failure occurred within 2 minutes of fire ignition.		
IP3	TP (PVC)	3 / 7	Tray	1(IRMS for 3/C and 7/C)/ 1(SCDU)	150N	SA for 35s	-	-Voltage to targets did fluctuate, and some chattering and drop out noted before re-locking -Minimal signs of voltage degradation (~10V drop) prior to fuse blow
IP4	TP (PVC)	3/7	Tray	1(IRMS for 3/C and 7/C)/ 4(SCDU)	150N	SA for <1s	SA Target for 1s	-Fuse Blown (FB) about 29s after SA.
					150Y	SA for 6s	Source for <1s	Inter-cable hot shorts involved all 4 circuits: this (circuit 2) as source and other three circuits (1,3,4) as targets
					200Y	FB	SA Target for <1s	Shorted ground causing fuse blown. After that inter-cable momentary shorts one with circuit 2 as energizing source and the other with circuit 4 as source.
					100Y	SA for 1s	Source for <1s	Two momentary inter-cable hot shorts impacting circuit 3, followed by a SA due to intra-cable shorting that lasted 1.2s before fuse blown.

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INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX TEST RESULTS

Test Number	Cable Type	SCDU Circuit Type	Cable Location	Bundle Size	CPT in VA (GRND.)	Intra-Cable Short Mode and Duration	Inter-Cable Interaction Detected ?	Test Observations
IT1	TP (XLPE)	MOV-1	B	12	150N	SA for 106s	Source for <1s	-No sign of voltage degradation prior to fuse blow
					150Y	FB	No	-No sign of voltage degradation prior to fuse blow
					200Y	SA for 231s	No	-Voltage degraded by ~20V prior to fuse blow
					100Y	HS & SA for 98s	Target for <1s	-SA sustained for 88s -Minor voltage drop (~10V) prior to fuse blow
IT2	TS (XLPE)	IC	A	12	150N	-	Possible	Configured for TS-TS inter-cable hot short and ungrounded. Faults are likely due to mutual ground faults
	TS/TP (XLPE/PE)	IC	A	12	150Y	-	No	Configured for TS-TP inter-cable hot short. At 286s fuse blown and no interaction in cable
	TP (PVC)	MOV-1	G	1	200Y	FB	-	Fuse blown and no SA
	TS/TP (XLPE/PE)	IC	C	6	100Y	-	No	Configured for TS-TS inter-cable hot short. Fuse blown and no hot shorts
IT3	TS/TS (XLPE/EPR)	IC	A	6	150N	-	Possible	After prolonged SAs, multiple ground faults rather than C to C interaction
	TS/TP (EPR/PE)	IC	A	6	150Y	-	<1s	After a momentary hot short, fuse blew
	TS/TP (XLPE/PE)	IC	C	6	200Y	-	<1s	After a momentary voltage spike, fuse blew
	TP (3/C PVC)	AC-1	G	1	100Y	FB	-	Shorted to ground prior to a fuse blow

Brookhaven Science Associates 23 BROOKHAVEN NATIONAL LABORATORY

INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX TEST RESULTS (CONTD.)

Test Number	Cable Type	SCDU Circuit Type	Cable Location	Bundle Size	CPT in VA (GRND.)	Intra-Cable Short Mode and Duration	Inter-Cable Interaction Detected ?	Test Observations
IT4	Mixed TS/TP (XLPE, TEF, PE)	IC	C	6	150N	-	Possible	After SAs, multiple ground faults rather than C to C interaction
	Mixed TS/TP (XLPE, TEF, PE)	IC	C	6	150Y	-	No	TP(PE) cable short to ground, followed by fuse blow
	Mixed TS/TP (XLPE, TEF, PE)	IC	A	6	200Y	-	No	TP(PE) cable short to ground, followed by fuse blow
	Mixed TS/TP (XLPE, TEF, PE)	IC	A	6	100Y	-	No	TP(Tefzel) cable short to ground, followed by fuse blow
IT5	Mixed TS/ TP (V-L)	MOV-1	A	6	150N	2 SAs for 29s	-	SAs occurred when water spray initiated, followed by fuse blow
	Mixed TS/TP (XLPE, TEF, PE)	IC	C	6	150Y	-	No	Fuse blown
	TS (EPR)	MOV-1	G	1	200Y	Did not fail	-	Indicated signs of degradation, but no failure
	Mixed TS/TP (XLPE, TEF, PE)	IC	A	6	100Y	-	No	Experienced early fuse blow
IT6	Mixed TS/TP (SR)	MOV-1	C	6	150N	FB	No	Grounded when water spray initiated, followed by fuse blow. No SA
	Mixed TS/TP (SR)	MOV-1	A	6	150Y	FB	No	Grounded when water spray initiated, followed by fuse blow. No SA
	Mixed TS/TP (EPR)	MOV-1	C	6	200Y	FB	No	Short between one source and an external ground, followed by fuse blow
	Mixed TS/TP (XLPO)	MOV-1	A	6	100Y	SA for 16s	No	Multiple SAs.

Brookhaven Science Associates 24 BROOKHAVEN NATIONAL LABORATORY

INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX TEST RESULTS (CONTD.)

Test Number	Cable Type	SCDU Circuit Type	Cable Location	Bundle Size	CPT in VA (GRND.)	Intra-Cable Short Mode and Duration	Inter-Cable Interaction Detected ?	Test Observations
IT7	Mixed TS/TP (PVC)	MOV-1	G	6	150N	SA for 15s	-	No voltage degradation prior to fuse blow
	Mixed TS/TP (EPR)	MOV-1	A	6	150Y	SA for 46s	Target No HS or SA	Inter-cable interaction occurred after the fuse blown
	Mixed TS/TP (XLPE)	MOV-1	A	6	200Y	SA for 31s	Source	Inter-cable interaction occurred after the fuse blown
	Mixed TS/TP (PVC)	MOV-1	E	3	100Y	SA for 24s	-	No voltage degradation prior to fuse blow
IT8	Mixed TS/TP (XLPE)	MOV-1	G	6	150N	Did not fail	-	-
	Mixed TS/TP (PE)	MOV-1	A	6	150Y	SA for 5s	Target	Erratic behavior with sporadic and short-lived HSs for 114s. Inter-cable shorting for 44s with no SA
	Mixed TS/TP (XLPE)	MOV-1	A	6	200Y	SA and HS for 24s	Source	Significant voltage degradation prior to fuse blown
	Mixed TS/TP (XLPE)	MOV-1	E	3	100Y	Did not fail	-	-
IT9	Mixed TS/TP (EPR)	MOV-1	G	6	150N	SA for 122s	No	Sporadic voltage spikes noted. Source of these spikes unknown
	Mixed TS/TP (EPR)	MOV-1	A	6	150Y	SA for 2s	No	SA occurred between 2 and 21 seconds
	Mixed TS/TP (PE)	MOV-1	A	6	200Y	FB	No	Multiple voltage spikes lasting a few seconds. Extensive chattering of one relay
	Mixed TS/TP (PE)	MOV-1	G	6	100Y	SA and HS for 457s	No	Sporadic voltage spikes noted. Source of these spikes unknown

Brookhaven Science Associates 25 BROOKHAVEN NATIONAL LABORATORY

INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX TEST RESULTS (CONTD.)

Test Number	Cable Type	SCDU Circuit Type	Cable Location	Bundle Size	CPT in VA (GRND.)	Intra-Cable Short Mode and Duration	Inter-Cable Interaction Detected ?	Test Observations
IT10	Mixed TS/TP (EPR)	MOV-1	G	6	150N	HS & SA for 226s	No	Other SAa lasted for 82s and 102s
	Mixed TS/TP (SR)	MOV-1	A	6	150Y	FB	No	Failed due to a fuse blown
	Mixed TS/TP (TEF)	MOV-1	A	6	200Y	HS & SA for 11s	No	No source voltage degradation prior to FB
	Mixed TS/TP (PE)	MOV-1	G	6	100Y	FB	No	Failed due to a fuse blown at 1567s
IT11	Mixed TS/TP (PVC)	MOV-1	A	6	150N	SA for 6s	No	No source voltage degradation prior to FB
	Mixed TS/TP (PE)	MOV-1	E	6 Air Drop	150Y	SA for 229s	No	No source voltage degradation prior to FB
	Mixed TS/TP (PVC)	MOV-1	G	6	200Y	FB	No	No source voltage degradation prior to FB
	Mixed TS/TP (XLPE)	MOV-1	A	6	None (Y)	SA for 33s	No	No source voltage degradation prior to FB
IT12	Mixed TS/TP (XLPE)	MOV-1	A	6	150N	FB	-	No source voltage degradation prior to FB
	Mixed TS/TP (EPR)	MOV-1	E	6 Air Drop	150Y	SA for 347s	-	No source voltage degradation prior to FB
	Mixed TS/TP (XLPE)	MOV-1	G	6	200Y	SA for 11s	-	No source voltage degradation prior to FB
	Mixed TS/TP (EPR)	MOV-1	A	6	None (Y)	SA foe 18s	-	No source voltage degradation prior to FB

INTERMEDIATE-SCALE CABLE FIRE TEST MATRIX TEST RESULTS (CONTD.)

Test Number	Cable Type	SCDU Circuit Type	Cable Location	Bundle Size	CPT in VA (GRND.)	Intra-Cable Short Mode and Duration	Inter-Cable Interaction Detected ?	Test Observations
IT13	Mixed TS/TP (XLPE)	MOV-1	F	6	150N	SA for 63s	-	No source voltage degradation prior to FB
	Mixed TS/TP (V-L)	MOV-1	F	6	150Y	Did not fail	-	-
	Mixed TS/TP (XLPE)	MOV-1	G	6	200Y	SA for 42s	-	No source voltage degradation prior to FB
	Mixed TS/TP (V-L)	MOV-1	G	6	None (Y)	Did not fail	-	-
IT14	Mixed TS/TP (XLPE)	MOV-1	F	6	150N	SA for 63s	No	Minor voltage degradation prior to FB
	Mixed TS/TP (EPR)	MOV-1	F	6	150Y	SA for 19s	No	No source voltage degradation prior to FB
	Mixed TS/TP (XLPE)	MOV-1	G	6	200Y	SA for 44s	No	No source voltage degradation prior to FB
	Mixed TS/TP (EPR)	MOV-1	G	6	None (Y)	HS for 9s	No	No source voltage degradation prior to FB

INTERMEDIATE-SCALE SCDU TEST RESULTS

- 16 SCDU tests for 61 individual trials
- Fuse blow failures
  - Over-current condition due to grounded circuit
  - Short between one of the energized conductors and the power supply return side conductor
  - No degradations prior to fuse blown
- Intra-Cable Spurious Actuations
  - SA follows periods of lock-in, drop-out, chatter, and re-lock
  - Percentage of SAs slightly higher for TS cables (18 in 25 failures or 72%) than for TP cables (13 in 19 failures or 68%)
  - Almost consistent, but somewhat higher than Omega Point test findings w/no CPT (0.6 conditional to cable failure) – contributed by NEI's radial bend in cable configuration, exposed to fire source flame zone, and use of 150VA CPT

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INTERMEDIATE-SCALE SCDU TEST RESULTS (CONTD.)

- Intra-Cable Shorting for TP Cables
  - Total failures – 19
  - Total spurious actuations – 13
  - Total hot shorts – 0
  - Total fuse blown – 6
- Intra-Cable Shorting for TS Cables
  - Total failures – 25
  - Total spurious actuations – 18
  - Total hot shorts – 1
  - Total fuse blown – 6

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INTERMEDIATE-SCALE SCDU TEST RESULTS (CONTD.)

- Inter-Cable Shorting
  - No spurious actuations observed where the fuse blow failures were possible
  - Inter-cable spurious actuation observed for ungrounded SCDU-1 circuits since no fuse blow failure was possible
  - Various cases of this behavior were observed
- Silicone Rubber and Vita-Link Cables
  - No significant failures for both cable types while the gas burner was running (i.e., IRMS – no IR value below 1000 Ω; SCDU – no fuse blown or SA failures)
  - For SR cables, some failures observed after the gas burner was turned off, but before water spray (IT9 and IT10)
  - For V-L cables, one case has a momentary drop in IR below 1000 Ω before water spray
  - Both cables failed during water spray
- Grounded versus Ungrounded CPTs
  - No effect on spurious actuation attributed to grounding configuration

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'Bin 2' Item A: Spurious actuations caused by inter-cable shorting for thermoset cables

- One solid case of inter-cable shorting as primary failure mode observed on IRMS
- Several cases where inter-cable shorting was secondary or tertiary failure mode on IRMS
- No spurious actuations on the SCDUs

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Bin 2 Item B: Spurious actuations caused by Inter-cable shorting between thermoplastic and thermoset cables

- No cases of spurious actuation on SCDUs
- One case of a hot short from a TS to a TP cable
- No cases where inter-cable shorting was primary failure mode for both cables
- One case where inter-cable shorting was secondary mode for one cable, primary for second cable
- Several cases involving secondary/secondary or tertiary failures

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Bin 2 Item C: Concurrent spurious actuations associated with failures impacting three or more cables

- Test program has seen as many as four out of four simulated control circuits spuriously actuate
- Different exposure locations and conditions indicated timing differences significantly

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Bin 2 Item D : Multiple spurious operations in control circuits with properly sized control power transformers (CPTs)

- Could not confirm NEI/EPRI results relative to CPTs
  - Testing of larger CPTs
  - No apparent affect on spurious actuations
  - No cases where voltage collapse was thought to have prevented spurious actuation
- What is meant by 'properly sized' is a key question
  - Relay coil pick-up current NOT in-rush
  - May be issue with interpreting manufacturer specs.

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Bin 2 Item E : Fire-induced hot shorts lasting more than 20 minutes

- No hot shorts lasting greater than 7.6 minutes
- NEI/EPRI saw max duration of 11.3 minutes
- All data appear to indicate that once cable degradation begins, it will cascade through all modes within a relatively short time

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SNL DESIREE-FIRE CABLE TESTS

SPURIOUS ACTUATION OF DC ELECTRICAL CIRCUITS DUE TO CABLE FIRES

Mano Subudhi
Brookhaven National Laboratory
November 2010

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a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

DESIREE-FIRE DC TEST OBJECTIVES

- To support the resolution of the Bin 2 Items
  - Item A – Inter-cable shorting between TS cables: Penlight/Intermediate-scale tests
  - Item B – Inter-cable shorting between TS and TP cables: Penlight/Intermediate-scale tests
  - Item C – Spurious actuations arising from failures impacting more than two cables at a time: Intermediate-scale tests
  - Item D – Multiple spurious actuations due to fire-induced cable failures for control circuits powered by a properly sized CPT : Intermediate-scale tests
  - Item E – Fire-induced spurious actuation signals lasting greater than 20 minutes : Intermediate-scale tests
  - Item F – Consideration of cold shutdown circuits : NOT ADDRESSED
- To address analytical uncertainties on failures of dc-powered control circuits
- To provide influencing variables on cable failures such as cable type, control circuit configuration, fire exposure conditions, and cable routing configuration

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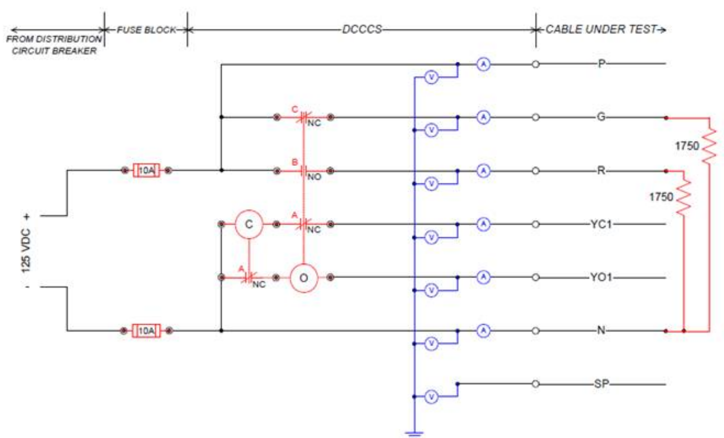
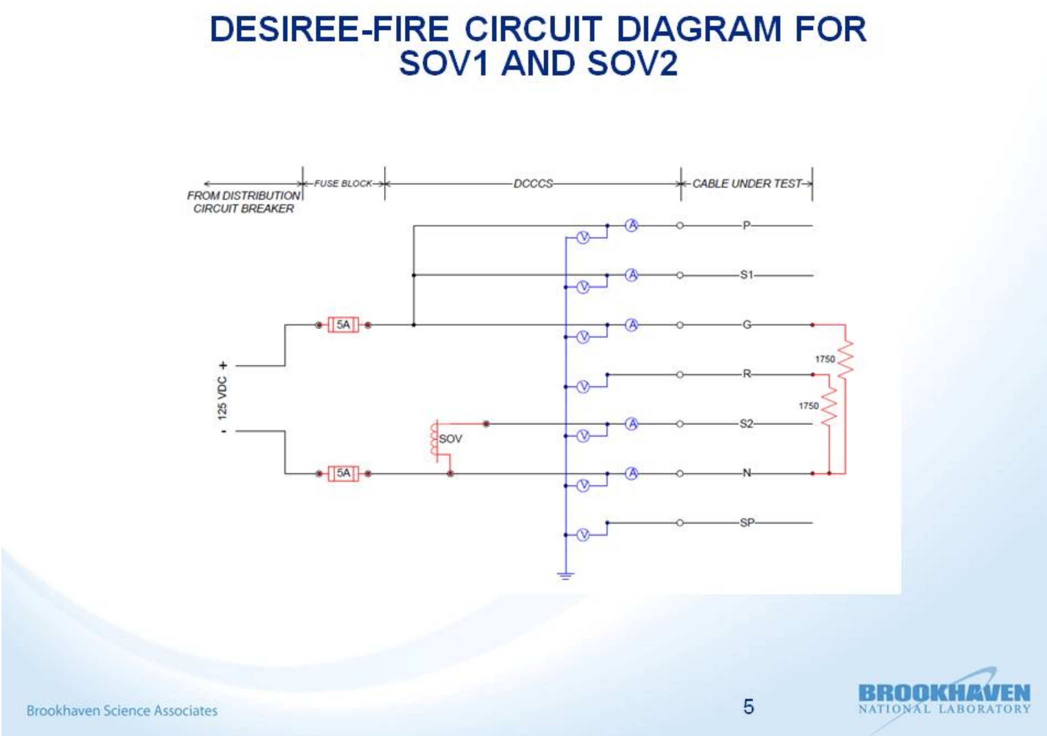
DESIREE-FIRE TESTS

- Small-scale radiant heating tests (*Penlight*)
  - 4 preliminary tests (Prelim 1 thru 4) to explore general failure behavior of cables under varying heat flux conditions
  - 50 additional tests (1 thru 50) and 3 Japanese cable tests (JPN-1 thru 3)
  - A total of 53 tests completed
  - Used MOV, SOV, 1" SOV and Large Coil, SWGR Close and Trip Coils, Inter-Cable, and SCDU circuits

- Intermediate-scale tests representative of in-plant conditions
  - 2 preliminary tests (Prelim 1 and 2)
  - 12 additional tests (1 through 12)
  - 1 Japanese cable test and 2 contingent tests
  - Used MOV, SOV, 1" SOV and Large Coil, SWGR, Inter-Cable, and Four SCDU circuits

DESIREE-FIRE CIRCUIT DIAGRAM FOR MOV1 AND MOV2




DESIREE-FIRE CIRCUIT DIAGRAM FOR SOV1 AND SOV2
FROM DISTRIBUTION CIRCUIT BREAKER
FUSE BLOCK
DCCCS
CABLE UNDER TEST
P
S1
G
R
S2
N
SP
5A
5A
125 VDC
SOV
1750
1750
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5
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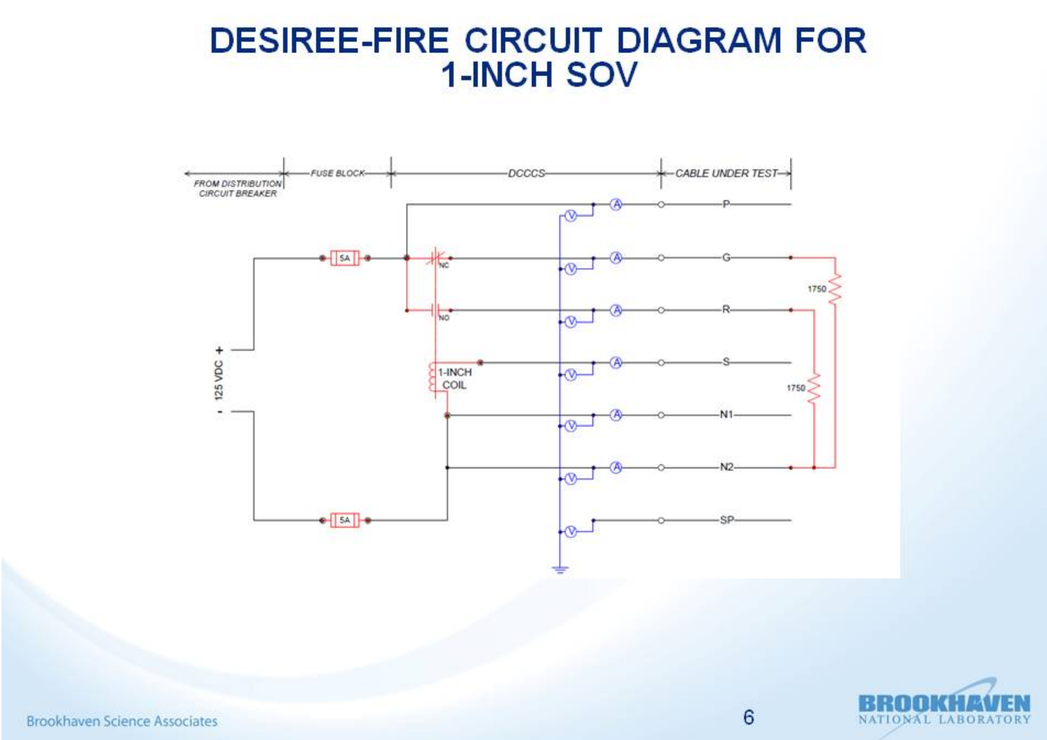
DESIREE-FIRE CIRCUIT DIAGRAM FOR 1-INCH SOV
FROM DISTRIBUTION CIRCUIT BREAKER
FUSE BLOCK
DCCCS
CABLE UNDER TEST
P
G
R
S
N1
N2
SP
5A
5A
125 VDC
NC
NO
1-INCH COIL
1750
1750
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6
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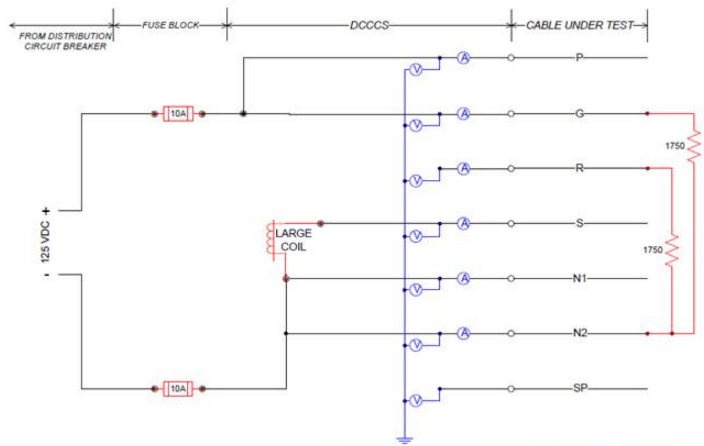
DESIREE-FIRE CIRCUIT DIAGRAM FOR LARGE COIL



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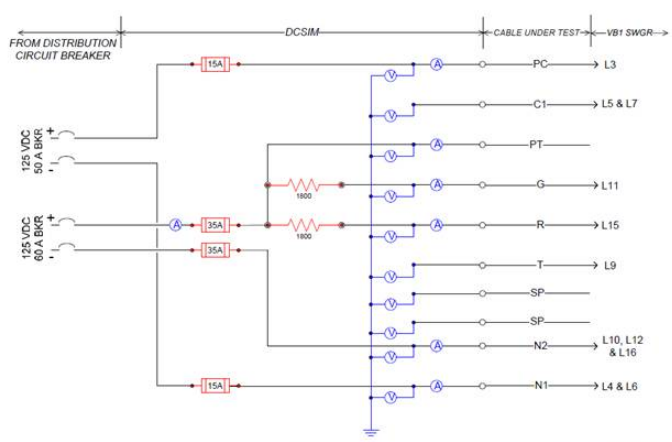
DESIREE-FIRE CIRCUIT DIAGRAM FOR SWITCHGEAR (TRIP AND CLOSE COILS)



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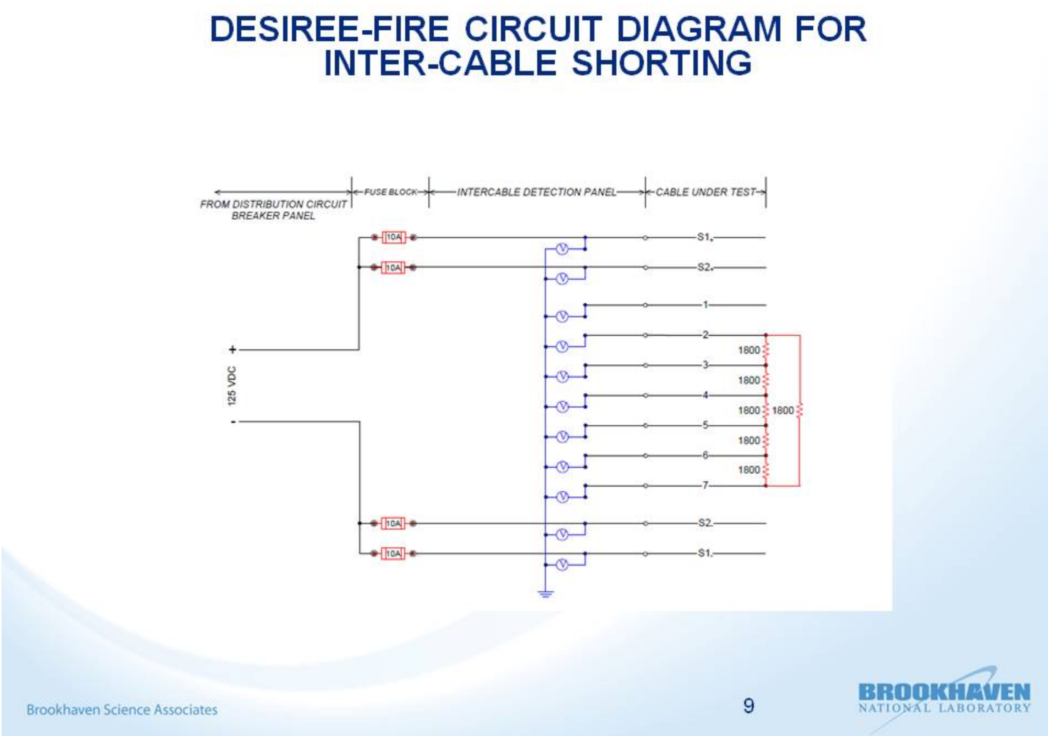
DESIREE-FIRE CIRCUIT DIAGRAM FOR INTER-CABLE SHORTING
FROM DISTRIBUTION CIRCUIT BREAKER PANEL
FUSE BLOCK
INTERCABLE DETECTION PANEL
CABLE UNDER TEST
10A
125 VDC
+
-
S1
S2
1
2
3
4
5
6
7
1800
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9
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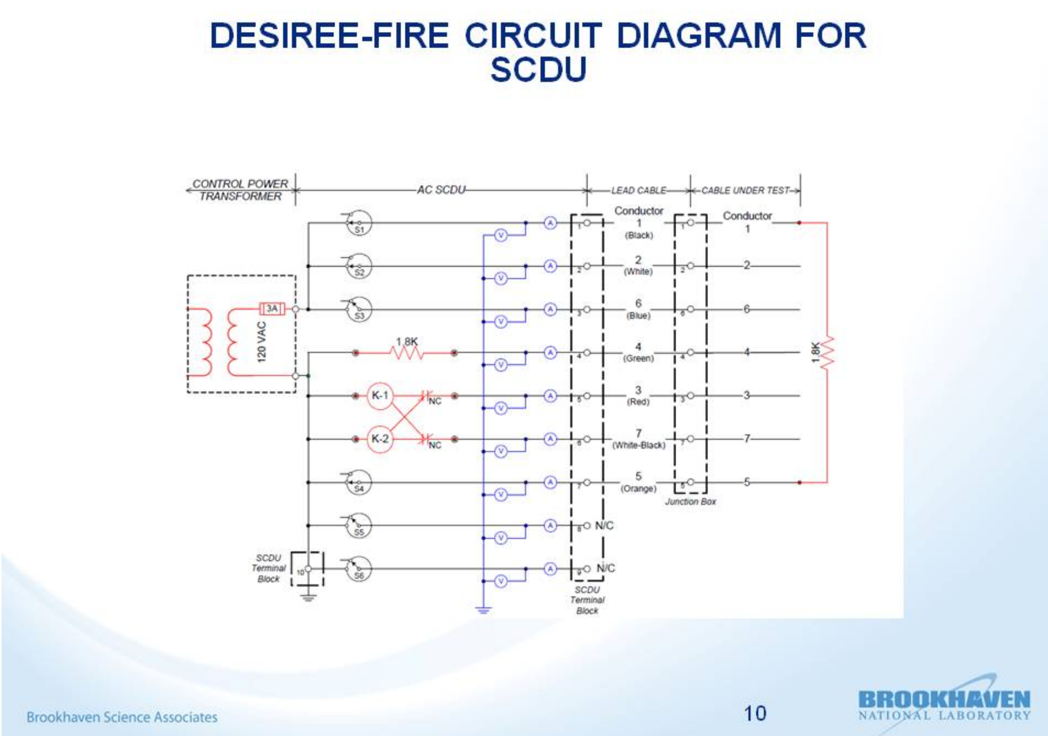
DESIREE-FIRE CIRCUIT DIAGRAM FOR SCDU
CONTROL POWER TRANSFORMER
AC SCDU
LEAD CABLE
CABLE UNDER TEST
3A
120 VAC
1.8K
K-1
K-2
NC
S1
S2
S3
S4
S5
S6
Conductor
1 (Black)
2 (White)
6 (Blue)
4 (Green)
3 (Red)
7 (White-Black)
5 (Orange)
N/C
Junction Box
SCDU Terminal Block
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10
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DESIREE-FIRE PENLIGHT SMALL-SCALE TESTS

- Heats target cables via grey-body radiation from a heated shroud – Representative of smoke-filled HGL exposure
- Well controlled, well instrumented tests
- Allows for many experiments in a short time
- Monitored individual cable types for thermal and electrical performance
- Cable tray and conduit configurations

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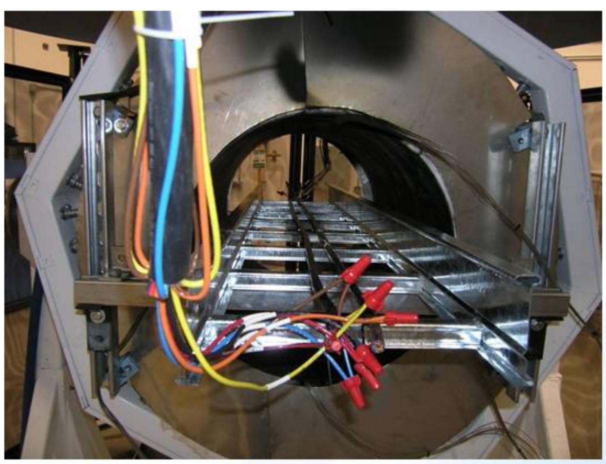
DESIREE-FIRE SMALL-SCALE TESTS (OPEN)



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DESIREE-FIRE PENLIGHT SMALL-SCALE TEST GROUPS

- Group 1 - DC Motor Starter (MOV) Circuit Tests (MOV1 and MOV2): 7, 8, 12, 22, 25, 27, 30, 33, 37, 41, 43, 44, 49, 50, JPN-3
- Group 2 - Small DC Solenoid Operated Valve (SOV) Circuit Tests SOV1 and SOV2): 1, 2, 9, 20, 23, 26, 28, 31, 34, 38
- Group 3 - DC Large Coil and 1-inch SOV circuit Tests (Large Coil and 1-inch Valve): 5, 6, 11, 36, 40
- Group 4 - Switchgear Circuit Tests (SWGR TRIP and CLOSE Coils): 3, 4, 10, 21, 24, 29, 32, 35, 39, 42, JPN-1, JPN-2
- Group 5 - Inter-Cable Circuit Tests (Inter-Cable): 45, 46, 47, 48
- Group 6 - Surrogate Circuit Diagnostic Unit (SCDU) Tests: Prelim 1 thru 4, 13 (+13 qual), 14, 15, 16, 17 (+17 qual), 18, 19

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DESIREE-FIRE PENLIGHT CABLE FIRE TESTS

Test Group Number	Cable Type	Number of Conductors	Raceway Type	Bundle Size	Shroud Temperature (°C/kW/m²)	Test Observations
1	TS or TP	7	Horizontal tray/ Conduit (Tests 37 and 41)	3 (conduit)/ 6 (tray)	275/4.2 – 700/41.4 (constant)	Out of 15 tests connected to MOV1 and MOV2 circuits, Test 27 did not fail; JPN-1 is not counted; 20 out of 28 circuits resulted in SAs and 5 cleared by one or both 10A fuses. Test 43 had multiple (4) SAs with durations of 57m, 23m, 24m, and 34s. Test 30 had a duration of 24m and Test 44 had a duration of 20m.
2	TS or TP	7	Horizontal tray/ Conduit (Tests 34 and 38)	3 (conduit)/ 6 (tray)	325/5.9 – 700/41.4 (constant)	Out of 10 tests connected to SOV1 and SOV2 circuits, Test 26 did not fail; 11 out of 20 circuits resulted in SAs and 6 circuits first failed by clearing one or both 5-amp fuses. Test 38 had a duration of 21m.
3	TS or TP	7	Horizontal tray/ Conduit (Tests 36 and 40)	3 (conduit)/ 6 (tray)	325/5.9 – 525/18.8 (constant)	Out of 5 tests connected to Large coil and SOV circuits, 7 out of 10 circuits had SAs; Test 11 had multiple SAs in both circuits.
4	TS or TP	7	Horizontal tray/ Conduit (Tests 35 and 39)	3 (conduit)/ 6 (tray)	325/5.9 – 525/18.8 (constant)	Out of 12 tests connected to close coil and trip coil circuits, 2 Japanese tests are not considered; 9 out of 20 circuits had SAs; Test 29 had a duration of 23m.
5	TS or TP	7	Horizontal tray	6 (tray)	350/7 – 470/14.1 (constant)	All 4 inter-cable bundles indicated C-to-C interactions between target and one or more source cables. Tests 45, 46, and 48 interaction occurred after the target cable failed internally. Test 47 interaction occurred with 2 source cable before its failure.
6	TS or TP	7	Horizontal tray	6 (tray)	300/5 – 470/14.1 (constant)	9 out of 24 circuits resulted in SAs and 13 circuits cleared the circuit fuse. Longest duration was 57m.

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DESIREE-FIRE PENLIGHT TEST: SPURIOUS ACTUATIONS/HOT SHORTS

CABLE Material	Group 1 MOVs	Group 2 SOVs	Group 3 1"/Large	Group 4 SWGR T/C	Group 6 SCDUs	Total Number SAs/HSs
TS-XLPE	4/6	3/6	4/6	6/8	4/4	21/30
TS-EPR	2/2	1/2		0/2		3/6
TS-SR	0/2	0/2				0/4
TS-Kerite	5/6				3/14	8/20
TS-XLPO						
TS-Armored	2/2	2/2		0/2	0/2	4/8
TP-PE	5/6	3/4	3/4	0/4	2/4	14/22
TP-PVC	0/2	1/2		2/2		3/6
TP-TEF	2/2	1/2		1/2		4/6
VITA-LINK						
TS/TP Comb.						
TOTAL	20/28	11/20	7/10	9/20	9/24	56/102

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SUMMARY OF DESIREE-FIRE PENLIGHT TEST RESULTS

- Group 1 – 20/28 (excl. JPN-1); Group 2 - 11/20; Group 3 - 7/10; Group 4 – 9/20 (excl. JPN-1&2); Group 6 – 9/24 SAs. Group 5 – 4/4 is considered separately. Thus, a combined 56/102 SAs and/or HSs Occurred
- Test Number 30 MOV2 open coil had a SA duration of 24 minutes; Test 38 SOV2 had a 21minute SA; Test 29 SWGR circuit had a 23 minute SA; Test 43 MOV2 circuit had multiple SAs for durations 57, 23, 24 minutes
- Like Test 43, Test 11 Large coil circuit had multiple SAs
- In Group 5 all circuit tests 45 thru 48 with inter-cable circuits indicated cable-to-cable interactions between the target cable and one or more of the source cables

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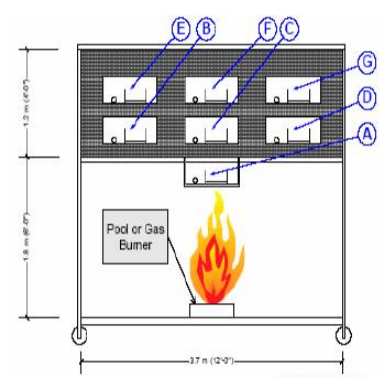
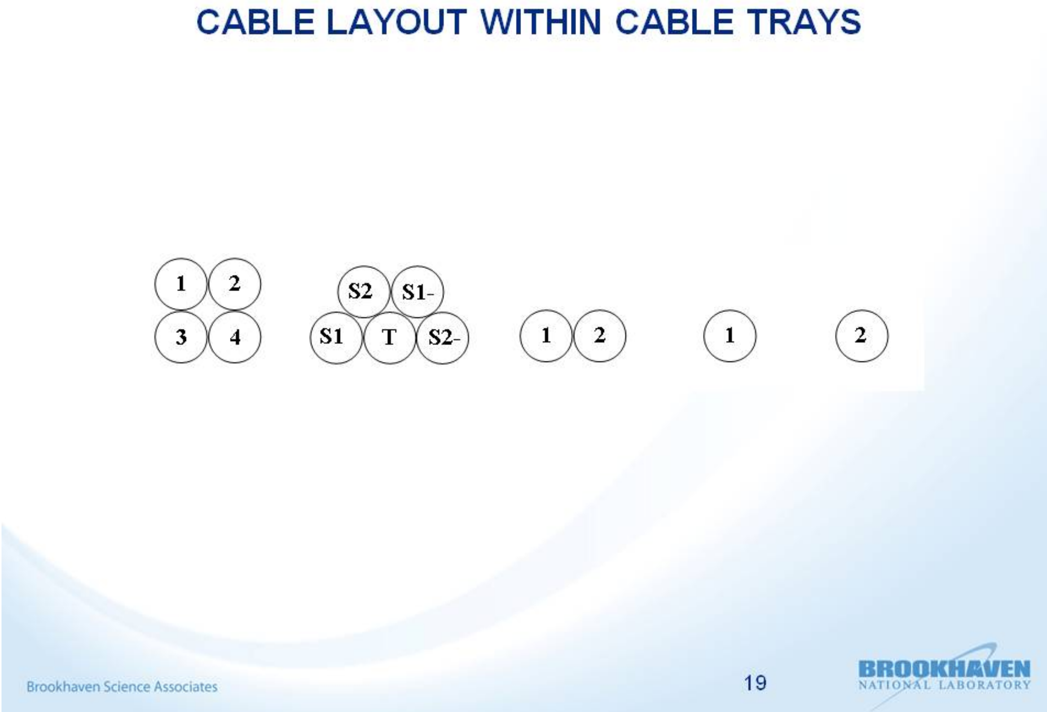
DESIREE-FIRE INTERMEDIATE-SCALE TESTS

- Less controlled, but a more realistic testing scale
- Hood is roughly the size of a typical ASTM E603 type room fire test facility (more open to allow for ready access)
- Propene (Propylene) burner fire source (173-327 kW typical)
- Different exposure conditions (flame region, plume, hot gas layer exposures)
- Cables in trays and conduits

LAYOUT OF INTERMEDIATE-SCALE TEST LOCATIONS




CABLE LAYOUT WITHIN CABLE TRAYS
1
2
3
4
S2
S1-
S1
T
S2-
1
2
1
2
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19
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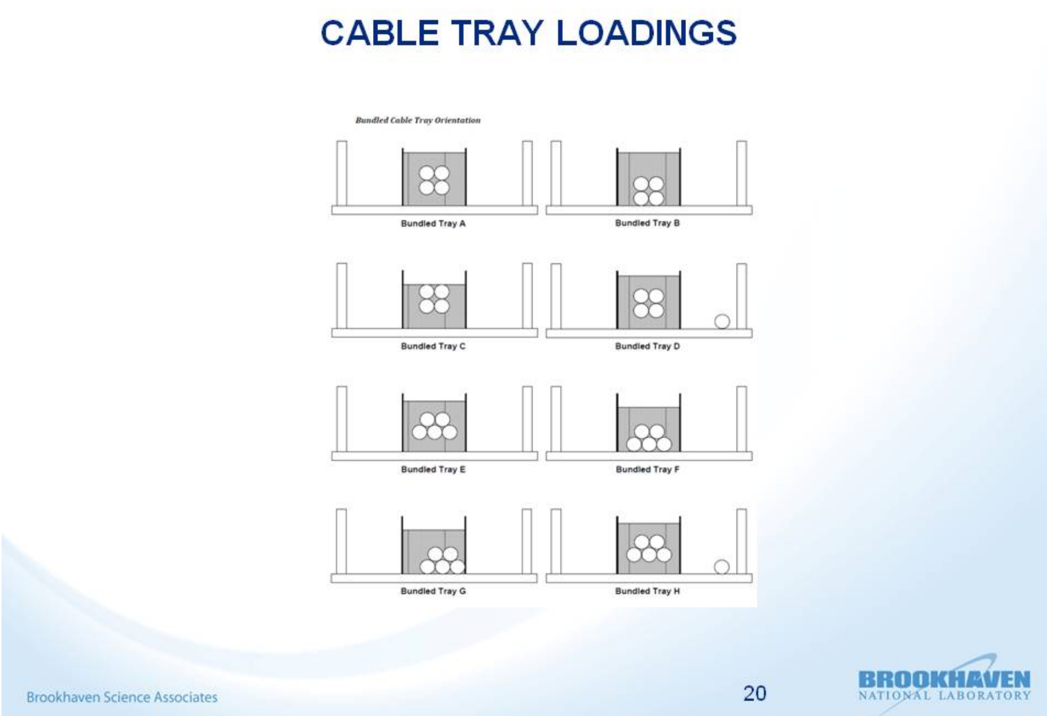
CABLE TRAY LOADINGS
Bundled Cable Tray Orientation
Bundled Tray A
Bundled Tray B
Bundled Tray C
Bundled Tray D
Bundled Tray E
Bundled Tray F
Bundled Tray G
Bundled Tray H
Brookhaven Science Associates
20
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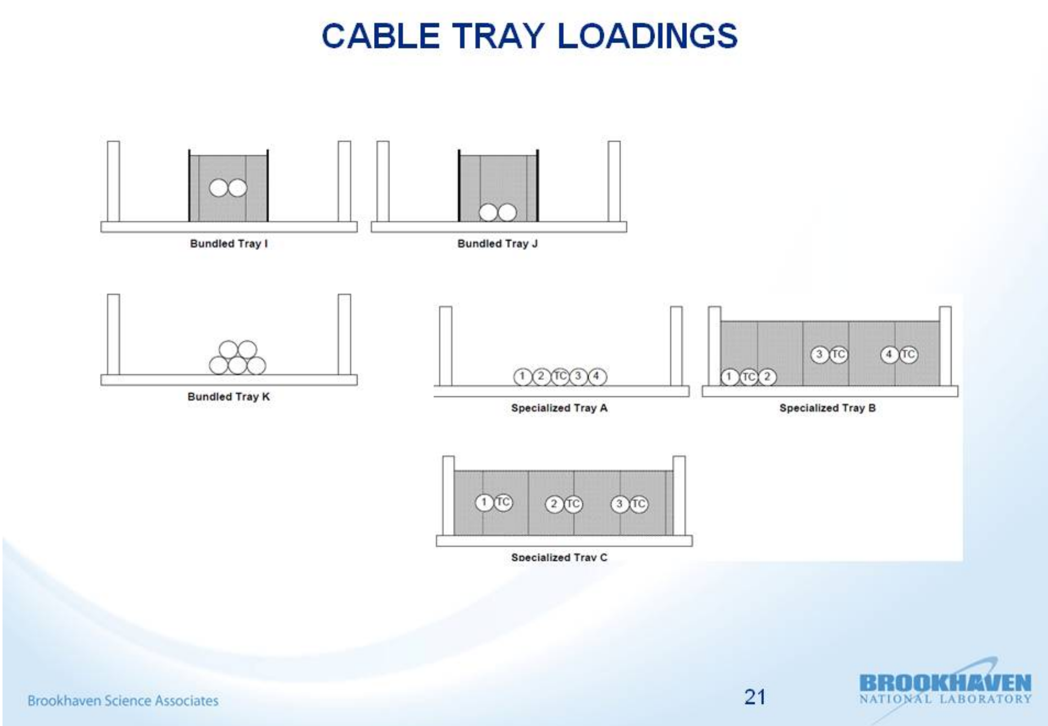
CABLE TRAY LOADINGS
Bundled Tray I
Bundled Tray J
Bundled Tray K
1 2 TC 3 4
Specialized Tray A
1 TC 2
3 TC
4 TC
Specialized Tray B
1 TC
2 TC
3 TC
Specialized Tray C
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21
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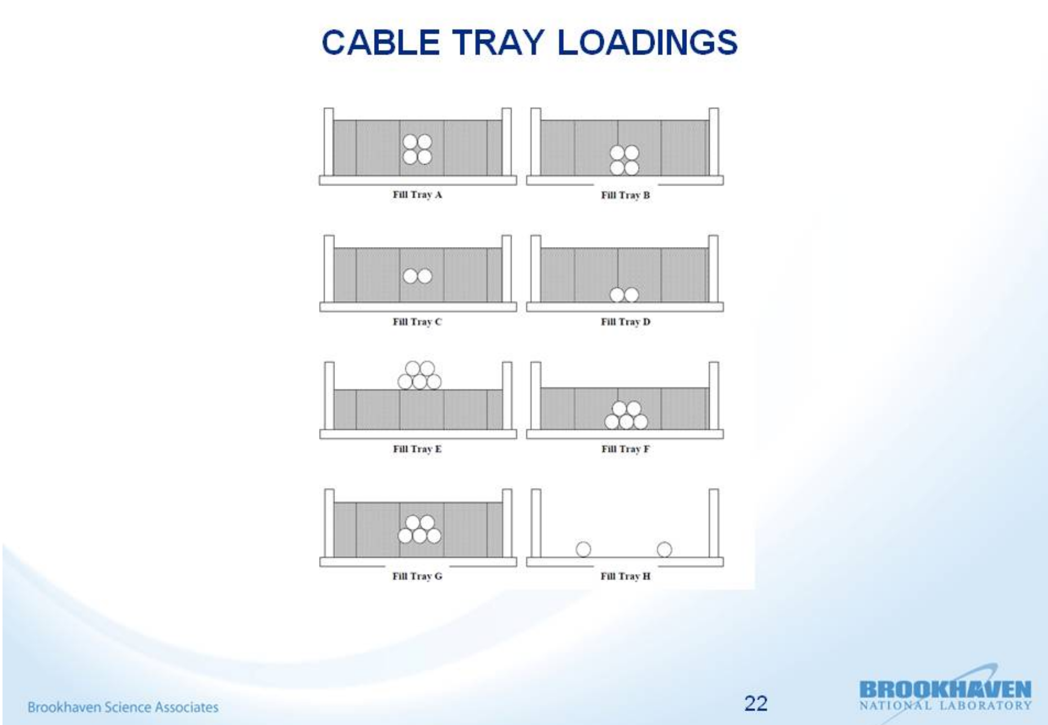
CABLE TRAY LOADINGS
Fill Tray A
Fill Tray B
Fill Tray C
Fill Tray D
Fill Tray E
Fill Tray F
Fill Tray G
Fill Tray H
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22
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DESIREE-FIRE INTERMEDIATE-SCALE TEST GROUPS

- Group 1 - DC Motor Starter (MOV) Circuit Tests (MOV1 and MOV2): Pre-2, 1 thru 12
- Group 2 - Small DC Solenoid Operated Valve (SOV) Circuit Tests SOV1 and SOV2): Pre-2, 1 thru 12
- Group 3 - DC Large Coil and 1-inch SOV circuit Tests (Large Coil and 1-inch Valve): Pre-1, 1 thru 12
- Group 4 - Switchgear Circuit Tests (SWGR TRIP and Close Coils): Pre-1, 1 thru 10, Cont-1 and Cont-2
- Group 5 - Inter-Cable Circuit Tests (Inter-Cable): Pre-1, 1 thru 12
- Group 6 - Surrogate Circuit Diagnostic Unit (SCDU) Tests: Pre-1 and Pre-2, 4, 8, 11, 12

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DESIREE-FIRE INTERMEDIATE SCALE FIRE TESTS

Test Number	Cable Type	Raceway Type	Raceway Loading	Monitoring Circuits	Fire Exposure (kW0	Comments
JPN-1	Japanese Japanese Japanese	Tray E Tray B Tray A	No Fill No Fill Fill Cables	SCDU-1 SCDU-2 SCDU-3	N/A	
Pre-1	None XLPE XLPE XLPE XLPE	Tray A Tray B Tray E Tray D Tray B	Fill Cable Only No Fill No Fill No Fill No Fill	None SCDU 3, 4 Lg Coil, 1" Coil Inter-Cable Bundle SWGR-C & T	N/A	
Pre-2	None PE PE PE	Tray B Tray A Tray D Tray E	Fill Cable Only No Fill No Fill No Fill	None MOV-1, SOV-1 SCDU-1,2 MOV-2, SOV-2	N/A	
1	None XLPE XLPE XLPE	Tray A Tray B and Conduit Tray C Tray D	Fill Cable Only Bundled Circuits Bundled Circuits Bundled Circuits	None MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2, SWGR-C & T	173-315	Tray B: MOV-1 and SOV-1 are in bundles without fill; Lg Coil and 1" Coil within fill tray
2	None XLPE XLPE XLPE	Tray B Tray C Tray D Tray A	Fill Cable Only Bundled Circuits Bundled Circuits Fill Cables	None MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2	171-327	
3	None XLPE XLPE XLPE	Tray C & E Tray D Tray A Tray B	No Fill Bundled Circuits Fill Cables Fill Cables	None MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2, SWGR-C & T	173-285	Tray B: MOV-2and SOV-2 are in tray with fill cables; SWGR C & T bundled in tray
4	XLPE XLPE XLPE XLPE	Tray D Tray A Tray B Tray C & E	Bundled Circuits Fill Cables Fill Cables Bundled Circuits	SCDU-1, 2, 3, 4 MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2, SWGR-C & T	145-285	Tray C: MOV-2 and SOV-2 bundled in tray; Tray E: Both SWGR circuits bundled in tray
5	None PE PE PE	Tray A Tray B and Conduit Tray C Tray D	Fill Cable Only Fill Cables Bundled Circuits Bundled Circuits	None MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2, SWGR-C & T	173-286	Tray B: MOV-1 and SOV-1 are in bundles without fill; Lg Coil and 1" Coil within fill tray

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DESIREE-FIRE INTERMEDIATE SCALE FIRE TESTS

Test Number	Cable Type	Raceway Type	Raceway Loading	Monitoring Circuits	Fire Exposure (kW0	Comments
6	PE PE PE PE	Tray B and Conduit Tray C Tray D Tray A	Fill Cables Bundled Circuits Bundled Circuits Fill Cables	SWGR-C & T MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2	173-248	Tray B: Fill cables in tray. SWGR-C & T in Conduit
7	None PE PE PE	Tray C & E Tray D Tray A Tray B and Conduit	No Fill Bundled Circuits Fill Cables Fill Cables	None MOV-1,SOV-1, SWGR-C & T Inter-Cable Bundle MOV-2, SOV-2, Lg Coil, 1" Coil	173-281	Tray B: MOV-1 and SOV-1 in tray; Lg Coil and 1" Coil in conduit
8	PE PE PE PE	Tray D Tray A Tray B Tray C	Bundled Circuits Fill Cables Fill Cables Bundled Circuits	SCDU-1, 2, 3, 4 MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2, SWGR-C & T	174-214	
9	None Armor & Kerite EPR Armor	Tray A Tray B Tray C Tray D	Fill Cable Only Fill Cables Bundled Circuits No Fill	None MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2, SWGR-C & T	173-282	
10	Kerite Kerite EPR Kerite	Tray C Tray D Tray A Tray B	Bundled Circuits Bundled Circuits Fill Cables Fill Cables	MOV-1,SOV-1 Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2, SWGR-C & T	173-318	
11	EPR EPR EPR EPR	Tray A Tray B Tray C Tray D	Fill Cables Fill Cables Bundled Circuits Bundled Circuits	SCDU-1, 2, 3 MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2	173-301	Tray C: Connected to 35A fuses
12	EPR EPR EPR EPR	Tray C Tray D Tray A Tray B	Bundled Circuits Bundled Circuits Fill Cables Fill Cables	SCDU-1, 2, 3 MOV-1,SOV-1, Lg Coil, 1" Coil Inter-Cable Bundle MOV-2, SOV-2	172-307	Tray C: Connected to 35A fuses
Cont-1	None XLPO	Tray A Tray B	Fill Cables Only No Fill	None SWGR-C & T	168	
Cont-2	None TEFZEL	Tray A Tray B	Fill Cables Only No Fill	None SWGR-C & T	140	

DESIREE-FIRE INTERMEDIATE SCALE TEST: SPURIOUS ACTUATIONS/HOT SHORTS

CABLE Material	Group 1 MOVs	Group 2 SOVs	Group 3 1"/Large	Group 4 SWGR T/C	Group 6 SCDUs	Total Number SAs/HSs
TS-XLPE	8/8	5/8	3/10	4/8	4/6	24/40
TS-EPR	2/4	2/4	3/4		2/6	9/18
TS-SR						
TS-Kerite	3/3	1/3	1/2	1/2		6/10
TS-XLPO				2/2		2/2
TS-Armored	1/1	1/1	1/2	0/2		3/6
TP-PE	5/10	5/10	4/8	5/8	1/6	19/42
TP-PVC						
TP-TEF				0/2		0/2
VITA-LINK						
TS/TP Comb.						
TOTAL	19/26	14/26	12/26	12/24	7/18	64/120

SUMMARY OF DESIREE-FIRE INTERMEDIATE SCALE TEST RESULTS

- Group 1 – 19/26 (excl. JPN-1); Group 2 - 14/26; Group 3 – 12/26; Group 4 – 12/24 (excl. JPN-1&2); Group 6 – 7/18 HS/SAs. Group 5 – 4/4 is considered separately. Thus, a combined 64/120 SAs and/or HSs Occurred
- Test Number P-1 MOV2 open coil had a SA duration of 6.6 minutes; All others are smaller than 2 minute duration
- In Group 5 all circuit tests with inter-cable circuits indicated cable-to-cable interactions between the target cable and one or more of the source cables
- Large fraction of Tests failed due to fuse blown before any hot short or SA
- SR, Kerite and Vita Link cables did not fail cases were observed

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CONCLUSIONS AND GENERAL INSIGHTS

- For DC Circuits (in comparison to AC Circuits):
  - The faulting behavior was more energetic and more damaging
  - Short circuit faulting often led to destructive damage to the cable conductors
  - Because of large fuse sizes used, cables were left energized even after they had experienced destructive damage
  - More long duration hot shorts and spurious operations were observed
- For AC circuits: Like CAROLFIRE tests, DESIREE-FIRE tests failed to reproduce the voltage degradation effect that had been noted by NEI/EPRI tests. Tests having CPTs (150VA and 200VA) showed substantial degradation of source voltage sufficient to prevent a SA locking in. Tests with smaller CPTs (75VA and 100VA) did not experience sufficient voltage degradation to prevent SA lock in

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EXPERT ELICITATION OF CABLE FIRE TESTS

SPURIOUS ACTUATION OF ELECTRICAL CIRCUITS DUE TO CABLE FIRES

Mano Subudhi, Jim Higgins, & Ken Sullivan
Brookhaven National Laboratory
November 2010

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a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

PROGRAM OBJECTIVES

- To identify phenomena that lead to fire-induced electrical circuit faults which can cause equipment to spuriously actuate
- To rank the current level of knowledge to each of the identified phenomena
- To quantify the probability (or likelihood) of cable and circuit failure phenomena identified above

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PHENOMENA IDENTIFICATION AND RANKING TABLE (PIRT)

- PIRT is a systematic approach to expert elicitation to improve the understanding of a technical issue or prioritize research
  - An expert panel is selected based on their knowledge and insight on the technical issue
  - The PIRT identifies the physical phenomena that dominate scenarios of interest
  - PIRT provides both qualitative and quantitative assessment of analytical and/or experimental data
- PIRT application to cable fires in nuclear power plants
  - Created two separate panels of experts: Electrical panel and PRA panel
  - Identified phenomena that lead to spurious actuations (SAs) of electrical circuits due to cable fires
  - Will provide each panel both qualitative and quantitative data from the NEI/EPRI (i.e., Omega Point) and SNL/NRC (i.e., CAROLFIRE /DESIREE-FIRE) cable fire test results
  - PIRT process will address the use of this data for Probabilistic Risk Assessment (PRA) and application to NFPA 805, "Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants"

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PROGRAM GOALS

- Task 1: Identify and contract expert panel members for an "Electrical Experts Group" and a "PRA Experts Group"
- Task 2: Review Omega Point and CAROLFIRE/DESIREEE-FIRE test results
  - Develop materials to be provided to each panel
  - Develop cable and circuit phenomena, parameters, or configurations which have a higher likelihood of initiating spurious actuations in the event of fire damage to the cable
  - Develop quantitative occurrence of these cables and circuit phenomena
- Task 3: Schedule and moderate expert elicitation and PIRT meetings
  - Arrange and participate in four to five PIRT meetings (two to three days of duration each) in each of the two subject areas
  - Facilitate and moderate all PIRT meetings
- Task 4: Prepare expert elicitation and PIRT reports

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Task 1: Selection of expert panel members for an "Electrical Experts Group" and a "PRA Experts Group"

- A maximum of eight members for each PIRT panel are primarily identified by the NRC/RES staff
- The selected experts for each panel represent a range of specific expertise areas and backgrounds
  - Researchers/Consultants
  - Regulators/Plant inspectors
  - Fire protection and electrical engineers working with practical field applications
- Factors considered in the panel member selection process
  - Availability and willingness to serve
  - Absence of financial conflicts of interest
  - Impartiality
  - Prior experience working in committees, subcommittees, and advisory panels

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Task 1: Expert panel member candidates for an Electrical Experts Group

- Harry Barrett, NRC
- Jeff Circle, NRC
- Steve Nowlen*, SNL
- Gabriel Taylor, NRC
- David Crane, Pyrolico Corp.
- Dan Funk*, Edan
- Thomas Gorman, PPL
- Andy Ratchford, Kleinsorg Group

* Members of both panels

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Task 1: Expert panel member candidates for a PRA Experts Group

- Ray Gallucci, NRC
- Martin Stutzke, NRC
- Steve Nowlen*, SNL
- Nathan Siu, NRC
- Dan Funk*, Edan
- Dennis Henneke, GEH
- Dave Miskiewicz, Progress Energy
- Kiang Zee, ERIN

* Members of both panels

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Task 3: Fire-induced electrical circuit faults which can cause equipment to spuriously actuate

- Under what conditions could a fire-induced cable damage in a nuclear power plant cause the spurious actuation of electrical power, control and instrumentation circuits affecting the safety of the plant?
- Based on the current level of knowledge how to prioritize the combinations of these conditions defining the phenomena identified above?
- What is the probability of such actuation occurring conditional to the fire-induced cable damage?

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PIRT PROCESS (TYPICAL)

- PIRT – Phenomena Importance Ranking Table
  - An expert elicitation process
  - Define the phenomena relevant to the defined applications
  - Rank the identified phenomena for importance against the PIRT figure of merit
  - Rank the current level of knowledge relative to each of the identified phenomena
- Ranking Table Outputs
  - Rank both importance and state of knowledge for all phenomena considered
- PIRT Results
  - Phenomena that are ranked of high importance and have a poor state of knowledge would be a research priority
  - Phenomena that are ranked high importance and have an excellent state of knowledge would have higher importance for PRA and plant design

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PIRT PROCESS – Fire-Induced Spurious Actuation

- PIRT – Fire-induced spurious actuation
  - Define the phenomena that lead to fire-induced electrical circuit faults which can cause equipment to spuriously actuate
  - Rank the identified phenomena for importance against the PIRT figure of merit
  - Quantify the probability (or likelihood) of cable and circuit failure phenomena identified
  - Rank the current level of knowledge relative to each of the identified phenomena and its likelihood of occurring in a plant set up
- PIRT – Ranking Table Outputs
  - Rank both importance and state of knowledge for all phenomena considered
  - Rank both the probability of spurious actuation and state of knowledge for all phenomena considered
- PIRT – Results
  - Will provide both quantitative and qualitative data for use in fire PRA and application of NFPA 805
  - Will provide guidance for future research and identification of any circuit configurations that may have not been known in the past fire modeling applications

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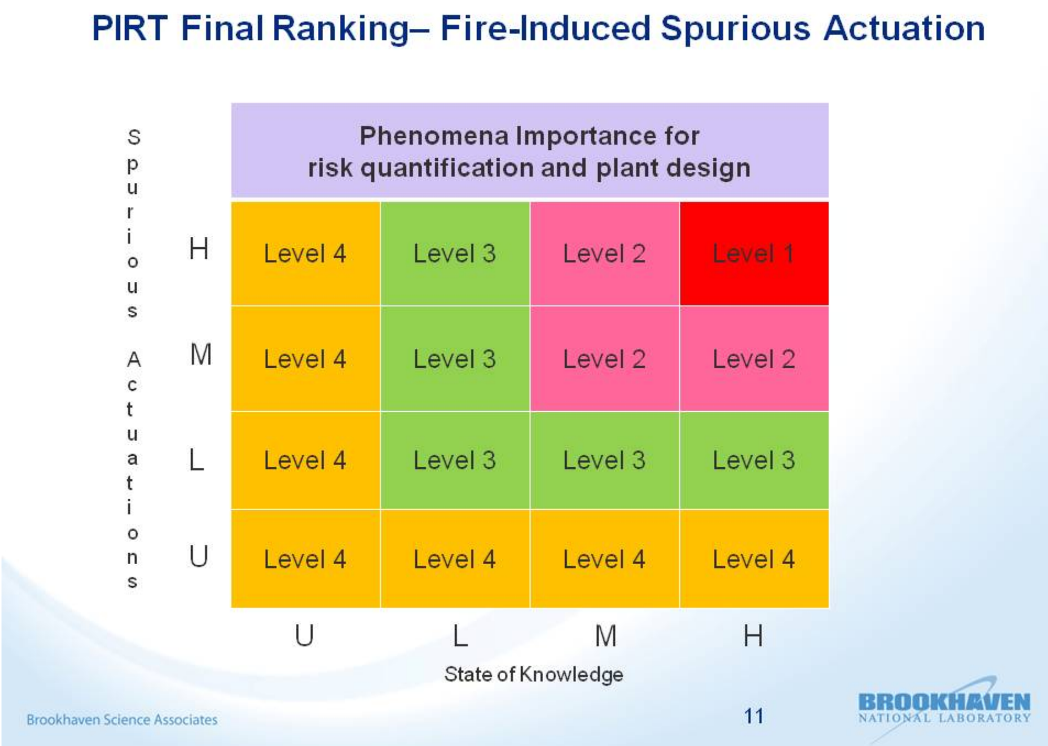
PIRT Final Ranking– Fire-Induced Spurious Actuation
Phenomena Importance for
risk quantification and plant design
Spurious Actuations
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State of Knowledge
Brookhaven Science Associates
11
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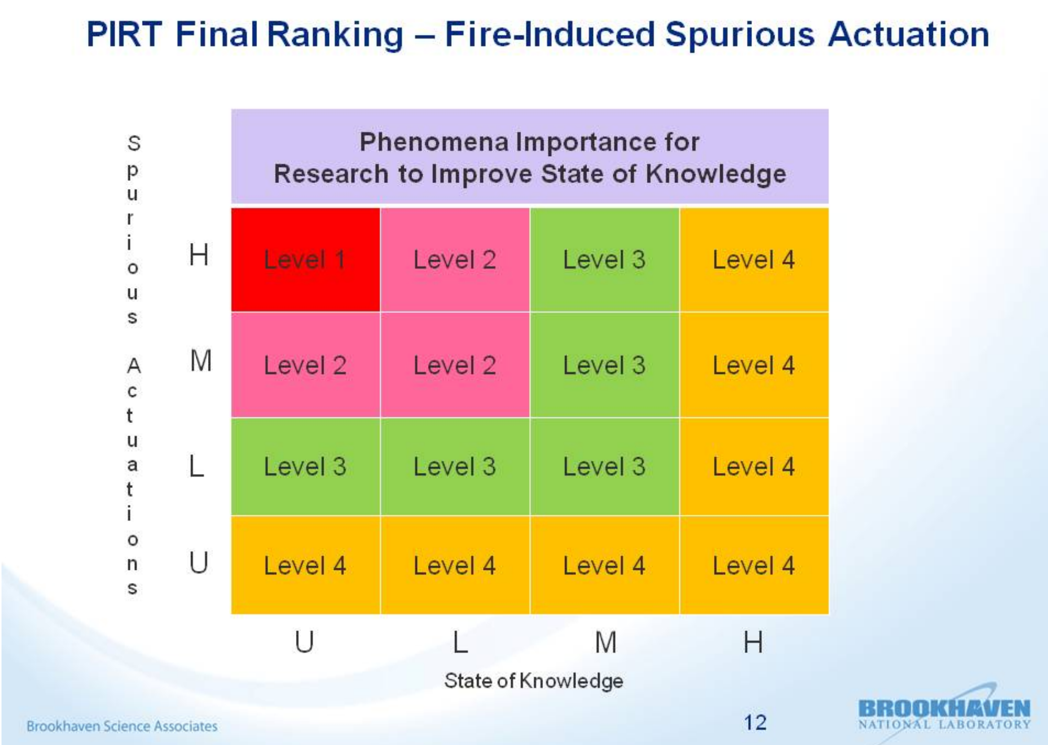
PIRT Final Ranking – Fire-Induced Spurious Actuation
Phenomena Importance for
Research to Improve State of Knowledge
Spurious Actuations
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Identification	Effect of Parametes on the Plant Cable Configuration (Base Case)	Phenomena Accuracy Ranking	Phenomena Vulnerability Ranking	Phenomena Importance Ranking	Statement of Knowledge Ranking	Data Adequacy Ranking
4.1	BASE CASE a. AC Circuit b. DC Circuit					
4.2	CABLE INSULATION TYPES a. Mix of XLPE, EPR, SR/KERITE TS Cables b. Mix of TS and TP Cables c. Mix of Power and Instrument Cables					

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PIRT PROCESS – Fire-Induced Spurious Actuation METRIC

- Purpose to predict fire-induced spurious actuation of safety related electrical circuits (e.g., power, control, and instrument) in nuclear power plants, given a fire with adequate exposure intensity and duration causing significant cable damage
- Assume that a spuriously actuated system or component would perform unwanted functions or indicate misleading information while achieving and maintaining safe shutdown of the reactor during a plant accident
- The plant accident may lead to core damage or loss of containment integrity – Safety Functions
- The plant accident further may jeopardize the health and safety of the public and plant personnel (NRC Mission)

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PIRT PROCESS – Fire-Induced Spurious Actuation Scenario METRIC

- Each scenario assumes the following conditions:
  - Cables (power, control, and instrument) in cable trays, conduits, or air drop configurations – based on plant-specific configurations
  - Cables are damaged by fire so that spurious actuation would occur between energized (source) conductors and un-energized (target) conductors – based on NEI and Sandia test results
  - Spurious actuations would energize target conductors which could lead to unwanted functions of safety related equipment or indicate misleading information – based on electrical circuits associated with the target conductor(s)
- Each scenario represents cable routing on cable raceways (e.g., cable trays, conduits) in a nuclear power plant. Within each scenario, a phenomena (or a sub-phenomena) represents cable types, routing configurations, cable conditions, and other cable routing characteristics
- For each phenomena or sub-phenomena, the metric is:
  - What is the likelihood (qualitatively) of spurious actuation(s) occurring under the given conditions for each phenomena?
  - What is the probability (quantitatively) of spurious actuation(s) occurring under the given conditions for each phenomena?

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PIRT PROCESS – Fire-Induced Spurious Actuation State of Knowledge

- Knowledge of the phenomena with respect to actual cable raceway configuration in a nuclear power plant
- Knowledge of actual fire damage of cables in a plant
- Knowledge of any test data to validate the spurious actuations in the event of fire damage
- Knowledge of spurious actuation of safety related components due to fire damage
- Availability of data for predicting the likelihood of the phenomena
- Feasibility of getting new validation data

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PIRT PROCESS – Fire-Induced Spurious Actuation
Parameters not affecting the phenomena

Fire intensity is assumed to be high enough to cause cable damage (as included in the fire modeling) that could lead to spurious actuations. Hence, the following parameters associated with thermal response of cables and circuit characterization are not considered as part of the spurious actuation phenomena:

- Fire exposure conditions – plume, radiant, hot gas layer
- Fire characterization – source, size, heating rate
- Cable routing configuration – bends, straights
- Raceway loading – neatly packed, randomly filled
- Circuit functions – circuit-to-cable configuration

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PIRT PROCESS – Fire-Induced Spurious Actuation
Parameters affecting the phenomena

Since it is assumed that the fire has damaged the cables in a particular fire zone leading to spurious actuations, the following parameters should affect the spurious actuation phenomena:

- Cable type – armored, unarmored
- Cable effects – Insulation thickness & Number and Size of conductors (P,C,I), Jacket material
- Cable insulation types – thermosetting (TS), thermoplastic (TP), TS/TP mix
- Cable grounding condition – proximity of grounded conductor or ground plane, ungrounded
- Source and Target conductor configurations
- Cable layout – cable tray, conduit, air drop – horizontal or vertical
- Cable fill or bundling configuration – spatial configuration of target and source conductors
- Cable electrical properties – power, control, instrument
- Cable faults – hot shorts, short to ground, open circuit
- Circuit configuration – AC/DC, Fuse size, CPT size

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PIRT PROCESS – Fire-Induced Spurious Actuation Cable Insulation Material Type - Scenarios

- Thermoset (TS) Cable Insulation Materials
  - TS – Cables (XLPE, XLPO, EPR)
  - TS – SR (VITA-LINK)
  - TS – Kerite
  - TS – Armored
- Thermoplastic (TP) Cable Insulation Materials
  - TP – Cables (PE,PVC, TEFZEL)
- Special Cable Insulation Materials
  - TS/TP Combinations

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Base Case for Spurious Actuation

- Base Case: unarmored 7/C and 1/C, AWG 12, TS control cable, horizontal cable tray, single layer fill, no ground wire, source and target conductors under hot gas layer (gradual heat-up), connected to a CPT

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PIRT PROCESS – Fire-Induced Intra-Cable/Inter-Cable Spurious Actuations for Each Scenario

For Each AC and/or DC Electrical Circuit

Given fire damage, assess the potential for hot shorts and/or spurious actuation of electrical cable for each cable material scenario. Consider the following as variation on the base case.

- Cable Characteristics
  - Effect in XLPE, EPR, SR, Vita Link, Kerite cables or mix
  - Effect in power and instrument cables or mix
  - Armored cables
- Cable Routing Configuration
  - Effect of cable tray orientation in vertical, conduit, air drop
  - Effect of source and target conductor locations
  - Effect of raceway fill; loading; bundling
- Cable Physical Properties
  - Effect of jacket material
  - Effect of conductor size/ number of conductors
  - Effect of insulation/jacket material thickness
  - Effect of ground wire (shielding/drain wire) or grounded circuits
- Miscellaneous Effects
  - Effect of fire exposure (time and temperature) – plume or hot gas layer
  - Effect on circuit type – power, control, instrument
  - Effect of circuit characteristics: cable lengths, fuse sizes, CPT size
  - Effect of water spray

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PIRT PROCESS – Fire-Induced Spurious Actuation Short Summary of NEI/EPRI and SNL/NRC Test Findings

- Given significant fire damage, cables may exhibit hot shorts, short to ground, or blown fuse (open circuit)
- Hot shorts will lead to intra-cable or inter-cable spurious actuations
- Intra-cable shorting is much more likely than inter-cable shorting
- High likelihood of the source conductor to short to grounded conductor than to an ungrounded conductor
- Both the electrical properties and the spatial configuration are important for potential of an SA occurring in an electrical circuit
- Highly dependent on detailed layout and cable configuration of the source and target conductors
- Water spray to significantly fire-damaged cables always caused blown fuse or open circuit
- Cables in less filled tray are more susceptible to fire damage than a tray with more fill

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PIRT PROCESS – Fire-Induced Spurious Actuation Figure of Merit

- **Top Level:** Protecting the health and safety of the public and the plant employees
- **Second Level:** Fire-induced spurious actuation leading to off-site release of radioactive materials due to false instrument readings or unwanted operation of electrical power and control circuits
- **Third Level:** Spurious actuation(s) that cause the loss of critical plant system and component leading to reactor control challenges, core damage, and a containment integrity challenge
- **Fourth Level:** Fire Probabilistic Risk Assessment (FPRA) and other applications of the fire modeling tools (including NFPA-805) to assess plant safety, adequacy of the fire protection program, and finding of non-compliance

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PIRT PROCESS – Fire-Induced Spurious Actuation Phenomena Importance Ranking

- **High (H):** First order importance to figure of merit
- **Medium (M):** Secondary importance to figure of merit
- **Low (L):** Negligible importance to figure of merit.
- **Uncertain (U):** Potentially important. Importance should be explored through reliable analysis and/or discovery experiments

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PIRT PROCESS – Fire-Induced Spurious Actuation Phenomena Accuracy Ranking

- **High (H):** At least one physical configuration of the cable routing exists that adequately represents the phenomenon in a fire zone of nuclear power plants
- **Medium (M):** At least one physical configuration of the cable routing exists that nominally represents the phenomenon in a fire zone of nuclear power plants
- **Low (L):** No such physical configuration of the cable routing exists that represents the phenomenon in a fire zone of nuclear power plants
- **Uncertain (U):** Probably such cable configuration exists in nuclear power plants, but the panel member is unaware of it

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PIRT PROCESS – Fire-Induced Spurious Actuation Phenomena Vulnerability Ranking

- **High (H):** Given a fire damage, the phenomenon is vulnerable to at least one or multiple spurious actuations
- **Medium (M):** Given a fire damage, the phenomenon may be vulnerable to at least one or multiple spurious actuations
- **Low (L):** Given a fire damage, the phenomenon has very little vulnerability to at least one or multiple spurious actuations
- **Uncertain (U):** Probably hot shorts leading to spurious actuations would occur, although there is greater chance of shorting to ground or open circuit before shorting to another conductor

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PIRT PROCESS – Fire-Induced Spurious Actuation Statement of Knowledge Ranking

- **High (H):** Plant-specific or testing database exists, or a highly reliable assessment can be made based on existing knowledge. Data are readily available to support the phenomenon and its vulnerability to spurious actuations.
- **Medium (M):** Existing plant-specific or testing database moderately support the phenomenon and its vulnerability to spurious actuations. Moderately reliable assessment can be made based on existing knowledge.
- **Low (L):** No existing plant-specific or testing database could support the phenomenon and its vulnerability to spurious actuations. Reliable assessment can not be made based on existing knowledge.
- **Uncertain (U):** The panel is unaware of the existing state of knowledge with respect to this phenomenon

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PIRT PROCESS – Fire-Induced Spurious Actuation Data Adequacy Ranking

- **High (H):** Data needed are readily obtainable based on existing experimental capabilities
- **Medium (M):** Data would be obtainable but would require moderate, readily attainable extensions to existing capabilities
- **Low (L):** Data are not readily attainable and/or would require significant development of new capabilities

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PIRT PROCESS – Fire-Induced Spurious Actuation Overall Importance Levels

- Overall importance levels are identified and designated Level 1 though Level 4, with Level 1 being the most important.
- Separate importance levels are identified for:
  - risk quantification and plant design
  - Research to Improve State of Knowledge
- If a phenomenon is of high importance and high state of knowledge, it is placed at the highest overall level for risk quantification and plant design
- If a phenomenon is of high importance and low state of knowledge, it is placed at the highest overall level for research to improve state of knowledge.

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Task 2: Omega Point and CAROLFIRE/DESIREE-FIRE Documents

Documents Reviewed

- Omega Point Tests (NEI/EPRI)
  - EPRI TR 1003326, "Characterization of Fire-Induced Circuit Faults – Results of Cable Fire Testing," December 2002
  - EPRI TR-1006961, "Spurious Actuation of Electrical Circuits Due to Cable Fires – Results of an Expert Elicitation," May 2002
- SNL CAROLFIRE AC Tests (NRC)
  - NUREG/CR-6931, Volume 1, "Cable Response to Live Fire (CAROLFIRE) Volume 1: Test Descriptions and Analysis of Circuit Response Data," April 2008
  - NUREG/CR-6931, Volume 2, "Cable Response to Live Fire (CAROLFIRE) Volume 2: Cable Fire Response Data for Fire Model Improvement," April 2008
  - NUREG/CR-6931, Volume 3, "Cable Response to Live Fire (CAROLFIRE) Volume 3: Thermally-Induced Electrical Failure (THIEF) Model," April 2008
- SNL DESIREE-FIRE DC Tests (NRC)
  - "Project Plan for Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-FIRE)," July 10, 2009
  - NUREG/CR-Draft, "Direct Current Shorting in Response to Exposure Fire (DESIREE)," September 2010
- Other Reports and Documents
  - NUREG/CR-6834, "Circuit Analysis – Failure Mode and Likelihood Analysis," September 2003
  - NUREG/CR-6978, "A Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire Modeling Applications," November 2008

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Task 2: NEI/EPRI and SNL/NRC TEST MATRIX

TEST Elements	NEI/EPRI Omega Point	CAROLFIRE Penlight	CAROLFIRE Intermediate	DESIREE-FIRE Penlight	DESIREE-FIRE Intermediate
AC/DC	AC SCDUs	AC IRMS	AC IRMS/ SCDUs	DC Circuits/ SCDUs	DC Circuits/ SCDUs
Raceway	Tray, Conduit Air Drop	Tray, Conduit	Tray, Conduit Air Drop	Tray, Conduit	Tray, Conduit
Cable Types	TS,TP,ARM	TS,TP,VL	TS,TP,VL	TS,TP,K,ARM	TS,TP,K,ARM
Mixed Cables	One Test	Most	Most	None	None
Tray Loading	Yes	Yes	Yes	No	Yes
Fire Exposure	P,R,HGL	R	P,HGL	R	P,HGL
Bundling	4 Cables (1 7/C Cable 3 1/C Cables)	3 Cables (C) 6 Cables (T)	4 Cables (Th) 6 Cables (T) 12 Cables (T)	N/A	N/A
No. of Tests	18	16	18	53	17

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Task 2: Omega Point and CAROLFIRE/DESIREE-FIRE TEST CABLE MATERIAL MATRIX

CABLE Material	NEI/EPRI Omega Point	CAROLFIRE AC Penlight	COROLFIRE AC Intermediate	DESIREE-FIRE DC Penlight	DESIREE-FIRE DC Intermediate
TS-XLPE	X	X	X	X	X
TS-EPR	X	X	X	X	X
TS-SR		X	X	X	
TS-Kerite				X	X
TS-XLPO		X	X		X
TS-Armored	X			X	X
TP-PE	X	X	X	X	X
TP-PVC		X	X	X	
TP-TEF	X	X	X	X	X
VITA-LINK		X	X		
TS/TP Comb.	X	X	X		

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Task 2: Omega Point and CAROLFIRE/DESIREE-FIRE Cable Specifications

- Typical Safety-Related Cable Specifications
  - Power Cables
    - Voltage 120 V – 4.16 kV (Off-site power ranging up to 15 kV or higher). Typical rating of 600V with 480 V circuit.
    - Current Rating in hundreds of amps
    - M/C (commonly used Triplex Cable - a cable with three, spiral wound, individually insulated conductors and typically no overall jacket and may include an uninsulated ground conductor)
    - 1/C (For single-phase light power applications use of either 2/C or 3/C cables is common. For single-phase 3/C applications, typically one conductor would be grounded)
    - 12 AWG or larger (conductor diameter of up to 1 inch)
  - Control Cables
    - Voltage rating of 600 V with 120 – 250 volt range circuit
    - Current rating in 1-5 amps
    - M/C cables (Typically 3 – 12 conductors in a cable)
    - 16 – 10 AWG
  - Instrument Cables
    - Voltage 50 Volts or less
    - Current ratings in milliamps
    - M/C cables (Typically 50 or more conductors)
    - 16 AWG or smaller (sometimes 12 AWG is used)

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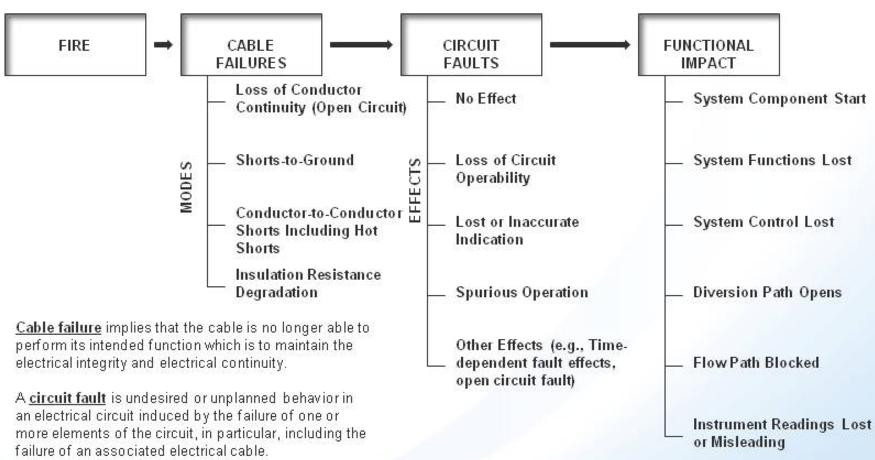
Task 2: Circuit Analysis Process



<u>Cable failure</u> implies that the cable is no longer able to perform its intended function which is to maintain the electrical integrity and electrical continuity.

A <u>circuit fault</u> is undesired or unplanned behavior in an electrical circuit induced by the failure of one or more elements of the circuit, in particular, including the failure of an associated electrical cable.

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Task 2: Definitions of Cable Failures (Ref. NUREG/CR-6834)

- Cable Fire Damage – If a cable connected to an electrical circuit (i.e., power, control , or instrument) is exposed to a fire (i.e., in the form of a plume, hot gas layer, and/or radiant heating directly above the fire), the damage of the cable may occur progressively from a base state of initial heating up to the end state of complete burn up to a crisp. Note that a cable is consisting of an insulation material (TS or TP) for each conductor, a jacket material (TS or TP) for all conductors, and other protective components (e.g., fillers, metal armor, aluminum foil shield) surrounding the conductors.
- Cable Functional Damage – For the case of an energized or un-energized conductor within a multi-conductor cable, the functional damage of the cable is identified with one of the following primary states of the electrical circuit: shorts to ground (i.e., raceway, ground/drain conductor, metal foil shield wrap, or armored sheath), short to another cable co-located in the same raceway, short to another conductor within the same cable, or an open circuit (fuse blow or breaker trip).
- Given the extent of the cable fire damage and the primary state of the cable's functional damage, our task here is to predict and rank scenarios that would spuriously actuate (e.g., spike, chatter, lock-in, drop-out, lock-out) an electrical circuit causing disruptions in the as-designed functional state of a safety-related equipment or device.

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Task 2: Cable and circuit phenomena, parameters, or configurations - Circuit Fault Modes (NUREG/CR-6834)

A. LOSS OF CONDUCTOR CONTINUITY (Open Circuit – fuse blow, breaker trip)

- Power Circuit Fault Modes
  - For operating components - Loss of motive power to equipment resulting in failure to perform their design functions
  - For standby components – Prevent equipment from starting and operating as designed
  - For certain components, maintaining a constant power for holding their current positions (e.g., SOVs or relays that are normally energized) – Change in the component position that can have adverse effects on system operation
  - For components requiring intermittent power (e.g., MOVs) for operation – Leave the component at its initial state and prevent from required operation
  - For electrical distribution cables – Loss of power to multiple safety components
- Control Circuit Fault Modes
  - Circuit controlling power to remotely operated breakers, relays, and motor contactors – Closed for power to reach the component
  - Circuit to shut off a component or change its position – Eliminate this capability
  - Circuit maintaining a continuous control signal (e.g., SOVs) – Change the state and would render the system unavailable
  - Circuit indicating status – Loss of status indication

NOTE: Individual conductors for a given component control circuit may be routed via the same multi-conductor cable (e.g., SOV position, remote operability, and loss of indication)

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Task 2: Cable and circuit phenomena, parameters, or configurations - Circuit Fault Modes

A. LOSS OF CONDUCTOR CONTINUITY (Open Circuit – fuse blow, breaker trip) CONTD.

- Instrument Circuit Fault Modes
  - Type of sensor (e.g., V/I signal or digital) - Loss of indication or false indication
- Typically, Loss of Continuity in Circuit Failures is a Secondary Concern
  - Cables experience shorts to ground well before the loss of continuity failure (specifically for control and instrument cables)
  - Higher voltage circuits may lead to a higher likelihood of loss of continuity for power circuits (This occurs after repeated short-duration shorts to ground)
  - Loss of continuity mimics the effects of opening of circuit protection devices, which typically results from over-current due to either shorts to ground or phase-to-phase shorting

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Task 2: Cable and circuit phenomena, parameters, or configurations - Circuit Fault Modes

B. SHORTS TO GROUND [a conductor-to-external ground short (e.g., Raceway) or a conductor-to-ground conductor short]

- Power and Control Circuits (impact is the same regardless of the source of the ground)
  - Grounded circuit – grounded portion of the circuit has no impact; however ungrounded power phases will divert power from the circuit (a high impedance short will sustain power flow, while a low impedance short will trip fuse or breaker leading to an open circuit)
  - Ungrounded circuit – short to ground involving either a non-energized conductor or any one phase of the power supply has no impact on the circuit
  - Multiple shorts to ground in an ungrounded circuit can mimic a hot short
  - Effect of two phases of an ungrounded power circuit short to ground concurrently is the same as a phase-to-phase short on that circuit and fuse or breaker would trip as a result
  - A higher-level circuit protection device leading to loss of multiple power bosses may trip if several power cables form concurrent high-impedance shorts
  - Random failure of the power circuit protection device may lead to loss of power to multiple safety components

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Task 2: Cable and circuit phenomena, parameters, or configurations - Circuit Fault Modes

B. SHORTS TO GROUND [a conductor-to-external ground short (e.g., Raceway) or a conductor-to-ground conductor short] CONTD.

NOTE: One circuit design feature that can influence the impact of a short to ground, in particular for power circuits, is breaker coordination

- Instrument Circuits
  - Short to ground may generate no impact, faulty indications, or a complete loss of signal depending on the nature of the circuit
  - Multiple shorts to ground on an ungrounded instrument loop can mimic conductor-to-conductor shorts for that same circuit
  - High impedance shorts may result in a misleading or biased instrument readings, where as a low impedance short would typically result in a complete loss of the signal

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Task 2: Cable and circuit phenomena, parameters, or configurations which have a higher likelihood of initiating spurious actuations in the event of fire damage to the cable - Circuit Fault Modes

C. CONDUCTOR-TO-CONDUCTOR SHORTS Including **Hot Shorts** (that can cause spurious actuations)

- Power Circuits
  - Concurrent hot shorts on all 3-phases of an AC power source may activate the component, although they are low likelihood of occurring
  - Shorts between circuits of different voltage can result in the application of destructive voltages to the lower voltage circuit
  - Shorts between phases of common power supply would lead to opening of circuit protection features for that circuit

- Control Circuits
  - For grounded control circuit, any energized conductor might represent power source conductor in a hot short, regardless of which circuit supplies the power

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Task 2: Cable and circuit phenomena, parameters, or configurations which have a higher likelihood of initiating spurious actuations in the event of fire damage to the cable - Circuit Fault Modes

C. CONDUCTOR-TO-CONDUCTOR SHORTS Including **Hot Shorts** (that can cause spurious actuations)

- Control Circuits (CONTD.)
  - For ungrounded control circuit,
    - "smart short scenario" - Two hot shorts form concurrently - one involving a positive side source conductor and a positive side target conductor, and the second involving a negative side source conductor from the same power supply circuit shorting to the corresponding negative side target conductor for the same control circuit.
    - A single hot short to the proper conductor could cause spurious actuation, when the energizing source conductor is powered from the same power source as the target control circuit (e.g., the same control power transformer or battery).
  - A conductor-to-conductor short on an ungrounded DC control circuit could also result in opening a circuit protection device (i.e., a fuse or circuit breaker) if a positive conductor shorts to a negative conductor from the same DC source (or vice versa).
  - Multiple shorts to ground on ungrounded DC circuits from the same battery (or on ungrounded AC circuits from the same transformer) may have the same functional effect as a hot short

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Task 2: Cable and circuit phenomena, parameters, or configurations which have a higher likelihood of initiating spurious actuations in the event of fire damage to the cable - Circuit Fault Modes

C. CONDUCTOR-TO-CONDUCTOR SHORTS Including **Hot Shorts** (that can cause spurious actuations)

- Control Circuits (CONTD.)
  - Other control circuit effects
    - Conductor-to-conductor shorts may lead to misleading indications should the short involve those conductors associated with the indication functions. This might involve loss of indication or contradictory indications.
    - Some conductor-to-conductor shorts may have no impact on the control system, or may only impact the control system only if an attempt is made to operate the system.
- Instrument Circuits
  - Instrumentation system malfunction or unavailable
    - A high impedance short (loss of insulation resistance without a dead short) between conductors of a low voltage, current-driven instrumentation signal wire might result in signal bias, producing misleading indications
    - Instrument cables exposed to fire will likely experience a progressive reduction in insulation resistance (IR) between separate signal conductors (or between the signal conductors and ground). The effect on the signal accuracy will increase in magnitude until the insulation is damaged to the point it no longer provides a barrier to electrical conduction, i.e., a low-impedance short forms. Substantial IR degradation can lead to a biased instrument reading.

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Task 2: Cable and circuit phenomena, parameters, or configurations which have a higher likelihood of initiating spurious actuations in the event of fire damage to the cable - Circuit Fault Modes

C. CONDUCTOR-TO-CONDUCTOR SHORTS Including **Hot Shorts** (that can cause spurious actuations)

- Instrument Circuits
  - Instrumentation system malfunction or unavailable (CONTD.)
    - Thermoplastic materials showed sharp transitions from an operable condition to low-impedance shorts and loss of the signal.
    - Thermoset cables showed a prolonged period of substantial IR degradation and the sustained transmission of a biased signal prior to the onset of low impedance shorting and loss of the signal.
  - Biased instrument readings might cause spurious operation of a pump or valve if the instrument reading governs the switching of auto-start (automatic initiation) control circuits
  - Instrumentation circuits may indicate wrong component status when connected to the start/stop logic

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Task 2: Cable and circuit phenomena, parameters, or configurations – Associated Circuit Concerns

- Associated circuits include any circuit (safety related or non-safety related) whose fire-induced damage could prevent operation or cause mal-operation of required accident mitigating systems or components
  - Circuits that share a common power supply with circuits for mitigating equipment,
  - Circuits that share a common enclosure (e.g., cable tray or conduit) with cables required for operation of mitigating equipment, or
  - Circuits of equipment whose spurious operation or mal-operation may adversely affect mitigating systems (e.g., open a flow diversion path sufficient to compromise the safety function).
- Spurious Operation of Associated Equipment
  - Cables that are not related to the circuits for accident mitigating equipment can be damaged by postulated fires

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Task 2: Cable and circuit phenomena, parameters, or configurations - Parameters affecting cable failures due to fire

- Cable physical properties and configuration factors
  - insulation/jacket composition – Thermoset (XLPE, XLPO, EPR, SR), Thermoplastic (PE, PVC, Tefzel), Vita-Link
  - number of conductors in a multi-conductor cable (3/C, 7/C, 12/C)
  - armoring (metal jacketed)
  - shielding of conductor pairs
  - presence of an un-insulated ground conductor or drain wire
  - aging condition
  - conductor size (AWG 8, 12, 14, 16, 18)
  - cable qualification status
- Routing factors
  - Cable raceway (cable trays, conduits, air drops)
  - overall raceway fill or loading
  - raceway orientation
  - bundling of cables
  - cable type combinations (TS/TS, TS/TP, TP/TP)

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Task 2: Cable and circuit phenomena, parameters, or configurations - Parameters affecting cable failures due to fire (CONTD.)

- Electrical function factors
  - circuit function (i.e., instrument, power, control)
  - cable ampacity load for power cables
  - circuit voltage and current ratings
  - circuit-to-cable wiring configuration
  - CPT size
- Fire exposure condition factors
  - exposure mode (flame impingement, thermal radiation, convection)
  - exposure intensity and duration
  - cable thermal response
  - water spray impact

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Task 2: Cable and circuit phenomena, parameters, or configurations

- Probable fire-induced cable failures leading to spurious actuations
  - short-to-ground and open circuit and/or fuse blow/breaker trip
  - short-to-another cable (inter-cable)
  - short to another conductor within the same cable (intra-cable)
- Parameters affecting spurious actuations in electrical circuits
  - circuit function (i.e., instrument, power, control)
  - insulation/jacket composition (e.g., TS, TP)
  - grounded circuits with cables on raceways, ground conductor, and shielding/armor
  - cable configurations: raceway (e.g., tray, conduit, air drop), bundling and loadings, cable type combinations, and orientation (e.g., horizontal, vertical)
  - circuit-to-cable wiring configuration, CPT size, and V/I ratings
  - fire exposure mode, intensity, and duration
  - cable thermal response
  - water spray effect

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Task 2: Quantitative occurrence of circuit phenomena

OMEGA POINT CABLE FIRE TEST RESULTS

- Conductor to Conductor Shorts (Likelihood)

Intra-cable shorting in cable trays	0.7 – 0.8
Intra-cable shorting in conduits	0.2 – 0.3
Intra-cable shorting in armored cable	0.2 – 0.3
Inter-cable shorting in cable trays	≤ 0.2
Inter-cable shorting in conduits	≤ 0.1
Inter-cable shorting in armored cable	0.0

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Task 2: Quantitative occurrence of circuit phenomena
OMEGA POINT CABLE FIRE TEST RESULTS

Spurious Actuation Likelihood	w/o CPT	w/ CPT
• Given intra-cable shorts in cable trays		
- w/ grounded conductor	0.5(0.25-0.6)	0.25(0.1-0.5)
- w/o grounded conductor	0.6(0.4-0.8)	0.4(0.1-0.7)
• Given intra-cable shorts in conduits		
- w/ grounded conductor	0.1(0.05-0.3)	0.05(0.01-0.1)
- w/o grounded conductor	0.4(0.1-0.6)	0.1(0.05-0.2)
• Given inter-cable shorts in cable trays		
- TS cables	0.1(0.05-0.25)	n/a
- TP cables	0.25(0.1-0.4)	n/a
• Given inter-cable shorts in conduits		
- TS cables	0.05(0.01-0.1)	n/a
- TP cables	0.1(0.05-0.2)	n/a
• Given inter-cable shorts in armored cable		
- w/ grounded conductor	0.05(0.01-0.7)	0.01(0.005-0.02)
- w/o grounded conductor	0.05(0.01-0.7)	0.01(0.005-0.02)

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Task 2: Quantitative occurrence of circuit phenomena
CAROLFIRE INTERMEDIATE-SCALE SCDU TEST RESULTS

- 16 SCDU tests for 61 individual circuits monitored
- Intra-Cable Shorting for TP Cables
  - Total failures – 19
  - Total spurious actuations – 13
  - Total hot shorts – 0
  - Total fuse blown – 6
- Intra-Cable Shorting for TS Cables
  - Total failures – 25
  - Total spurious actuations – 18
  - Total hot shorts – 1
  - Total fuse blown – 6

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Task 2: DESIREE-FIRE PENLIGHT TEST: SPURIOUS ACTUATIONS/HOT SHORTS

CABLE Material	Group 1 MOVs	Group 2 SOVs	Group 3 1"/Large	Group 4 SWGR T/C	Group 6 SCDUs	Total Number SAs/HSs
TS-XLPE	4/6	3/6	4/6	6/8	4/4	21/30
TS-EPR	2/2	1/2		0/2		3/6
TS-SR	0/2	0/2				0/4
TS-Kerite	5/6				3/14	8/20
TS-XLPO						
TS-Armored	2/2	2/2		0/2	0/2	4/8
TP-PE	5/6	3/4	3/4	0/4	2/4	14/22
TP-PVC	0/2	1/2		2/2		3/6
TP-TEF	2/2	1/2		1/2		4/6
VITA-LINK						
TS/TP Comb.						
TOTAL	20/28	11/20	7/10	9/20	9/24	56/102

Task 2: DESIREE-FIRE INTERMEDIATE SCALE TEST: SPURIOUS ACTUATIONS/HOT SHORTS

CABLE Material	Group 1 MOVs	Group 2 SOVs	Group 3 1"/Large	Group 4 SWGR T/C	Group 6 SCDUs	Total Number SAs/HSs
TS-XLPE	8/8	5/8	3/10	4/8	4/6	24/40
TS-EPR	2/4	2/4	3/4		2/6	9/18
TS-SR						
TS-Kerite	3/3	1/3	1/2	1/2		6/10
TS-XLPO				2/2		2/2
TS-Armored	1/1	1/1	1/2	0/2		3/6
TP-PE	5/10	5/10	4/8	5/8	1/6	19/42
TP-PVC						
TP-TEF				0/2		0/2
VITA-LINK						
TS/TP Comb.						
TOTAL	19/26	14/26	12/26	12/24	7/18	64/120

Task 2: INFLUENCE FACTORS ON SPURIOUS ACTUATIONS

- Hot shorts (HSs) and spurious actuations (SAs) would occur, provided there exists significant fire damage to cables located in trays, conduits, or air drop configurations
- TP cables are far less resistance to heating than TS cables; Therefore, TP cables would exhibit SAs earlier than TS cables
- SR and Vita-Link cables typically do not fail easily under extreme fire conditions; Both TS and TP cables have similar likelihood for HS or SA given a fire damage; No significant difference in HS or SA for TS-TS, TP-TP or TS-TP cable mix bundle configurations
- Jacket material has very weak effect on HS or SA
- Fire exposure intensity, heat input rate, and duration would determine when and how long a HS/SA would occur after a cable fire event is detected
- Inter-cable interactions are typically secondary or tertiary effect after intra-cable interaction followed by grounding or open circuit in case of multi-conductor cables
- Inter-cable SA could occur in an ungrounded circuit since no fuse blow failure is possible
- Open circuit not likely to occur prior to HS or SA; However, if available, grounding or fuse blown would precede or follow HS or SA

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Task 2: INFLUENCE FACTORS ON SPURIOUS ACTUATIONS (CONTD.)

- Armored cable and cables in conduit have lower likelihood for HS or SA, depending on their grounding condition
- Raceway orientation has little effect, while raceway loading has significant effect on fire damage as well as HS or SA events
- Number of source and target conductors and their configurations with respect to each other and their proximity to grounding plane have significant effect on HS or SA
- Grounding condition, circuit fuse size (AC or DC), and cable length from the fire source have significant effect on HS or SA
- Power, control, and instrumentation circuit characteristics, including AC or DC, have significant impact on HS or SA behavior of the circuit
- CPT effect is marginal (except NEI study which indicated that CPT has significant effect)
- Water spray would end the cable performance depending on the fire damage condition of the insulation and could have very little effect on HS or SA
- DC circuit faults are more energetic, destructive, and longer HS or SA durations than AC circuit faults

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Task 2: INFLUENCE FACTORS ON SPURIOUS ACTUATIONS

TEST Elements	NEI/EPRI Omega Point	CAROLFIRE Penlight	CAROLFIRE Intermediate	DESIREE-FIRE Penlight	DESIREE-FIRE Intermediate
Cable Insulation Type – TS or TP	M	M	M	M	M
Jacket Material		L			
Armored Cable	H			M	M
Size/Number of Conductors	H	H			
Cable Ground Wire			H		
Raceway Type	M	M	M	M	M
Raceway Orientation	L	L	L	L	L
Raceway Fill	H		H	M	M
Source/Target Configuration	H		H		
Fire Exposure	M			M	M
Circuit AC/DC (P,C,I)				M	M
Circuit CPT	H		L	L	L
Circuit Grounding				H	H
Circuit Fuse Size				H	H
Circuit Cable Length					
Water/Chemical Spray	L		L		

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Task 2: Effect on core damage frequency due to fire-induced electrical circuit faults which can cause equipment to spuriously actuate

Change in CDF due to spurious actuations in an electrical circuit per reactor-year:

$$\Delta CDF = F_f * P_E * P_{AS} * P_{DM} * P_{SA} * P_{CCD}$$

Where,

- F_f frequency of fires of any size anywhere within the fire area of interest per year
- P_E fire size parameter; fraction of fires in the area capable of damaging combination of fire temperature and duration
- P_{AS} probability that automatic suppression will fail to control the fire
- P_{DM} probability that detection and manual suppression will fail to control the fire
- **P_{SA} probability of spurious actuations of one or more circuit components for a specific combination of fire temperature and duration**
- P_{CCD} conditional probability of core damage given fire-induced failures including spurious actuations of one or more components/combinations

* Cable damage as a result of fire burning of insulation and water/chemical spray (if used as fire suppression)

Brookhaven Science Associates 57

Task 2: Probability of spurious actuations given a fire-induced cable damage

Probability of spurious actuation of one or more electrical circuit components for a specific combination of fire temperature and duration:

$$P_{SA} = P_{CD} * P_{SACD}$$

Where,

P_{CD} probability of cable damage given a specified set of time-temperature and fire severity conditions

P_{SACD} probability of spurious actuations given cable damage

Daniel Funk's Suggestion

$$P_{SA} = CCF * P_{CC} \text{ (Independent of cable damage); } P_{DF}$$

Where,

P_{CC} probability that a conductor-to-conductor short will occur prior to a short-to-ground or short to a grounded conductor

CCF a factor that accounts for the relative number of source conductors and target conductors

P_{DF} probability that a fire of a given intensity (HRR and temperature) will result in cable failure

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Task 3: Factors affecting cable types, configurations, fire types and electrical circuits

- Cable physical properties
  - insulation/jacket composition – Thermoset , Thermoplastic, Others
  - number of conductors (1/C, 3/C, 7/C, 12/C)
  - armoring, shielding, drain wire
  - number of source and target conductors
- Cable routing configurations
  - cable raceway (cable trays, conduits, air drops) orientation
  - overall raceway fill or loading and bundling of cables
  - cable type combinations (TS/TS, TS/TP, TP/TP)
- Fire exposure conditions
  - exposure mode (flame impingement, thermal radiation, convection)
  - exposure intensity and duration
  - cable thermal response and duration of spurious actuations
  - water spray impact due to fire suppression
- Electrical functions
  - circuit function (i.e., instrument, power, control)
  - cable ampacity load for power cables
  - circuit voltage and current ratings
  - circuit-to-cable wiring configuration
  - CPT size

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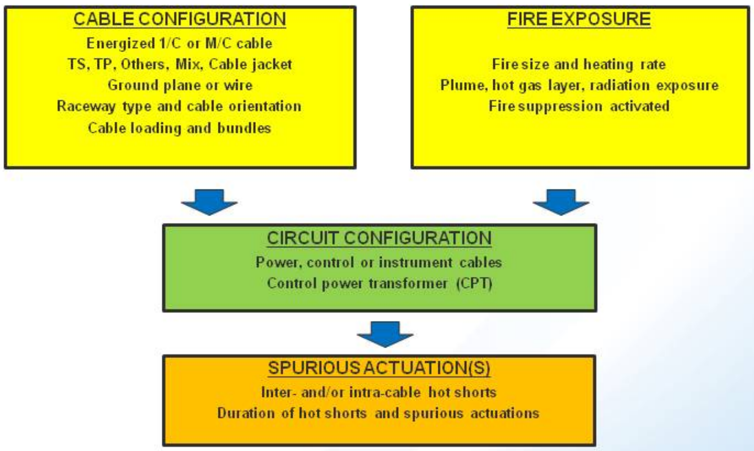
Task 3: Factors affecting fire-induced electrical circuit faults which can cause equipment to spuriously actuate



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Task 3: Spurious Actuation Scenario - Base Case (*Variations*) Conductor-to-Conductor (intra- or Inter-Cable) Shorts

- Cable Configuration
  - TS cables with 1/C and 7/C mix (*TP, TS/TP mix*)
  - No armoring, shielding, or drain wire (*armoring, shielding, presence of drain wire*)
  - One source conductor energized (*multiple sources*)
  - Cables on a horizontal tray (*conduit, vertical, air drop*)
  - Cables in a single layer, no bundles (*multiple layer, random, bundles*)
- Fire Exposure
  - Hot gas layer exposure (*plume, radiation*)
  - Fire to degrade cables to cause spurious actuations
  - Fire suppression not activated (*water or chemical spray activated*)
- Circuit Configuration
  - Control circuit (*power, instrument*)
  - Circuit connection through a CPT (*no CPT in circuit*)
  - Ac/dc circuit configuration (*Fuse size*)

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10. SUPPLEMENTARY NOTES

Gabriel Taylor, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Volume 1 of this report documents the results of a Phenomena Identification and Ranking Table (PIRT) exercise that was undertaken on fire-induced electrical circuit failures that may occur in nuclear power plants when cables are damaged by fires. This program was sponsored by the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) under the NRC-RES/EPRI Memorandum of Understanding (MOU) collaborative research agreement. The electrical expert PIRT panel was comprised of a group of experts sponsored equally by the NRC and EPRI. Staff from Brookhaven National Laboratory (BNL) facilitated the efforts of the PIRT panel. The objective of this PIRT was to identify phenomena that can affect the fire-induced failure modes of electrical circuits after cables are damaged by fire. The PIRT panel used the results from recent fire tests performed by EPRI and NRC, identifying and ranking the parameters that can influence the hot short failure modes of electrical control circuits. Using these influencing parameters, the results of cable-fire tests, expert judgement, and operating experience, the PIRT panel developed circuit configurations vulnerable to hot short modes of circuit failures that can engender the spurious operation of certain end devices. In addition to completing the PIRT exercise on control circuits, the PIRT panel reached technical consensus on several issues in analyzing fire protection circuits such as power-cabling consequential hot shorts, open circuits on the secondary of current transformers, multiple high-impedance faults, and concerns about common enclosure and common power supplies. The PIRT panel noted the dearth of data on instrumentation circuits to support a structured evaluation of the influencing phenomena and therefore, the panel suggested conducting further research to advance the current knowledge base.

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