NUREG/CR-7150, Vol. 2
BNL-NUREG-98204-2012

EPRI 3002001989
Final Report

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

Volume 2:

Expert Elicitation Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D.C. 20555-0001

Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, CA 94304-1338

United States Nuclear Regulatory Commission
Protecting People and the Environment

ELECTRIC POWER
RESEARCH INSTITUTE

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at http://www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and Title 10, "Energy," in the *Code of Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   Mail Stop SSOP
   Washington, DC 20402–0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161–0002
   www.ntis.gov
   1–800–553–6847 or, locally, 703–605–6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: U.S. Nuclear Regulatory Commission
Office of Administration
Publications Branch
Washington, DC 20555-0001
E-mail: DISTRIBUTION.RESOURCE@NRC.GOV
Facsimile: 301–415–2289

Some publications in the NUREG series that are posted at NRC's Web site address http://www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852–2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
www.ansi.org
212–642–4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

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

Volume 2: Expert Elicitation Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure

NUREG/CR-7150, Vol. 2
BNL-NUREG-98204-2012

EPRI 3002001989

Prepared by
M. Subudhi and G. Martinez-Guridi
Brookhaven National Laboratory

Final Report
May 2014

G. Taylor
NRC Technical Project Manager

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research (RES)
Washington, D.C, 20555-0001

U.S. NRC-RES Project Manager
M.H. Salley

Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, CA 94304-1338

EPRI Project Managers
R. Wachowiak
A. Lindeman

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATION(S) PREPARED THIS REPORT:

Brookhaven National Laboratory

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

Electric Power Research Institute

THE TECHNICAL CONTENTS OF THIS DOCUMENT WERE **NOT** PREPARED IN ACCORDANCE WITH THE EPRI NUCLEAR QUALITY ASSURANCE PROGRAM MANUAL THAT FULFILLS THE REQUIREMENTS OF 10 CFR 50, APPENDIX B AND 10 CFR PART 21, ANSI N45.2-1977 AND/OR THE INTENT OF ISO-9001 (1994). USE OF THE CONTENTS OF THIS DOCUMENT IN NUCLEAR SAFETY OR NUCLEAR QUALITY APPLICATIONS REQUIRES ADDITIONAL ACTIONS BY USER PURSUANT TO THEIR INTERNAL PROCEDURES.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2014 Electric Power Research Institute, Inc. All rights reserved.

ABSTRACT

The Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE) is a unique program in using an expert elicitation exercise by a Probabilistic Risk Assessment (PRA) panel to build upon information developed in an electrical engineering panel's Phenomena Identification and Ranking Table (PIRT) exercise. These two exercises designed to work in series were 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's Memorandum of Understanding collaborative research agreement. NUREG/CR-7150, Volume 1 of the JACQUE-FIRE program details the findings of the PIRT exercise undertaken on the failures of electrical control circuits that may occur in nuclear power plants as a result of fire damage to cables.

Volume 2 documents the results of the PRA panel's expert elicitation that is used to develop conditional probabilities of hot short-induced spurious operation occurrence of various control circuit applications and their durations, given fire damage to electrical cables. The PRA panel chosen for this expert elicitation comprised a group of ten experts sponsored equally by the NRC and the EPRI. Staff from Brookhaven National Laboratory (BNL) facilitated the efforts of the PRA panel and also served as technical evaluators.

The objective of the PRA panel's expert elicitation is to estimate the conditional probabilities of the hot short-induced spurious operation failure mode of control circuits and its duration, given fire-induced cable damage. These results are intended for use in fire PRA applications. Using an enhanced Senior Seismic Hazard Analysis Committee's (SSHAC's) Level 2 process for the expert elicitation (NUREG/CR-6372), the panel suggested parametric distributions of the probability of occurrence, and duration of fire-induced circuit-failure phenomena. Distributions are developed for control circuit configurations where applicable test data are available, as well as when there are none, but expert judgment reasonably can offer quantitative estimates.

The electrical PIRT study in Volume 1 identified the configurations of the electrical control circuits that could be vulnerable to hot short-induced spurious operations, applying the physics and physical parameters that influence the modes of fire-induced circuit failure. For these control circuits, the PRA panel derived the distributions of conditional probability on the hot short-induced spurious operation of certain end devices and also the conditional probability distributions of their spurious operation duration. Both conditional probability distributions were derived using the results from recent cable-fire tests undertaken by the EPRI, Duke Energy, and the NRC and expert judgment. These conditional probabilities advance the state-of-the-art and are intended for revising, directly replacing, or creating new probabilities in NUREG/CR-6850 (Tables 10-1 through 10-5) and in its Supplement 1 (Figure 16-1 and Table 16-1) that the nuclear power industry currently use in their fire PRAs.

Since the information in the supporting appendices of this report is voluminous, some of this material is included in an enclosed compact disk located inside the back cover of this report. The compact disk also contains the detailed information used by the PRA panel in the formulation of this report.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The risk from hot short-induced spurious operation resulting from fire damage is currently part of the method for quantifying fire risk to nuclear power plants documented in NUREG/CR-6850 (EPRI 1011989), “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Plants.” The quantification aspect of the current version of NUREG/CR-6850 with respect to hot short likelihood is based on a limited set of experimental data and expert judgment performed in the early 2000s. NUREG/CR-6850 currently does not provide guidance on the quantification of spurious operation duration.

Over the past decade, there have been numerous studies and testing to advance the understanding of cable response from fire effects. Most recently, work 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’s Memorandum of Understanding collaborative research agreement conducted a two part expert panel project to better understand the risks associated with fire-induced control circuit damage.

The Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE) is a unique program in using an expert elicitation exercise by a Probabilistic Risk Assessment (PRA) panel to build upon information developed in an electrical engineering panel’s Phenomena Identification and Ranking Table (PIRT) exercise. NUREG/CR-7150 (EPRI 1026424), Volume 1 of the JACQUE-FIRE program details the findings of the PIRT exercise undertaken to evaluate the hot short phenomena that influence failure modes of electrical control circuits, which may occur in nuclear power plants (NPPs) as a result of fire damage to cables.

Volume 2 documents the results of the PRA panel’s expert elicitation that is used to develop the conditional probabilities of hot short-induced spurious operations of various control circuit applications and their durations, given fire damage to electrical cables. Since the information in certain appendices of this report is voluminous, some appendix material is included in an enclosed compact disk located inside the back cover of this report. The PRA panel chosen for this expert elicitation comprised a group of ten experts sponsored equally by the NRC and the EPRI. Staff from Brookhaven National Laboratory (BNL) facilitated the efforts of the PRA panel and also served as the technical evaluators.

The objective of this expert elicitation is to advance the state-of-the-art in estimating the conditional probability[1] of (1) hot short-induced spurious operation phenomena in various control circuit configurations (e.g., single break and double break) used in NPPs and (2) spurious operation durations where the length of their persistence could affect the circuit function of the component or device considered. As concluded in Volume 1, these phenomena encompass fire-induced intra-cable hot short, inter-cable hot short and ground fault equivalent hot short (GFEHS) failure modes of cable conductors that have the potential to cause spurious operation in various end devices (e.g., solenoid-operated valve (SOV), motor-operated valve (MOV), and

---

[1] In this report, the “probability” and “likelihood” were used interchangeably, although the meaning of likelihood is the state of being probable.

circuit breaker). The spurious operation herein, as defined in Volume 1, is a “circuit-fault mode wherein an operational mode of the circuit is initiated (in full or in part) due to failure in one or more components of the circuit, including the cables.”

To achieve this objective, the PRA panel started with the information developed by the PIRT panel, then followed an enhanced Level 2 expert elicitation process developed by the NRC’s Senior Seismic Hazard Analysis Committee (SSHAC). The main objective of the SSHAC process is to “provide a representation of the informed scientific community view of the important components and issues.” The members of the panel assumed independent roles of technical integrator (TI) team member, proponent, resource expert, or member of a participatory peer review panel (PPRP). The primary goals of this structured process were to minimize the technical- and procedural-biases that might have evolved out of the elicitation process and to preserve each proponent’s recommended methods and estimated conditional probability values whilst developing the final results representing a larger technical community. Accordingly, the eventual goal of this project was to generate a representation of the informed scientific community's view of each particular conditional probability of occurrence and duration of spurious operation of control devices given that fire damage to their electrical cables has occurred.

The control circuit cases for hot short-induced spurious operation evaluated by the PRA panel were categorized in Volume 1 using the following five (5) circuit variables:

1. Circuit Configurations – Single Break, Double Break
2. Circuit Type Cases – SOV, MOV, Medium Voltage Circuit Breaker
3. Circuit Grounding/Power Supply Types – Grounded AC, Ungrounded AC (with Individual Control Power Transformers (CPTs)), Ungrounded DC (or Ungrounded Distributed AC)
4. Target Cable Constructions – Thermoset (TS)-insulated Conductor Cable, Thermoplastic (TP)-insulated Conductor Cable, Metal Foil Shield Wrap Cable, Armored Cable
5. Conductor Failure Modes – Intra-cable hot short, Inter-cable hot short, GFEHS

These five variables resulted in developing spurious operation conditional probability tables for the following two control circuit configurations, namely;

1. Single Break (or Contact) Control Circuits
    a. Base Case - SOV
    b. MOV
    c. Medium Voltage Circuit Breaker

2. Double Break (or Contact) Control Circuits (for ungrounded circuits)
    a. Base Case - SOV
    b. MOV

The evaluation of the duration probability of hot short-induced spurious operation associated with these control circuits yielded two probability distributions (with uncertainties); one for AC-powered control circuits, and the other for DC.

To support the PRA panel’s work, the NRC staff developed a roll-up table containing fire-test data from all available cable fire test programs. Typically, the proponents did not base their final estimates solely on these values from the roll-up table, but instead, used this information to support their final recommendations. The TI team assessed the expert’s inputs and developed a process of integration that was used to calculate the conditional probability distributions for all single break and double break control circuit configurations.

The results from this effort provide realism to advance the state-of-the-art for quantifying circuit failure risk in fire PRAs and are intended for revising, directly replacing, or establishing new probabilities in NUREG/CR-6850 (EPRI 1011989) for use in fire PRAs. This report (Volume 2) documents the technical recommendations made by the panel of experts on quantification of the hot short-induced spurious operations and the associated hot short duration. These estimates of conditional probability are intended to supersede probabilities for Tables 10-1 through 10-5, entitled “Failure Mode Probability Estimates Given Cable Damage,” of NUREG/CR-6850 and for Figure 16-1 and Table 16-1 of Supplement 1 to NUREG/CR-6850, and entitled “Fire Probabilistic Risk Assessment Methods Enhancements.”

In addition to developing the conditional probabilities, the PRA panel made several recommendations for the application of this information in fire PRAs.

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. As part of this program, a project was initiated to improve on the knowledge of the fire impact upon cables. Tests were conducted to measure the failure thresholds of various cable types and to measure the occurrence of spurious actuations of equipment due to hot shorts resulting from cable damage. This report addresses the PRA application of this data, with the primary objective to develop a set of probabilities for spurious actuation of equipment. Additional focus was given with regards to the duration of the spurious events.

To accomplish this goal a PRA expert panel was assembled, sponsored equally by EPRI and the NRC, with the intention to be representative of all "stakeholders" including research, regulators, and licensees. The panel included representatives with PRA, and/or electrical expertise, with backgrounds in the applications of these results. This PRA expert panel, therefore, builds upon the PIRT panel's conclusions provided in NUREG/CR-7150 Volume 1. As part of the expert elicitation, a modified SSHAC process was followed. This process provided a formal framework intended to make the process efficient and limit potential biases. In this regard, the process appears to have been a success.

The information in this report revises a significant portion of Task 10 of NUREG/CR-6850 (EPRI 1011989). The results are presented such that the bounding values can be applied based on a minimum set of parameters, and more specific values can be applied if more rigors are used to define the circuit configuration and conditions. Unfortunately, the application is not a simple update of the numbers. The use of Option #2 (Computational Probability Estimates) as a technical approach for calculating spurious operation likelihood has been eliminated. Also, a new failure mode has been identified, the Ground Fault Equivalent Hot Short (GFEHS). These changes may require some previous plant analyses to be updated for future applications. Along with updated spurious operation duration probabilities for AC circuits, this report includes duration probabilities for DC circuits. The report also provides guidance for use of these values in PRA analyses.

Based on the increased scope refinement of data, and the improved guidance for application, this report represents an overall improvement in the state-of-the-art for performing a Fire PRA.

PREFACE

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

In 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 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 and EPRI published Volume 1 of this NUREG/CR-7150 (EPRI 1026424), *Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE) - Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure.* This report identified configurations of control circuits that are vulnerable to fire-induced failure mode, hot short-induced spurious operation of control devices, after cables are damaged by fire. Part of the charter for this PIRT panel was to provide the information necessary as a starting point for the PRA panel's expert elicitation documented in this Volume 2.

In 2013, the NRC published the 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 its applications based upon this methodology.

CITATIONS

This report was prepared by the following:

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973
Principal Investigators:
M. Subudhi
G. Martinez-Guridi

U.S. Nuclear Regulatory Commission,
Washington, D.C. 20555-0001
Contributors:
R. Gallucci
N. Melly
M. Salley
N. Siu
M. Stutzke
G. Taylor
J. Xing

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185
Contributor:
S. Nowlen

Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, CA 94304
Contributor:
R. Wachowiak

Constellation Energy Group Inc.
750 East Pratt Street
Baltimore, MD 21202
Contributor:
R. Cavedo

Hughes Associates, Inc.
900 Washington St., Suite 830
Vancouver, WA 98660
Contributor:
D. Funk

GE Hitachi Nuclear Energy
3901 Castle Hayne Road, M/C L30
Wilmington, NC 28403
Contributor:
D. Henneke

Engineering Planning and Management
5520 Dillard Drive, Suite 250
Cary, NC 27518
Contributor:
D. Miskiewicz

ERIN Engineering and Research Inc.
2001 N. Main Street, Suite 510
Walnut Creek, CA 94596
Contributor:
K. Zee

This report describes research sponsored jointly by the U.S. Nuclear Regulatory Commission's (NRC) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE), Volume 2: Expert Elicitation Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD, 2012, and Electric Power Research Institute (EPRI), Palo Alto, CA, NUREG/CR-7150, BNL-NUREG-98204-2012, and EPRI 3002001989.

ACKNOWLEDGMENTS

This project was completed using an expert panel, which included staff from Brookhaven National Laboratory (BNL), Sandia National Laboratories (SNL), the U.S. Nuclear Regulatory Commission (NRC), and the Electric Power Research Institute (EPRI). The concept of the project was developed for the NRC by Mr. Mark Henry Salley, along with EPRI's Mr. Kenneth T. Canavan and Mr. Richard Wachowiak, who afforded management guidance and technical direction throughout the project. Near the completion of this project Ashley Lindeman of EPRI replaced Richard Wachowiak and helped with closure of this project and publications. Mr. Nicholas Melly and Mr. David Gennardo of NRC offered technical support in developing the data file from all recent cable-fire tests so that the panel could use them in estimating the probabilities for various control circuit configurations. At BNL, Ms. Maria Anzaldi helped prepare this manuscript.

The authors thank the members of the PRA expert panel, Robert Cavedo, Daniel Funk, Raymond Gallucci, Dennis Henneke, David Miskiewicz, Steven Nowlen, Nathan Siu, Gabriel Taylor, Jing Xing, and Kiang Zee for their dedication to this process of expert elicitation. 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 and conditional probability distributions reported in this document.

A special thanks to Mr. David Goforth of Duke Energy for providing the proprietary report describing the armored control cable testing that was undertaken in 2006. Because of the proprietary nature, the test data in this report was exclusively used by the panel members for estimating probabilities.

We gratefully acknowledge the technical contributions of Martin Stutzke of NRC, who developed the "CS-Model" of the Weibull distribution for estimating the spurious operation duration conditional probability plots. We also specially thank Gabriel Taylor of NRC for providing technical direction and support throughout the project, and assisting in writing and addressing peer review comments on the draft version of this report.

The authors acknowledge and thank members of the entire PRA panel for providing review comments on the first draft of this report. Finally, our special thanks to Ms. Avril Woodhead at BNL for technically editing the entire report.

LIST OF ACRONYMS

A or Amp	Ampere
AC	Alternating Current
AOV	Air-Operated Valve
AWG	American Wire Gauge
BNL	Brookhaven National Laboratory
CAROLFIRE	Cable Response to Live Fire
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CFR	Code of Federal Regulations
CPT	Control Power Transformer
CSPE	Chloro-Sulfonated Polyethylene
DB	Double Break
DC	Direct Current
DESIREE-Fire	Direct Current (DC) Electrical Shorting in Response to Exposure Fire
ELECTRA-FIRE	Electrical Cable Test Results and Analysis during Fire Exposure
EPM	Engineering Planning & Management
EPR	Ethylene-Propylene Rubber
EPRI	Electric Power Research Institute
FAQ	Frequently Asked Questions
FPP	Fire Protection Program
GDC	General Design Criteria
GEH	General Electric Hitachi
GFEHS	Ground Fault Equivalent Hot Short
HAI	Hughes Associates, Inc.
HGL	Hot Gas Layer
IN	Information Notice
IRMS	Insulation Resistance Measurement System
JACQUE-FIRE	Joint Assessment of Cable Damage and Quantification of Effects from Fire
k-s	Kolmogorov-Smirnov
KATE-Fire	Kerite Analysis in Thermal Environment of Fire
LOCA	Loss of Coolant Accident
LOP	Linear Opinion Pooling
MLE	Maximum Likelihood Estimate
MOV	Motor-Operated Valve
MRR	Median Rank Regression
MSIV	Main Steam Isolation Valve
MSO	Multiple Spurious Operations
#/C	‘#’ 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
P (SO)	Probability of Spurious Operation

PDF	Probability Density Function
PIRT	Phenomena Identification and Ranking Table
PORV	Power-operated Relief Valve
PPRP	Participatory Peer Review Panel
PRA	Probabilistic Risk Assessment
PSHA	Probabilistic Seismic Hazard Analyses
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling
RES	Office of Nuclear Regulatory Research, NRC
SAFT	Scale-Accelerated Failure Time
SCDU	Surrogate Circuit Diagnostic Unit
SB	Single Break
SNL	Sandia National Laboratories
SOKC	State-Of-Knowledge Correlation
SOV	Solenoid-operated Valve
SRV	Safety Relief Valve
SSCs	Structures, Systems, and Components
SSHAC	Senior Seismic Hazard Analysis Committee
STD	Standard
TFI	Technical Facilitator/Integrator
TI	Technical Integrator
TP	Thermoplastic
TS	Thermoset
US	United States
V	Volt
XLPE	Cross-linked Polyethylene

1
INTRODUCTION

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 of its consequences. In meeting these objectives, the FPPs for operating NPPs are designed to offer reasonable assurance, through defense-in-depth principles, that a fire will not prevent the safe-shutdown of the reactor. The goals of the defense-in-depth 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 defense-in-depth concept offers 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 reactor from being shut down safely.

To achieve defense-in-depth, each operating reactor has a fire protection program approved by the Nuclear Regulatory Commission (NRC) 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 a 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 has encouraged utilities operating NPPs to use risk-informed, performance-based approach 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 these 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).

1.1 Background

The Browns Ferry Fire of 1975 (Ref. 7) and confirmatory testing of representative circuits revealed that fire-induced failures of electrical circuits, leading to spurious operation of equipment, 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 circuit’s specific design and construction, the location and type of cable with respect to the site of the fire (e.g., the cable’s jacket and insulation construction, orientation, raceway routing and fill, circuit grounding), and the cable’s failure modes.

Electrical cables damaged from fire are known to exhibit several circuit failure modes, namely, open circuit fault, short circuit (e.g., hot short) fault, and short-to-ground fault. An open circuit fault is defined as a fire-induced break in the conductor resulting in a loss of continuity. A short circuit (or hot short) fault is defined to be a breakdown of the cables' insulation due to fire damage that results in individual conductors of the same or different cables to come in contact with each other and may result in an impressed voltage or current on the circuit being analyzed. Thus, fire-induced hot short faults could only cause spurious operation(s) in a control circuit that could also be recoverable. A short-to-ground fault is defined as a breakdown of the cables' insulation resulting in the potential of a conductor to be applied to ground/neutral. Figure 1-1 illustrates various fire-induced failure modes using simplistic circuit schematics.

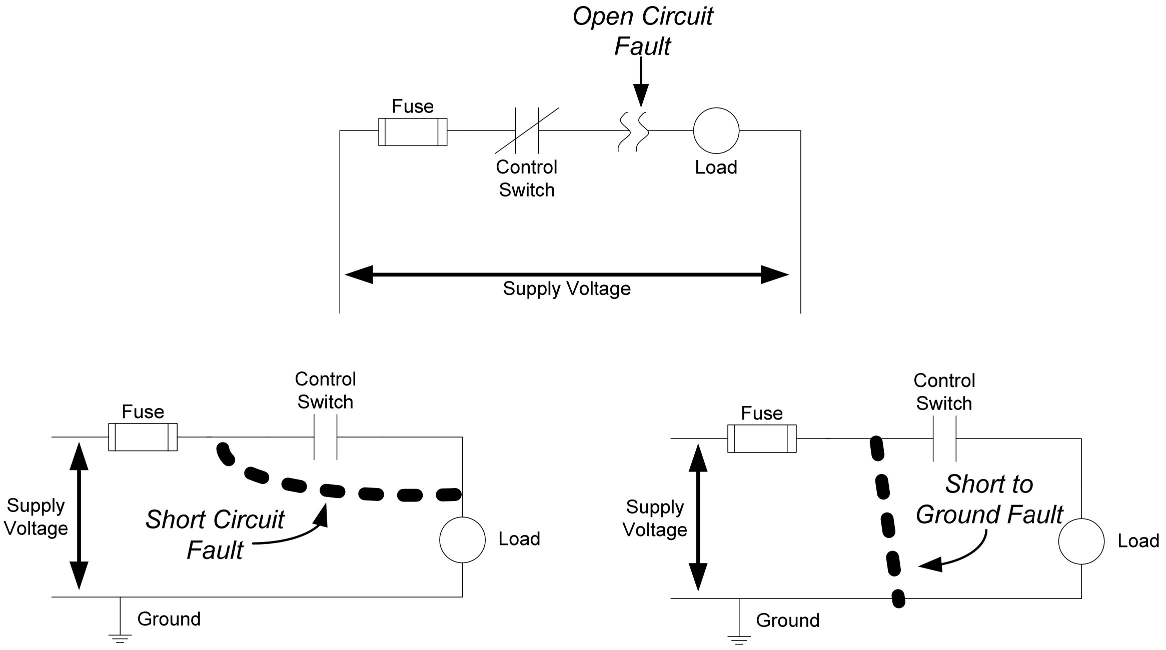


Figure 1-1. Illustration of Fire-Induced Electrical Circuit Failure Modes

Once a cable is damaged by fire, short circuit faults can cause the malfunction of a component or system, including hot short-induced spurious operation of safety components, or false indications of instrumentation and control circuits. As defined by the Phenomena Identification and Ranking Table (PIRT) panel in Volume 1 of NUREG/CR-7150, a spurious operation is a circuit failure 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. Even though these failure modes were identified to have occurred during the Browns Ferry Fire of 1975, the likelihood of these phenomena remained a topic of debate through the early 2000's (Ref. 8).

To better understand these hot short-induced spurious operation 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. The testing 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. 9). Subsequently, NRC sponsored the CAROLFIRE (CAble Response tO Live FIRE) test program to (1) obtain 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. 10); (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 findings from this CAROLFIRE test program on electrical performance and fire-induced cable failure (Ref. 11). In 2012, NRC also published the results of the DESIREE-Fire (Direct Current Electrical Shorting In REsponse to Exposure Fire) that encompasses cable-failure modes and effects on the behavior of direct current (DC) control circuits (Ref. 12). This project was sponsored by the NRC-RES with support from EPRI under a collaborative research agreement termed the NRC-RES/EPRI Memorandum of Understanding.

In May 2002, EPRI 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 results of the EPRI/NEI cable-fire test to develop best estimate conditional probabilities for the spurious operation of devices in electrical circuits due to fire-induced damage to electrical cables (Ref. 13). These results were incorporated into the current method for conducting fire Probabilistic Risk Assessments (fire PRAs) documented in NUREG/CR-6850, EPRI 1011989, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities” (Ref. 14).

The fire PRA method documented in NUREG/CR-6850, EPRI 1011989 (Ref. 14) contains a “Circuit Failure Mode Likelihood Analysis” Task, which estimates the probability of hot short cable failure modes of interest, which in turn can be correlated to specific component failure modes. This Task 10 of NUREG/CR-6850 relies solely on a subset of the EPRI/NEI test data (Ref. 9) and the results of the expert elicitation available at the time of developing the fire PRA method (Ref. 13). Within this task, five lookup tables are provided which contain conditional likelihood estimates for the various circuit configurations and hot short failure modes. The analyst chooses a value based on cable/circuit characteristics, raceway configuration, and hot short failure mode(s) of interest. When NUREG/CR-6850 was published, there was no guidance on modeling spurious operation duration in the fire PRA.

Supplement 1 to NUREG/CR-6850 (EPRI 1019259), Section 16, “Hot Short Duration” (Ref. 15) offered staff interim guidance on modeling the duration of hot shorts for AC circuits, while noting its limitations. Based on then available data, the guidance offers a two-parameter Weibull distribution to represent the probability of a hot short lasting greater than or equal to time, t, in minutes. The complementary cumulative distribution function (CCDF) of this Weibull distribution is given in Supplement 1 as follows:

$$P(T \geq t) = \exp(-\lambda t^{\beta})$$

Where, β is a shape parameter and λ is a scale parameter.

The interim guidance in Supplement 1 to NUREG/CR-6850, however, included several conditions of use, as follows:

1. The probabilities of hot short duration should not be applied to the spurious operation of equipment caused by grounding of one or more conductors (i.e.,

spurious actuations not caused by hot shorts). For them, no credit should be given for hot short durations.

2. The probabilities of the duration of hot shorts should not be applied if the spurious operation so caused would not clear once the cable is grounded. For these cases, no credit should be given for the duration of the hot short. A review should ensure that clearing the hot short will clear the spurious operation; including identifying the devices (e.g., fuse or circuit breaker) that would clear the hot short after the cable has grounded.

3. Given a short-to-ground on an auxiliary or "off-scheme" circuit, credit for recovering from a spurious operation must include a functional circuit analysis demonstrating the effect of a short-to-ground on that circuit. For cases where functional circuit analysis cannot demonstrate recovery, no credit can be given for the duration of the hot short since the short to ground will not clear by itself.

4. The probabilities of the duration of spurious operations should not be used for DC circuits.

In an effort to advance the state-of-knowledge, the NRC in collaboration with EPRI conducted a two-part expert panel exercise program, <u>J</u>oint <u>A</u>ssessment of <u>C</u>able Damage and <u>QU</u>antification of <u>E</u>ffects from <u>FIRE</u> (JACQUE-FIRE). The JACQUE-FIRE program is unique in using an expert elicitation exercise to build upon information developed in an electrical engineering PIRT exercise. The results of this PIRT exercise are documented in Volume 1 of NUREG/CR-7150[1] (Ref. 16).

The PIRT study used the findings on cable fire tests from EPRI/NEI (Ref. 9) and NRC-sponsored testing conducted under the CAROLFIRE (Ref. 11) and DESIREE-Fire (Ref. 12) programs; all these three sets of test data were analyzed, and then summarized into a more useful format in NUREG-2128 (Ref. 17). Volume 1 details the exercise that PIRT panel conducted with experts knowledgeable about the design of NPP electrical circuits, and which identified and ranked the parameters that influence the likelihood of occurrence of the modes of fire-induced cable-damage failures. Thus, the purpose of Part 1 of the JACQUE-FIRE program was to break the problem down by its physical attributes.

Part 2 of the JACQUE-FIRE program, documented in this report (Volume 2 of NUREG/CR-7150), convened a second group of experts with knowledge in fire PRA applications (i.e., referred to as "The PRA panel") to quantify the conditional likelihood for hot short-induced spurious operations of control circuits caused by fire damage. The PRA panel members were also tasked with quantifying the probability of the spurious operation duration. Specifically, there was a need to quantify the durations for both AC and DC control circuits since no technically acceptable guidance was available for DC, and also to use the additional data for AC control circuits to re-quantify guidance presented in Supplement 1 to NUREG/CR-6850 (Ref. 15). These estimates of conditional probability advance the state-of-the-art and are intended to supersede the probabilities for Tables 10-1 through 10-5, entitled "Failure Mode Probability Estimates Given Cable Damage," of NUREG/CR-6850 (Ref. 14) and for Figure 16-1 and Table

---

[1] Hereafter the reference to Volume 1 and Volume 2 of NUREG/CR-7150 are identified as "Volume 1" and "Volume 2," respectively. Note that Volume 1 is also recognized as "PIRT Report" and this report is the Volume 2 of NUREG/CR-7150.

16-1 of its Supplement 1, entitled “Fire Probabilistic Risk Assessment Methods Enhancements” (Ref. 15).

The use of two panels was chosen to support both performance-based and deterministic fire protection regulatory areas. The PIRT panel identified the physical attributes that influence cable failure modes. For deterministic fire protection, the PIRT results supported clarification and development of new guidance. The PIRT results also served the performance-based arena by providing a foundation of valuable information to the PRA panel to start the quantification effort.

1.2 NRC-RES/EPRI Goals

NRC-RES furthers the regulatory mission of the NRC by providing technical advice, technical tools, and information for identifying and resolving safety issues, making regulatory decisions, and promulgating regulations and guidance. RES conducts independent experiments and analyses, develops technical bases for supporting realistic safety decisions by the agency, and prepares the agency for the future by evaluating safety issues involving current and new designs and technologies. RES develops its program with consideration of Commission direction and input from the program offices and other stakeholders.

The current state-of-the-art fire PRA method documented in NUREG/CR-6850, EPRI 1011989 (Ref. 14) was published in 2005. The fire PRA task associated with quantifying the conditional likelihood of an electrical cable experiencing a hot short-induced spurious operation (given cable damage) was developed based on an expert elicitation by EPRI (Ref. 13) using a limited set of 18 specific test configurations (Ref. 9). Since the publication of this fire PRA method, the NRC in collaboration with EPRI has conducted additional tests to help quantify the likelihood of fire damaged cables causing mal-operation of electrical components and systems.

Thus, the NRC-RES with collaboration from EPRI initiated this project to use the additional data and expert judgment to advance the state-of-the-art quantification of the conditional likelihood of an electrical cable hot short-induced spurious operation (given cable damage). The eventual goal of this NRC-RES/EPRI collaboration effort is to use the results presented in this report and replace, and create new likelihood estimates for conducting the circuit failure likelihood analysis Task 10 documented in NUREG/CR-6850, EPRI 1011989 (Ref.14).

1.3 Project Objectives

The objective of the work documented in this report (Volume 2) is to use an expert elicitation process to develop the best estimate conditional probabilities on the likelihood of occurrence of hot short-induced spurious operation failure modes to be used in fire PRA applications, given the occurrence of fire-induced cable damage, and to assess their durations. The structured process for the expert elicitation uses the available data from cable-fire tests (Refs. 9, 11, 12 & Duke Energy’s proprietary report[2]), to estimate the probabilities of spurious operation occurrence and duration for the control circuit configurations identified by the preceding PIRT panel. The PRA panel evaluates such configurations, for which there is applicable data, as well

---

[2] Duke Energy performed tests on armored control cables in 2006 and provided EPRI members of the PRA panel with a copy of a proprietary report on these tests. NRC members of the PRA panel had access to this report (NRC Agency-wide Document Management and Access and Management System (ADAMS) Accession No. ML071200168).

as for those where there is none, but where expert judgment, PRA application knowledge, and plant operating experience reasonably support quantitative estimates. To meet the objectives of this work and support fire PRA applications, the best estimates of conditional probabilities developed by this panel are represented by parametric distributions that can be used in current fire PRAs.

This expert elicitation project uses all of the available data to re-quantify the estimates developed previously by EPRI and it also complements the previous work by providing estimates for scenarios that were not addressed by the EPRI work or in the fire PRA method documented in NUREG/CR-6850, EPRI 1011989 (Ref. 14). Based on these results, the PIRT panel and the PRA panel together, in this two-volume NUREG/CR report set, offer qualitative- and quantitative-information for use in fire PRAs. The results of this work may also be useful for informing guidance related to deterministic post-fire safe-shutdown circuit analysis.

1.4 The Approach

The expert elicitation process was based on methods employed by other expert panels that the NRC has used, where there were only limited data to address the technical issues with the desired levels of certainty and accuracy. The staff from NRC and Brookhaven National Laboratory (BNL) reviewed several formal expert-judgment processes used previously for various purposes to:

- Assess human performance and reliability (Ref. 18),
- Assess the performance of radioactive waste repositories (Ref. 19),
- Support the performance of full-scope PRAs (Ref. 20),
- Develop seismic hazard curves (Ref. 21), and
- Estimate the frequencies of loss-of-coolant accidents (LOCAs) (Ref. 22).

The NRC, EPRI, and BNL staff identified many of the issues to be evaluated during the project's first meeting (January 31st to February 2nd 2012). Subsequently, it was decided to adopt the method described in NUREG/CR-6372, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," (Ref. 21). This method was developed to support the assessment of seismic hazard curves for NPP sites in the United States, but has broader applicability.

The selected method is supported by Section 1-4 of the ASME/ANS RA-Sa, 2009 standard (Ref. 23), which offers guidance and requirements regarding the use of expert judgment in the following topics:

- Objective of Using Expert Judgment,
- Identification of the Technical Issue,
- Determination of the Need for Outside Expert Judgment,
- Identification of Expert Judgment Process,
- Identification and Selection of Evaluator Experts,
- Identification and Selection of Technical issue Experts, and,
- Responsibility for the Expert Judgment.

The approach outlined in NUREG/CR-6372 is one way to meet the standard requirement for the use of obtaining expert judgment.

In NUREG/CR-6372, the Senior Seismic Hazard Analysis Committee (SSHAC) developed a structured, multi-level assessment process[3] that since was employed in numerous studies of natural hazards; the NRC's Regulatory Guide 1.208 (Ref. 24) recommends it for developing new models for use in probabilistic seismic hazard analyses (PSHA). NUREG-2117 (Ref. 25), a follow-on document to NUREG/CR-6372, provides additional guidance for assessing seismic hazards. NUREG-2117 was developed after reviewing and assessing the lessons learned during the many projects that were undertaken using the SSHAC guidelines since their 1997 publication.

The SSHAC guidelines define four levels at which to conduct hazard assessments, ranging from the simplest ones (Level 1) to those most comprehensive and demanding (Level 4). These four levels are defined in order of increasing resources (i.e., number of participants and funds available), and sophistication. In Levels 1 to 3, a technical integrator (TI) adopts the role of "evaluator," and is empowered to represent the composite state of the information of the technical community on a particular issue. The TI develops a composite distribution of conditional probabilities representing the community's viewpoint. Thus, the goal is to represent the technical community's beliefs and not to develop a group consensus distribution. In Level 4, the SSHAC process applies the technical facilitator/integrator (TFI) approach wherein a group of expert "evaluators" is identified and their judgments (as well as those of other experts) are elicited. It involves a two-stage elicitation procedure "…in which the panel members are asked in Stage I to represent their own positions as independent evaluators of data, models and interpretations (the traditional role of a scientist); and in Stage II, to play the role of integrators who attempt to represent the composite position of the community as a whole…"(Ref. 21). Other important differences between the simpler processes in Levels 1 or 2 and the more involved Levels 3 or 4 concern complexity, cost, and schedule, which also include workshops, the inclusion of a participatory peer review panel (PPRP), and generally larger groups of experts.

The main objective of the SSHAC process is "…to provide a representation of the informed scientific community's view of the important components and issues …" (Ref. 21). Based on the available resources and the goals of this project, the NRC decided to use an enhanced SSHAC Level 2 approach. The enhancement was based on the recognition that a number of aspects of the SSHAC Levels 3 and 4 would improve the quality of the expert elicitation process. In particular, this project employed a TI team of four experts (rather than a single expert), expert interactions at workshops (rather than the TI contacting each expert individually and remotely by phone or email), and a PPRP composed of three experts who attended SSHAC workshops.

1.5 The PRA Panel

NRC/RES and EPRI spent considerable time before the project began identifying members for the expert elicitation PRA panel. As a whole, the panel possesses collective expertise in electrical circuits, post-fire safe-shutdown circuit analysis, fire PRA, and reliability modeling. The panel representation was balanced between the regulator (i.e., five members from the NRC/National Laboratories) and the nuclear power industry (i.e., five members from EPRI/Nuclear Power Industry).

---

[3] This is commonly referred to as "The SSHAC Process."

The PRA panel members[4] are listed below, along with their affiliations, and their resumes are given in Appendix A.

Robert Cavedo, Constellation Energy (CE)[5]
Daniel Funk, Hughes Associates, Inc. (HAI)
Raymond Gallucci, U.S. Nuclear Regulatory Commission (NRC)
Dennis Henneke, GE Hitachi Nuclear Energy (GEH)
David Miskiewicz, Engineering Planning & Management (EPM)
Steven Nowlen, Sandia National Laboratories (SNL)
Nathan Siu, U.S. Nuclear Regulatory Commission (NRC)[5]
Gabriel Taylor, U.S. Nuclear Regulatory Commission (NRC)[6]
Jing Xing, U.S. Nuclear Regulatory Commission (NRC)[5]
Kiang Zee, ERIN Engineering & Research (ERIN)

The project sponsors, NRC-RES's Mark Henry Salley and EPRI's Rick Wachowiak, attended a number of meetings/workshops and offered general assistance and oversight. Nicholas Melly and David Gennardo of NRC organized the EPRI/NEI, NRC/SNL, and Duke Energy's cable-fire-test data in a summary ("roll-up") table intended to help the panel members when estimating conditional probabilities. During deliberations, they also offered insights to the panel regarding the data. Finally, BNL's Mano Subudhi and Gerardo Martinez-Guridi served as evaluators on the TI team (e.g., proposing approaches for aggregating the panels input into an integrated distribution and performing statistical evaluations), and as moderators of panel meetings held at the NRC/RES's Church Street Office in Rockville, Maryland.

1.6 Report Organization

The following sections and appendices document the technical approach and results of the PRA panel expert elicitation on estimating the conditional probability distributions for various control circuit configurations, given fire has damaged the electrical cables:

Main Sections

- Section 2 is an overview of the deliberations of the PRA panel in estimating the conditional probability distributions. This encompasses the elicitation process used by the panel, defines all case studies included in this project, establishes the generic models for integrating the proponents' inputs, and discusses the PPRP findings on the panel's expert elicitation process.

- Section 3 discusses the PRA panel, specifically the proponents' evaluation of single break and double break control circuit configurations. Also included are details of the panel's evaluation of SOV, MOV, and circuit breaker control circuits in assessing their failure probabilities. Further, the section describes the technical approach used for estimating the duration likelihood plots for the spurious operation.

- Section 4 and Section 5 present the integration of proponent inputs and the final results for various end device cases associated with single and double break designs,

---

[4] Daniel Funk, Steven Nowlen and Gabriel Taylor also participated in the Electrical Expert PIRT Panel.
[5] These members served a peer review role in the SSHAC process.
[6] Gabriel Taylor replaced Martin Stutzke after first two meetings; both are NRC staff.

respectively, of control circuits.

- Section 6 summarizes the results of estimations of the likelihoods of durations for hot short-induced spurious operations for AC- and DC-powered control circuits.
- Section 7 presents guidance for applying the results in Sections 4 through 6 in typical plant fire PRA.
- Section 8 gives the summary discussions and conclusions of the PRA panel.
- Section 9 lists the references noted in the main body of this report.

Appendices

- Appendix A includes the resumes of PRA panel members and moderators.
- Appendix B presents the project plan and the SSHAC process used in the expert elicitation process. Also, it includes an assessment by the moderator of the processes of the PIRT and PRA panels' expert elicitation.
- Appendix C summarizes the proponent considerations in estimating the conditional probabilities for various single and double break configurations. It also describes the statistical Weibull Model that was used in developing duration plots for the AC and DC control circuits. The proponents' reports are attached to this Appendix.
- Appendix D details the development of the roll-up table containing all major fire test data.
- Appendix E summarizes the files used in integrating the proponents' inputs for developing the final conditional probability distributions.
- Appendix F presents the PPRP report on the PRA panel's expert elicitation work.
- Appendix G includes selected viewgraphs that BNL presented to the PRA panel for calibration training (regarding the SSHAC process, the estimation of probabilities, and potential sources of bias).
- Appendix H discussed the technical integrator and proponent opinion on application of likelihood estimates for multiple spurious operation (MSO) cases.

Compact Disk (e-files)

The information in some of the appendices is voluminous. In order to preserve the information used by the panel in making their decisions, it is included in the compact disk that is part of this Volume 2. This disk contains detailed information about the following appendices:

- Appendix C – Proponent reports.
- Appendix D – Roll-up table test data files.
- Appendix E – Calculation files from integrating proponent inputs.
- Appendix G – Selected viewgraphs used in this project.

2
OVERVIEW OF PRA PANEL'S ACTIVITIES

This section describes activities of the PRA panel in the overall process used for this expert elicitation exercise, including the methods and procedures.

The expert elicitation PRA panel convened five separate times in 2½ to 3-day meetings from January 2012 through May 2013 at the NRC's RES building in Rockville, Maryland. The TI team, consisting of evaluator experts met separately for two additional 2-day meetings in January and April of 2013 at the same RES building to evaluate the proponents' estimated probability of occurrences and durations of spurious operation for various control circuit configurations.

The first meeting was held from January 31st to February 2nd, 2012. This first meeting served as a transition to:

- Transfer the PIRT panel's findings to the PRA panel,
- Familiarize the members of the PRA panel with the control circuits identified by the PIRT panel that could be vulnerable to hot short-induced spurious operations in the event of a fire, and,
- Explain the data documented in NUREG-2128 (Ref. 17), including its limitations, that the PIRT panel used.

In this first meeting, the NRC's staff gave an overview of the project's goals and objectives, along with describing the roles of the participants. BNL's staff presented a summary of findings on the work from the electrical expert PIRT panel, followed by the NRC staff discussing the data from the EPRI/NEI and the NRC/SNL testing. Selected viewgraphs from these presentations are included in Appendix G. This meeting also served as the PRA panel's preliminary deliberations on the following items:

- Needed format and data processing[1] from EPRI/NEI and NRC/SNL data for the PRA panel to use in estimating the conditional probability distributions for control circuit cases for the hot short-induced spurious operation probability of occurrence and their durations,
- The PIRT's ranking of influencing parameters and the thirteen specific control circuit configurations identified by the PIRT panel in the PIRT Report (i.e., Volume 1), Section 3.3.3, for the PRA panel to consider, and,
- The expert elicitation process and the statistical estimation methodologies and models that could be used in achieving the primary objectives of this project, i.e., estimating the

---

[1] Experts provided feedback on methods to provide the test data that would be helpful in their analysis.

spurious operation conditional probability distributions given cable damage from fire for various hot short-induced failure modes in PIRT-identified control circuit configurations and the associated spurious operation duration estimation.

Section 2.1 describes the enhanced SSHAC Level 2 process that was followed in this project. Section 2.2 identifies and discusses selection of case studies evaluated by the PRA panel. Section 2.3 describes the approach used by the TI team to derive the conditional probability distributions of spurious operation given cable damage due to fire. Section 2.4 discusses the PPRP's comments and findings on the PRA panel's expert elicitation activities.

2.1 Enhanced SSHAC Level 2 Process Used by the PRA Panel

The expert elicitation process developed by the SSHAC, described in NUREG/CR-6372 (Ref. 21), has four levels, referred to as "SSHAC Level 1, 2, 3, and 4."

In March 2012, BNL presented the information about SSHAC's levels to get feedback from NRC/RES, EPRI, and the panel of experts on the appropriate SSHAC level to apply for this study. In this presentation, BNL detailed the differences among all four levels, and discussed the expert elicitation processes relating to the following attributes:

- Number of participants,
- Interaction among experts,
- Peer review of the process,
- Ownership of the final results,
- Process transparency,
- Regulatory assurance (i.e., defensible community distribution),
- Project cost,
- Project duration, and,
- Management challenges.

Considering the specific characteristics of the attributes associated with each of the four levels, NRC/RES selected an enhanced SSHAC Level 2 for this project. The approach followed all requirements of the Level 2 but added the interaction of experts via in-person workshops, a technical integrator team rather than a single technical integrator and also added a PPRP. The PPRP were present in all workshops and reviewed the activities of the project from the technical and process points of view. These three elements, though not necessary for Level 2, typically are required for Level 3 and Level 4. The NRC/RES and EPRI, along with the PRA panel considered that these additional elements would enhance the elicitation process in understanding the data from resource experts, and in developing methods and models that are appropriate for both proponents and the TI team, as well as minimizing any technical and procedural biases.

The experts on the PRA panel were assigned different roles. The three roles included evaluator experts that constituted the TI team, resource experts, and proponent experts. The role of resource experts included presenting data, models, and methods in an impartial manner and to discuss their understanding and limitations of the data, models or methods. Proponent experts provided the role of advocating a specific model, method or parameter to use in developing the estimates requested by this project. Two members of the PRA panel plus the BNL staff made up the TI team. The TI team consisting of evaluator experts, independent of the proponents, is ultimately responsible for developing the composite representation of the informed technical community.

Table 2-1 presents the project participants and outlines the roles and responsibilities in this enhanced SSHAC Level 2 process. Each individual identified in the table had a specific role. Two panel members served a dual role, as resource and proponent experts. Additionally, these two experts had served as members of the PIRT panel, and are familiar with (and/or participated in) all recent cable-fire test programs conducted by the EPRI, the NRC, and Duke Energy. Martin Stutzke of NRC was initially a member of the PRA panel. However, due to other developing RES PRA projects he was unable to be a full time member. Regardless, though not a member of the PRA panel, he developed a model for assessing the duration of spurious operations. He also played an advisory role for modeling and analysis. He developed the model that the TI team used in generating the plots of spurious operation duration conditional probability. Appendix B presents the project plan, which details the roles and responsibilities of each expert in Table 2-1, the goals of each workshop, and other SSHAC Level 2 elicitation-process-related activities.

Table 2-1. SSHAC Roles by the PRA Panel

ROLE IN SSHAC LEVEL 2 PROCESS	PERSONNEL
Project Sponsor	Mark Henry Salley Richard Wachowiak
Project Management	Nicholas Melly Richard Wachowiak
Technical Integrator (TI) Team (Evaluator Experts)	Raymond Gallucci Gerardo Martinez-Guridi David Miskiewicz Mano Subudhi (Moderator)
Proponent Experts	Dennis Henneke Steven Nowlen* Gabriel Taylor* Kiang Zee
Resource Experts	Daniel Funk Steven Nowlen* Gabriel Taylor*
Participatory Peer Review Panel (PPRP)	Robert Cavedo Nathan Siu Jing Xing
*During the workshops and conference calls, each of these individuals identified when he was acting as a proponent expert and when as a resource expert.	

In addition to the first meeting held in January 2012, three additional SSHAC-defined workshops[2] attended by all PRA panel members were held. Two additional separate meetings

---

[2] "Workshop #1," "Workshop #2," and "Workshop #3" are SSHAC terms. In this project multiple meetings were needed to complete "Workshop #2."

were held by the TI team. Numerous interactions[3] by the panel members also were employed to discuss and clarify issues (both technical and procedural), and their potential solutions.

2.1.1 PRA Panel Participation in SSHAC Workshops

The expert elicitation workshops were held to provide information to assist the TI team's technical assessments. BNL staff moderated the workshops and ensured that ground rules for the workshops were established and presented at the beginning of each workshop. The ground rules were stated consistently and enforced throughout each workshop by the moderator and occasionally by the PPRP panel members. The moderators were also responsible for ensuring that the agenda was followed and all presentations were delivered in an impartial manner. A short time was set aside at the end of each day for any of the observers at the workshop (including the project management) or the PPRP members, to make statements or pose questions to the panel.

SSHAC Workshop #1 was held during June 5-7, 2012. The purposes of this workshop were to identify (1) the technical issues of highest significance to evaluating the probabilities of spurious operations, and, (2) the data and information that was available to support these evaluations. In the first part of this workshop, BNL detailed all the attributes associated with the SSHAC Level 2 process chosen for this project. The presentations encompass the objectives of the project, roles and responsibilities of all participants, deliverables, and workshops and their ground rules.

The second part of Workshop #1 focused on the available fire test data to address the issues identified in the first part of the workshop. The discussions included a series of presentations by resource experts who had developed specific data-sets. The goal of this part of the workshop was to assist the members of the PRA panel in identifying the data and information that became part of the project database and commensurate with the technical issues of significance for the project, and in understanding the attributes of these data-sets (e.g., any limitations) to the extent possible.

Two meetings were held for SSHAC Workshop #2 during October 9-12 and November 27-29, 2012. The goals of Workshop #2, "Alternative Interpretations," were (1) to present, discuss, and debate alternative viewpoints on key technical issues; (2) to identify the technical bases for the alternative hypotheses, and to discuss the associated uncertainties; and, (3) to provide a basis for the subsequent development of preliminary probabilistic evaluation models that consider these alternative viewpoints. Workshop #2 also provided an opportunity to review the progress being made on developing the roll-up table and to elicit additional input, as needed, about this activity.

A key attribute of Workshop #2 was the discussion and debate of the merits of alternative models and viewpoints on key technical issues. Proponents discussed their interpretations and the data supporting them. In the spirit of capturing the spectrum of thinking across the entire technical community, a goal of this workshop was to offer an effective forum for the exchange of ideas. Proponent experts were encouraged to interact within the structure facilitated by the moderators.

After Workshop #2, the proponents were asked to provide their final inputs on three case studies (solenoid-operated valve (SOV), motor-operated valve (MOV) and Medium Voltage

---

[3] Interactions included telephone conferences, email exchanges, and Go-to-Meeting presentations.

Circuit Breaker) initially identified by the TI team. Accordingly, the proponents developed methods and models for estimating the conditional probabilities for these case studies. Each proponent provided their report containing technical approaches and estimates of conditional probability and the duration of spurious operation for various control circuit configurations.

By the end of January 2013, all four proponent experts provided their inputs to TI team to develop the final conditional probability distributions and duration plots. During January 30-31, 2013 and April 9-10, 2013, the TI Team members met separately to discuss the inputs from the proponents on the three case studies, and to formulate models for integrating the inputs from the proponent reports into a representation of the "larger informed technical community," as established by the SSHAC process.

Some examples of technical issues addressed by the TI team evaluators during these meetings involved the following:

- Developing conditional probability distributions from the proponent's input for each sub-case under three case-studies,
- Establishing a feedback process between the TI team and the proponents,
- Integrating the proponent's estimated conditional probability-distributions,
- Formulating event-tree-like structures to be used by the proponents for the MOV case,
- Choosing the models and methods to be used by proponents for the circuit breaker case,
- Detailing the assumptions made and test data used by proponents in their estimations,
- Using the single break control circuit results to model double break configurations,
- Developing aggregate[4] conditional probability distributions,
- Describing the models and methods used in developing a conditional probability distribution for the duration of spurious operations, and,
- Assessing the preliminary results of conditional probability distributions evaluated by the TI team.

Several telephone conferences and individual calls to proponents during and in-between these TI team meetings clarified certain technical issues and assumptions made in the proponents' reports. There was considerable interaction between the TI team and the proponents in developing the conditional probability distribution for the duration of spurious operations. Additional feedback from proponents was solicited for parameters to be used in this model for estimating this distribution; it is discussed in Section 3.4.

SSHAC Workshop #3 was held during May 7-9, 2013, and its goal was to present and discuss the preliminary models used and calculations performed. Workshop #3 provided a forum for the TI team to receive feedback from the rest of the PRA panel. In addition to the PRA panel, the PIRT panel members were invited to attend the final day of this workshop to give their opinions on the technical approach and the preliminary results.

At this workshop, members of the PPRP and the PIRT panel asked questions about the preliminary probabilistic models and results. This helped ensure that significant issues were not overlooked. It also allowed the TI team to understand the relative importance of their models,

---

[4] "Aggregate" represents a mathematical summation of probability distributions for all possible circuit failure modes due to hot shorts within a specific cable insulation-power supply scenario.

uncertainties, and assumptions used in their assessment of conditional probability distributions. This feedback formed the basis for finalizing the models after the workshop.

Thus, the final workshop consisted of two parts in which the TI team presented the following: (1) preliminary models, particularly emphasizing the manner in which alternative viewpoints and uncertainties had been incorporated; and, (2) conditional probability calculations that gave insight into the preliminary models. The assumptions made by the TI team in integrating the proponent inputs were explained to all proponents and each one was allowed to defend or agree with these assumptions. In discussing the preliminary models, the technical bases for the assessments were described to support a discussion of the implications and constraints provided by the available data. The PPRP questioned and probed aspects of the preliminary model to understand the manner in which the views of the larger technical community were considered. The final PPRP report summarizing their conclusions is included in Appendix F.

Following Workshop #3, the TI team adjusted their methods and models to accommodate this feedback and evaluated the final community distributions for all cases identified by both panels. The final methods and the models used in the development of the "Community Distributions"[5] are discussed in Section 2.3.

2.2 Case Studies Considered by the PRA Panel

A hot short-induced spurious operation is defined in Volume 1 as follows: "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; examples are a pump spuriously starting, or the spurious repositioning of a valve." Fire-induced intra-cable hot short, inter-cable hot short and ground fault equivalent hot short (GFEHS) failure modes potentially can cause spurious operation in various end-devices (e.g., SOVs, MOVs, and Circuit Breakers). An illustration of the intra-cable, inter-cable and ground fault equivalent hot short failure modes is presented in Figure 2-1. An **intra-cable hot short** failure mode occurs when fire damage results in a relatively low impedance fault between two or more conductors of the <u>same multi-conductor cable</u>. An **inter-cable hot short** failure mode occurs when fire damage results in a relatively low impedance fault between two or more conductors of two or more <u>separate cables</u> (inter-cable fault). A **ground fault equivalent hot short** occurs when fire damage results in

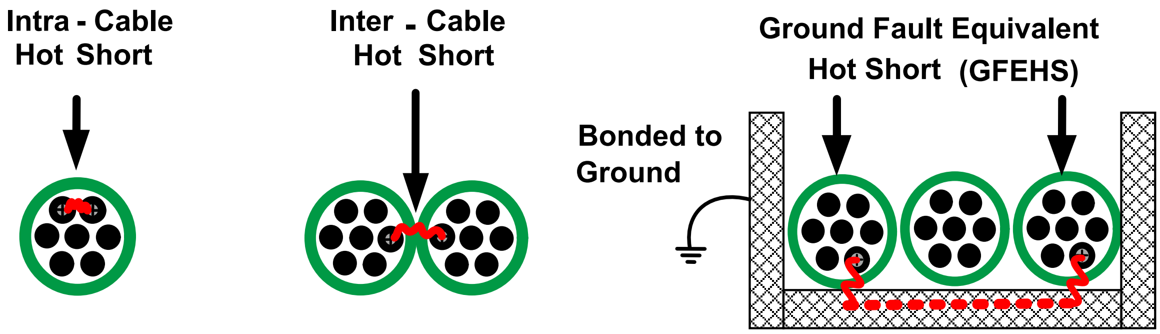


Figure 2-1. Illustration of Fire-Induced Hot Short Failure Modes

---

[5] "Community Distribution" is an expression of the technical community's knowledge rather than consensus.

conductors of the same or difference cable developing a relatively low impedance fault with a ground plane. For the GFEHS to cause a hot short induced spurious operation, both a source and target conductor must short to the same ground plane and have a compatible power supply. **Source conductors** are those which can supply energy (voltage, current). **Target conductors** are associated with end devices such as a conductor connected to a solenoid or a conductor connected to a contactor of a motor starter.

Additionally, in Tables 3-9 through 3-13 of Volume 1, the PIRT panel set up the tables for duration probabilities different from those of the spurious operation probability tables, since the physical influencing factors that most affect spurious operation duration differ from those affecting its probabilities. Ultimately, these duration tables were not used by the PRA panel.

2.2.1 PIRT Results Relating to Control Circuit Configurations

In Volume 1, after identifying all influencing parameters that would have high impact on the hot short-induced spurious operation in control circuits during a fire, the PIRT panel identified the thirteen (13) circuit configurations. Then, the panel took account of these configurations and presented the control circuit characterizations.

The PIRT panel included the following categorizations in selecting the control circuit configurations that are to be considered by the PRA panel;

For Spurious Operation Conditional Probability

- Control Circuit Configurations – Single Break (SB), Double Break (DB)
- Control Circuit Cases – SOV, MOV , Circuit Breaker (single break or contact only)
- Circuit Grounding/Power Supply Types – Grounded AC, Ungrounded AC (powered from individual CPTs), Ungrounded DC (or Ungrounded Distributed AC)
- Target Cable Constructions –Thermoset (TS) Target from TS Source Conductors, Thermoplastic (TP) Target from both TS and TP Source Conductors, Metal Foil Shield Wrap Target Cable, Target Cable with Un-insulated Drain Wire, Armored Target Cable
- Conductor Failure Modes – Intra-cable hot short, Inter-cable hot short, GFEHS

For Spurious Operation Duration Conditional Probability

- Fire Exposures – Flame, Plume, and Hot Gas Layer
- Circuit Grounding/Power Types
    - Spurious Operation Durations – Grounded AC, Ungrounded AC w/CPTs, and Ungrounded DC or Ungrounded Distributed AC (≤ 10 amp) Configurations
    - Hot Short Durations – Ungrounded DC or Ungrounded Distributed AC (≤ 10 amp and > 10 amp) Configurations
- Fuse or Breaker Size – ≤ 10 amp and > 10 amp
- Conductor Failure Modes – Intra-cable hot short, Inter-cable hot short, GFEHS

The PRA panel discussed and evaluated all PIRT tables representing single and double break control circuit spurious operations and their durations taking into account the available data. After deliberating during SSHAC Workshops #1 and #2, the PRA panel consolidated many of these PIRT tables and simplified them commensurate with the availability of the data and considering the practical use of the estimated probabilities in fire PRAs. This is discussed in Section 3.1.4.

2.2.2 Hot Short Characterization

The PIRT tables in Section 3.4 of Volume 1 identify several cable hot short-induced failure mode configurations as implausible or incredible scenarios. These two dispositions are defined in Section 2.1.3 of Volume 1. Since the PRA panel used these characterizations for all its case studies, the following are the PIRT panel's definitions of these terms that were acceptable to the panel.

Incredible – 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 arguments to support its happening during a fire.

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 either in operating experience or during a fire test.

The PRA panel accepted and used these definitions[6] and hence, did not determine any probability distributions for those scenarios classified as "incredible," based on the PIRT panel recommendations. For those scenarios classified as "implausible" the PRA panel used the available test data (if any), expert judgment, or a combination of both to estimate spurious operation conditional probability distributions. Additionally, the PRA panel did not use their numerical estimates to categorize or re-categorize any of the sub-cases.

2.2.3 Initial Case Studies Included in Proponent Reports

The case studies evaluated by the PRA panel evolved during the course of the expert elicitation process. Initially the proponent experts were asked to provide probability of occurrence estimates for the following case studies:

Conditional Probability of Occurrence Estimates:

- Single Break Control Circuits
    - SOV (Base Case)
    - MOV
    - Medium Voltage Circuit Breaker

- Double Break Control Circuits
    - SOV (Base Case)

---

[6] The last sentence, "Any likelihood value assigned to these types of phenomena would have little meaning" of PIRT panel's definitions in Volume 1 is deleted from both definitions, per the PRA panel recommendation.

Duration Conditional Probability Estimates:

- Circuit Grounding/Power Configurations
  - Spurious Operation Durations – Grounded AC, Ungrounded AC w/CPTs, and Ungrounded DC or Ungrounded Distributed AC (≤ 10 amp) Configurations
  - Hot Short Durations – Ungrounded DC or Ungrounded Distributed AC (≤ 10 amp and > 10 amp) Configurations

The TI team developed templates that were to be used by the proponents to collect their input in a consistent manner. The case studies were extensively discussed and debated by the panel members during meetings of the SSHAC Workshop #2. General instructions and sample sub-cases of the case studies for estimating single break, double break, and duration conditional probability are given in Appendix C. As a result of the PRA panel interactions during Workshop #2 and #3, these initial case studies were expanded as discussed below.

2.2.4 Proponent Expert Input and Technical Integrator Team Assessments

All four proponents estimated the conditional probability of occurrence for the 34 sub-cases including the aggregate columns for that of the base case, a single break control circuit. Each proponent expert used the data and expert judgment in estimating these values. Some proponent experts did not provide information for all sub-cases.

The following are the number of proponents addressing each of the initial case studies:

- Single Break SOV (Base Case) – All four Proponents
- Single Break MOV – Three Proponents (Proponents #1, #3, and #4)
- Single Break Circuit Breaker – Two Proponents (Proponents #1 and #3)
- Double Break SOV (Base Case) – Three Proponents (Proponents #1, #2, and #3)
- Spurious Operation Durations – Two Proponents (Proponents #1 and #3)
- Hot Short Durations – One Proponent (Proponent #4).

The proponent reports are included in Appendix C. The proponent expert input for the conditional probability of spurious operation occurrence was received in a relatively consistent format (median and quantiles). This information was then processed by the TI team into the community distributions following the process described in Section 2.3.

Spurious Operation Duration Plots

The evaluation of the hot short-induced spurious operation duration conditional probability evolved substantially from the start of the project to the final estimates. Originally, the approach for estimating duration was treated similarly to the likelihood of spurious operation, in that the influencing parameters ranked as "highly important" from the PIRT panel were used to structure the requested input. When the input was received from the proponents, none evaluated all of the sub-cases defined by the PIRT panel. Proponent #1 provided spurious operation distributions for a limited subset of the sub-cases. Proponent #3 provided two distributions, one for AC and the other for DC powered control circuits. Proponent #4 provided a single distribution for hot short duration. Proponent #4's approach was discarded by the TI team as it estimated hot short duration and not hot short-induced spurious operation duration probabilities which was of interest for this project.

Following several discussions at the PRA panel workshops, proponent submittals, and the TI team's preliminary evaluations, the TI team decided to adopt Proponent #3's approach, consisting of a "top-level" evaluation, one distribution for AC and another for DC control circuit configurations, rather than the detailed assessment provided by Proponent #1 for sub-cases that the PIRT panel recommended. Therefore, for the duration of spurious operation cases, the PRA panel concluded that the two plots would be adequate for fire PRA applications. The TI team selected the two-plot approach for two reasons. First, limiting the number of duration distributions simplifies the analysis in that the user doesn't have to determine the predominant thermal conditions damaging the cable. Second, the TI team believed that having a limited number of duration distributions based on a larger data set outweighed alternative approaches which used limited data to develop numerous duration distributions. Once the approach was selected, the TI team requested the proponents to provide feedback on the approach to interject their expert judgment.

The PRA panel members held several teleconferences and presentations to address the spurious operation duration probability for control circuits. The PRA panel concurred with the TI team's decision to apply the approach suggested by Proponent #3, instead of adopting the PIRT panel's recommended duration tables in Volume 1. To adequately represent the informed scientific community, a model was developed to allow proponent input to adjust the shape of the distribution. This model includes adjustments to the mean value and the uncertainty bounds (by introducing a "c-parameter" for the mean adjustment and an "s-parameter" for the uncertainty bounds), as discussed in Section 3.4. The proponents were asked to recommend values for these two scalar parameters and to provide their best judgment on the floor levels (with uncertainty bounds) for AC and DC control circuits.

Double Break MOV Case

The initial case studies listed in Section 2.2.3 do not include the MOV cases for double break control circuits; therefore, the proponents did not address them in their reports. During BNL's presentation of the draft conditional probability results to both the PRA and PIRT panels in Workshop #3, this case was debated by the panel members. Although this circuit design is not typical, it likely exists in some NPPs. Therefore, the PRA panel decided to include this case. To calculate the conditional probability values for these double break MOV circuits, the proponents and other participants suggested methods and approaches to the TI team that could be used for ungrounded AC with CPTs and ungrounded DC (or ungrounded distributed AC) control circuits. This was discussed later via a teleconference with all members of the TI team. Thereafter, the TI team agreed to include an MOV case for the double break control circuits.

2.2.5 Project's Final Case Studies

Based on the discussions detailed in Section 2.2.4, the original set of case studies listed in Section 2.2.3 was revised to accommodate changes in the project's scope. The following final set of case studies was included in this expert elicitation:

- Conditional Probability of Occurrence Estimates
    - Single Break Control Circuits (all power supply configurations)
        - Base Case - SOV

    - MOV
    - Medium Voltage Circuit Breaker
  - Double Break Control Circuits (ungrounded AC and DC power supply)
    - Base Case – SOV
    - MOV

- Duration Conditional Probability Estimates
  - AC Control Circuits
  - DC Control Circuits

Section 3 describes the methods and models the proponents used in addressing each of these final case studies. The single break SOV and MOV cases each included 34 sub-cases of cable and control circuit configurations. There was only one ungrounded DC control circuit for the medium voltage circuit breaker case. Double break SOV and MOV cases were considered for ungrounded AC (with individual CPTs) and ungrounded DC (or ungrounded distributed AC) control circuits. Since in ungrounded AC with individual CPTs power supply the AC test data for the GFEHS mode (for single break case) is not explicitly separated from the inter-cable hot short mode as in the case of ungrounded DC, there were only 13 sub-cases for each of the SOV and MOV cases, comprising of various cable-hot short mode configurations. However, the ungrounded DC (or ungrounded distributed AC) for the SOV and MOV cases each encompassed 16 sub-cases.

Section 4 discusses the final conditional-probabilities for single break control circuits, and Section 5 presents those for double break cases. Section 6 shows the duration probabilities as two plots (with tabulated values) of the duration probabilities for AC and DC control circuits. The tables with the final results include the beta-distribution parameters (i.e., alpha and beta) and the values of three characteristics of this probability distribution (i.e., 5%, Mean, 95%) that could be used directly in fire PRA applications. Since this study encompasses all plausible modes of circuit failure for each control circuit configuration, the aggregate columns in these final probability tables used the combination (i.e., Boolean OR) of applicable failure-modes for a given power supply configuration.

2.3 Technical Integration Process to Obtain Community Distributions

The main objective of the SSHAC process is "…to provide a representation of the informed scientific community's view of the important components and issues …" "Informed" in this sense means that the community of experts was given the same data and level of interaction as were the evaluators (Ref. 21). Accordingly, the goal herein was to generate a representation of the informed scientific community's view of each particular conditional probability and duration of spurious operation, assuming fire damage to the associated cables. As described, this representation was in the form of a probability distribution, [i.e., the "Community Distribution"] because it is an expression of the community's knowledge.

This section describes the process used to arrive at this community distribution, based on the proponents' inputs. It was applied for estimating each community distribution of probability of spurious operation under certain conditions; the results are detailed in Sections 4 and 5. The "conditions" are the specific circumstances that are fixed in each sub-case representing a circuit configuration, such as damage to electric cables due to fire including the target-cable configuration (e.g., thermoset-insulated conductors) in a power supply configuration (e.g., grounded AC).

The process used entailed six steps. Training experts in Step 1 was given to the panel members at the beginning and reminded during each SSHAC workshop, while Steps 2-6 were typically carried out by the TI evaluators for each calculation of the community distribution in the order presented below.

1. Training Experts
2. Receiving Input from Proponents
3. Developing Simplified Representation of Proponent Inputs and Incorporating Feedback from Proponents
4. Consolidating Input from Proponents
5. Deriving a Parametric Community Distribution
6. Developing Community Distributions for Aggregated Failure Modes

In practice, however, two reasons made Steps 2-6 an iterative process:

1. The SSHAC process encourages interactions between the resource experts, proponent experts, the TI team, and the PPRP during and between the workshops; hence, sometimes the step outcomes required revisions.

2. The many sub-cases, their complexity and the number of issues addressed required refining some steps, or modifying the approach to resolve challenges that initially were not evident.

An exception to this process was the development of the spurious operation duration probability. For this, the TI team concluded that the approach offered by one proponent and informed by all proponents reasonably represents that of the informed scientific community; this is discussed in Section 3.4 and the results are given in Section 6. As the PPRP points out in their report, the methods chosen by the panel may underestimate the uncertainties in the early portion (pre-floor) of the duration distribution.

2.3.1 Training of PRA Experts

The experts were trained in two areas:

1. **The SSHAC process.** Initially, training was given in the basic concepts of this process, including the process goal, different levels of study, different types of experts, their associated roles and responsibilities, and the expected deliverables. Appendix G contains the viewgraphs for this training. In addition, a brief refresher course was given at the beginning of every workshop.

2. **Normative expertise.** The experts were trained to help them to express their knowledge in probabilistic terms, while minimizing biases. The training focused on normative expertise, that is, on expertise to reach coherent, unbiased probability assessments. It covered the following topics: Coherence, Calibration, Biases, and a real-case example.

Since the probability (or duration) of spurious operation is an unknown, it involves uncertainty. Therefore, an expert's probability distribution must be elicited to express such uncertainty. To make the best use of available resources, this project requested just a few distribution percentiles from each proponent, and then used these percentiles to derive a distribution approximating the proponent's beliefs. Hence, the training included a method of bisection, viz., eliciting three quantiles of the expert's distribution; first, the median ($p_{0.5}$), followed by the lower and upper quartiles ($p_{0.25}$ and $p_{0.75}$). Finally, a probability distribution was fitted to these quantiles, as explained under "Fitting and Feedback from Proponents," in Section 2.3.3 below.

2.3.2 Receiving Input from Proponents

The input requested of each of the four proponents comprised of three quartiles ($p_{0.25}$, $p_{0.5}$, and $p_{0.75}$) for each sub-case that was evaluated. The following are some points relevant to this input:

1. Some proponents chose to provide the 0.05 and 0.95 quantiles ($p_{0.05}$ and $p_{0.95}$) for some sub-cases instead of the lower and upper quartiles because they felt more comfortable expressing their knowledge in this way.

2. Some proponents provided the 0.05 and 0.95 quantiles for several sub-cases in addition to the lower and upper quartiles. The five quantiles ($p_{0.05}$, $p_{0.25}$, $p_{0.5}$, $p_{0.75}$, and $p_{0.95}$) were used in the subsequent step, "Fitting and Feedback from Proponents."

3. Not all the proponents provided input for all sub-cases; thus, in some instances input was available from a subset of the four proponents, for example, only three proponents gave input for one particular sub-case, and therefore, the assessment was based only on them.

2.3.3 Fitting and Feedback from Proponents

After gathering the proponents' input, a probability distribution was fit to the quantiles given by each proponent for each sub-case. The beta distribution was selected for this fitting because of three features: 1) its range is the interval [0, 1], corresponding to the values of probabilities; and, 2) it is a flexible distribution that can adopt different shapes; and 3) it can be treated using standard PRA software tools. The probability density function (PDF) of a beta random variable, P, is

$$f(p) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} p^{\alpha-1}(1-p)^{\beta-1}$$

for $0 \leq p \leq 1$, with parameters $\alpha, \beta > 0$. Here, the distribution is denoted as Beta (α, β). Γ is the gamma function.

The basic approach for fitting a beta distribution was to fit it to the three (or five) quantiles given by a proponent, plus two additional points that are known: $P(P \leq 0) = 0$, and $P(P \leq 1) = 1$, where $P(P \leq p)$ is the probability that the random variable, P, is less than or equal to the value p (Ref. 26). That is, a beta distribution was fitted to these five (or seven) points. However, the points that a proponent supplied did not necessarily follow the shape of a beta distribution (or any other parametric probability distribution). Furthermore, from a practical point of view, it sometimes was difficult to fit a distribution to all the points available, or, if it was, the resulting distribution might not accurately reflect a proponent's knowledge. To resolve this problem, a beta distribution was fitted to each possible combination of a proponent's quantiles (plus the two additional points) for each sub-case, so that the proponent could choose the beta distribution most closely representing his knowledge for each sub-case. For example, if a proponent gave three quantiles for one sub-case, there are seven possible combinations (three of each quantile alone, three of pairs of quantiles, and one having all three quantiles); then, he selected the one most appropriate based on his best judgment. If a proponent offered five quantiles for one sub-case, that is, thirty-one (31) combinations, a beta distribution was fitted to each of them so he could choose one.

Thus, the beta distributions from all combinations of quantiles for each sub-case assessed by a proponent were sent to him, and he then selected the one most closely representing his opinion. Hence, each proponent offered feedback on the best distribution for each sub-case that he had evaluated.

Accordingly, the main outcome of fitting and feedback was a beta distribution representing a proponent's judgment for each sub-case he assessed.

2.3.4 Consolidating Input from Proponents

As mentioned earlier, the objective of the SSHAC process is to offer a representation of the informed scientific community's view; hence, the TI team consolidated into a single distribution of the beta distributions from all proponents offering input to a particular sub-case so that it encapsulates their opinions; hence, it is named the Community Distribution within the SSHAC context.

The type of consolidation is mathematical aggregation that essentially consists of eliciting one distribution from each individual proponent, and then mathematically combining them into a single one. The method of mathematical aggregation implemented was the Linear Opinion Pooling (LOP) that, according to O'Hagan et al. (Ref. 26), "…provides a simple, robust, general method for aggregating expert knowledge…" This widely used technique offers a means whereby an integrated distribution $f(\theta)$ is obtained as a function of the individual distributions $\{f_1(\theta), \ldots, f_n(\theta)\}$, wherein θ is an unknown quantity, such as the probability of spurious operation given certain conditions.

The LOP method is a weighted average of the individual distributions, as shown below.

$$f(\theta) = \sum_{i=1}^{n} w_i f_i(\theta)$$

where $f_i(\theta)$ is the individual distribution of proponent i, n is the number of proponents providing input for a particular sub-case, and $f(\theta)$ is the aggregated distribution. The weights, w_i, sum to 1:

$$\sum_{i=1}^{n} w_i = 1$$

In almost all cases, the TI team assigned equal weights to the individual proponent distributions. In only four sub-cases (involving single break SOV circuits) they assigned different weights to different proponents (see Section 4).

2.3.5 Deriving a Parametric Community Distribution

The aggregated distribution, $f(\theta)$, obtained by applying the LOP method to a particular sub-case is the community distribution for this sub-case. This distribution also is named as the LOP distribution. However, for two reasons, it was considered that providing this distribution was impractical:

1. The distribution resulting from linearly combining several beta distributions typically is not a parametric one, so a table of values describing the distribution for each sub-case would be needed. This is a cumbersome approach, and it is much easier to enter a parametric distribution into a PRA software code than a table of values.

2. In some sub-cases, the LOP distribution displayed "fluctuations" (i.e., peaks and valleys) resulting from differences between the proponents' distributions. In other words, sometimes these distributions differed such that the LOP distribution had several modes, and/or steep rises or falls that was not deemed by the TI team representative of the assessments of the informed scientific community, but rather, the result of mathematically aggregating distributions for a small number of proponents.

To resolve this issue, a beta distribution was fitted to the LOP curve, and this beta distribution then was considered to be the final community distribution for the particular sub-case. This approach has the advantages: 1) The beta distribution is completely characterized by its two parameters (α and β), and its mean, standard deviation, or any quantile can be obtained with this information, 2) the beta distribution is a parametric distribution that can be used in PRA codes, and, 3) the beta distribution's behavior is smooth, and its quantiles are similar to those of the LOP distribution.

Fitting a beta distribution to the LOP distribution entailed two main steps:

1. Numerically assessing one hundred quantiles of the LOP distribution, that is, from the 0.01- and 0.02-quantiles to the 0.99- and 1.0-quantiles, so that the fitting process accounted for the entire range of the LOP distribution.

2. Fitting a beta distribution to these quantiles using the statistical computer package "rriskDistributions" [Belgorodski et al. 2012 (Ref. 27)] which implements least squares estimation with the default value of the absolute convergence tolerance for reaching zero of 0.001.

Finally, we compared the mean values of the LOP distribution and of the fitted beta distributions to verify that they were the same when rounded up to two significant digits.

Figure 2-2 illustrates the process of applying the LOP method and fitting a beta distribution to the resulting LOP distribution for one single break sub-case (i.e., SB 01_04)[7] of solenoid-operated valve (SOV). PDF means probability density function, and p(SO/fire) is the probability

---

[7] For reference, see Table 3-1 for Single Break Sub-Case SB 01_04.

of spurious operation given fire damage. The dotted distributions are those of four proponents (Prop1 to Prop4), the thin continuous curve is the integrated distribution or LOP distribution resulting from applying the LOP method, and the thick continuous distribution is the fitted beta distribution, that is, the community distribution. The numbers in parentheses are the parameters of a beta distribution (e.g., α = 4.6 and β = 2.6 for the Community Distribution identified as "CD" in Figure 2-2), and the last number to the right is the mean of the distribution. In this case, the means of the LOP distribution and of the fitted beta distribution are the same, viz., 0.64.

In many sub-cases, the means of the LOP distribution and of the fitted beta distribution were the same after rounding to two significant digits, but there were some wherein the means differed. For the latter, a different approach was employed consisting of determining a beta distribution having the same mean and 0.95 quantile as those of the LOP distribution. Keeping the same mean is important because it is the figure that mostly is used in decision-making and in deriving point-estimates; preserving the 0.95 quantile is relevant because this is a measure of how large a quantity may be, and often decision makers are interested in it. Additionally, several proponents were more concerned with ensuring fidelity at the upper end of the distribution and were less interested in fitting to the lower percentiles.

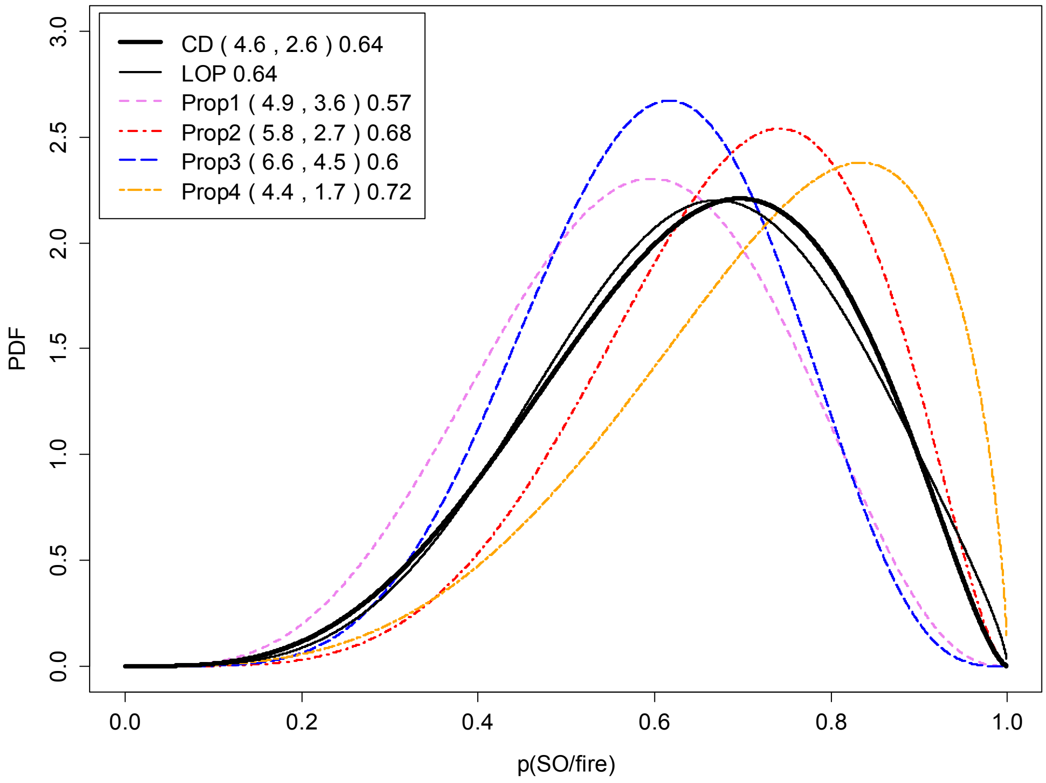


Figure 2-2. Example of Applying LOP and Fitting a Beta Distribution to the Resulting LOP Distribution [SB 01_04]

Deriving a beta distribution having the same mean and 0.95 quantile as those of the LOP distribution consisted of numerically solving the following two equations for the parameters of a beta distribution (α and β):

$$\text{LOP's mean} = \alpha / (\alpha + \beta)$$

$$\text{LOP's 0.95 quantile} = F^{-1} (\alpha, \beta)$$

Where, $F^{-1}(\alpha, \beta)$, the quantile function of the beta distribution, is the inverse of the cumulative distribution function, F, and is a function of α and β.

The beta distribution with the estimated parameters α and β yields the final community distribution. Figure 2-3 is an example of determining the community distribution in this way for one single break sub-case (i.e., Single Break 01_05) of SOV control circuits. The LOP distribution and the resulting beta distribution representing the Community Distribution (identified as "CD" in Figure 2-3) have the same mean (9.7×10^{-4}) and 0.95 quantile (3.5×10^{-3}, not shown in the figure).

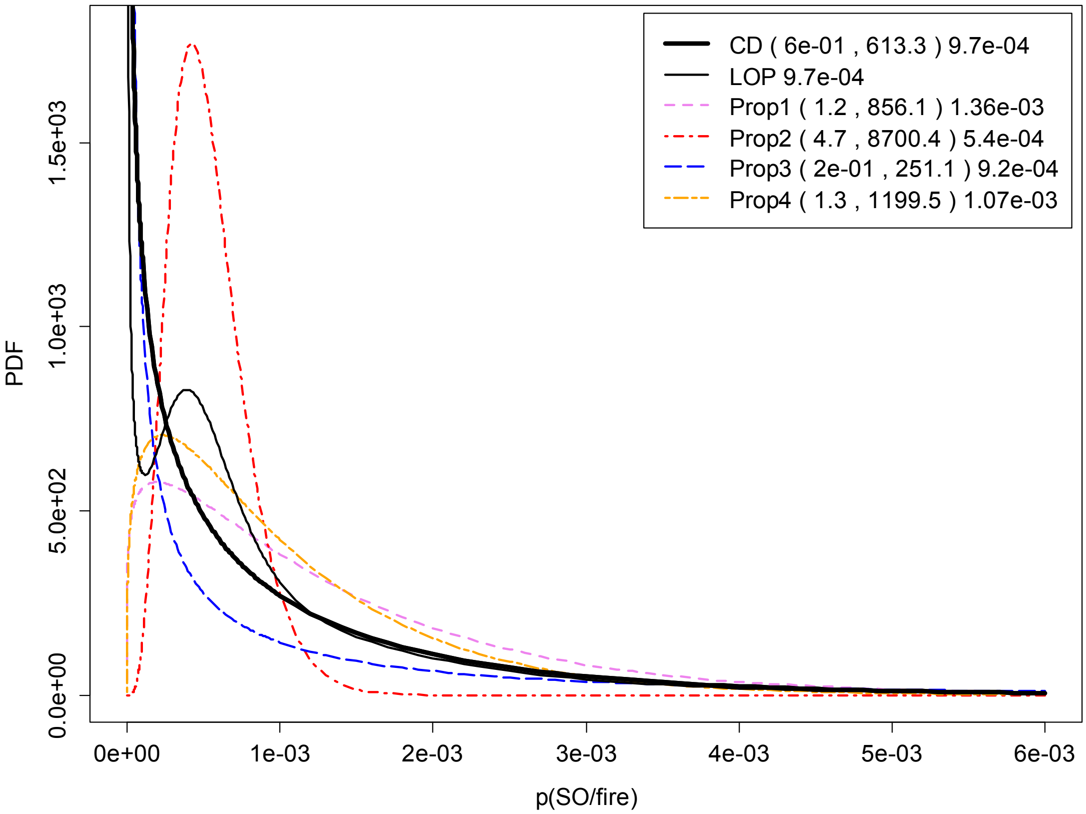


Figure 2-3. Example of Estimating a Beta Distribution Having the LOP's Mean and 0.95 Quantile [SB 01_05]

2.3.6 Combining Individual Community Distributions

In many NPPs fire PRA scenarios, any one of the hot short failure modes may trigger a spurious operation. For example, a TS-insulated target cable in a grounded AC configuration may fail due to an intra-cable or inter-cable hot short. The process described above determines the community distribution for each of these failure modes independent of each other. It also is of interest to assess the community distribution for the "aggregate" sub-case, that is, a spurious operation due to any of these possible failure modes. As several proponents suggested, and the TI team agreed, the aggregate of the possible failure modes was evaluated by linking these modes under an "OR" gate.

As mentioned in Sections 4 and 5, individual events were combined by linking the corresponding hot shorts by an "AND" gate in some sub-cases. All the fault trees (i.e., "OR" and "AND" gates) were implemented with the PRA code SAPHIRE 7 for Windows [Wood et al. 2008 (Ref. 28)], and uncertainty propagation (i.e., evaluation of parameter uncertainty) was carried out using the Latin Hypercube Sampling method (a special type of Monte Carlo simulation) with the maximum number of samples (99,998) allowed by this version of SAPHIRE.

The outcome of the combination of two or more beta distributions is not a beta distribution, or any other parametric distribution commonly used in PRAs. The non-parametric distribution resulting from propagating the parameter uncertainty can be characterized by the nineteen quantiles generated by SAPHIRE 7. A beta distribution was determined from these quantiles using the process "Deriving a Parametric Community Distribution" in Section 2.3.5 above. For establishing a beta distribution from these quantiles, the only difference with that process is that the means of the non-parametric distribution and of the beta distribution should be equal when they are rounded off to two significant digits.

Figure 2-4 is an example of determining the community distribution (i.e., a beta distribution) using the quantiles generated by SAPHIRE 7 for one of the aggregate sub-case (i.e., Single Break 04_10 in Table 3-1) for SOV control circuits. Here the community distribution of the aggregate represents an armored target cable in an ungrounded DC configuration causing spurious operation due to an intra-cable hot short or GFEHS. The CDF in this figure stands for cumulative distribution function, and the thick curve is the community distribution (identified as "CD" in Figure 2-4). The dots in the graph are these quantiles, and the thin line is a straight line joining consecutive pairs of quantiles so it approximates the non-parametric distribution, labeled "Empirical" in the legend.

Since the information from the proponents was received in terms of quantiles, it was natural to fit the cumulative distribution function (CDF) of the beta distribution to the quantiles from each proponent (Subsection 2.3.3, "Fitting and Feedback from Proponents"). Then, the LOP equation was applied to the resulting CDFs for each sub-case (Subsection 2.3.4, "Consolidating Input from Proponents"). The individual proponents' distributions and the parametric community distribution (Subsection 2.3.5, "Deriving a Parametric Community Distribution") were plotted as probability density functions (PDFs) because this kind of graph facilitated understanding and discussing the results of the elicitation by the experts (see, for example, Figure 2-2). Finally, as described in this subsection, the individual community distributions were combined, as necessary, by means of the SAPHIRE code. An individual community distribution resulting from this combination was plotted as a CDF (as shown in Figure 2-4) because the output from this code was provided in terms of nineteen quantiles. The purpose of this graph is to show the fitting of a beta distribution to the quantiles, and this community distribution was the outcome of mathematically combining probability distributions, not the result of expert elicitation.

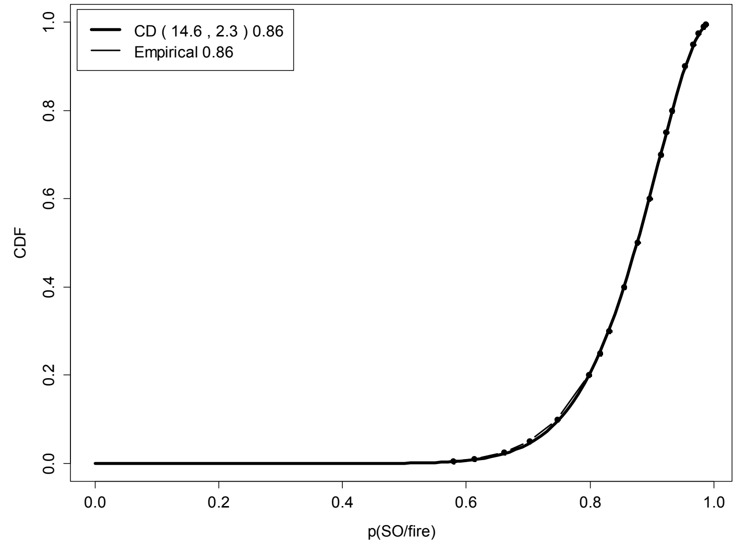


Figure 2-4. Example of Determining a Beta Distribution Using the Quantiles Generated by SAPHIRE 7 [SB 04_10]

2.4 Participatory Peer Review Panel Findings

The objective of the participatory peer review panel (PPRP) was to address the project's conformance to the requirements of the enhanced SSHAC Level 2 expert elicitation process and the extent to which all technical assessments were adequately defended and executed.

The PPRP provided useful feedback to this project that helped ensure the intent of the SSHAC process being followed and address numerous comments on the technical approach being explored during the PRA panel's deliberations. The PPRP documented its effort in summary reports by a panel member after each SSHAC workshop and a final PPRP report by the panel's chairperson after reviewing the final draft version of this report (Volume 2). In addition, the PPRP provided suggestions for improving the presentation of information in the final draft version of NUREG/CR-7150, Volume 2. Most of these suggestions were incorporated where possible prior to the publication of this NUREG/CR report.

Appendix F presents the final report as received from the PPRP. This report delineates PPRP's observations that were:

(1) Potential weaknesses in the project's execution of the SSHAC's enhanced Level 2 elicitation process,

(2) Less clear connection with the project results but suggest lessons for future elicitation projects, and,

(3) Considered to be project's good elicitation practices.

The report also details suggestions for technical presentation and writing of Volume 2 of NUREG/CR-7150, which would make it more accessible to a broader audience.

3

PROPONENTS' DEVELOPMENT OF SPURIOUS OPERATION CONDITIONAL PROBABILITY ESTIMATIONS

This section summarizes the technical assessment used for, and the information and conclusions from, the proponents' development of estimating the conditional probabilities of spurious operation occurrence and duration for typical control circuits used in NPPs. As discussed in Volume 1 of NUREG/CR-7150, fire-induced intra-cable hot short, inter-cable hot short, and GFEHS failure modes potentially can cause spurious operation in various end devices (e.g., SOV, MOV, and medium voltage circuit breaker). Given these failure modes and an understanding of the predominant cable-circuit configurations and phenomena that could affect the outcome of fire-induced circuit failure, the proponent experts were asked to do the following:

1. Estimate the conditional probabilities of hot short-induced spurious operation occurrence for specific control circuits due to fire damage to electrical cables, and,

2. Estimate the likelihood of durations of hot short-induced spurious operations due to fire damage to electrical cables.

To support their estimates and better inform the TI team, the proponents were asked for technical justification to support their values. Here, the proponents commonly relied upon information from the PIRT panel work documented in Volume 1, NRC- and Industry-sponsored fire test data, and their own expertise. Section 2.2.3 identified the case studies where estimates were desired.

The estimates developed by the PRA panel addresses control circuits only. Two applications where these assessments explicitly do not apply are "Power Circuits and Cables," and "Instrumentation Circuits and Cables." For the former, the PIRT panel offered guidance in Volume 1 by taking technical positions on certain power circuit configurations. For instrumentation circuits, they provided an extended discussion of circuit types, their potential modes of faulting and other concerns, but concluded that there was no applicable data available then to characterize these circuits and their behavior given cable failure due to a fire. The PRA panel briefly discussed the quantification of instrumentation circuit with regard to fire-induced circuit failure modes, but it was subsequently determined that addressing instrumentation circuits would have required significant additional resources that were judged to be outside the scope of this project.

This work **does not** offer conditional probability estimates for the following specific cable configurations:

- Trunk Cables (high conductor count multi-conductor cables, typically greater than 12 conductors per cable),

- Panel Wiring (i.e., wiring within an electrical cabinet) Cables, and,
- Instrumentation Cables.

However, based on the PIRT panel's recommendations in Volume 1 on these cable configurations, the PRA panel, in the interim, offers its guidance in Section 7.4.

Two major circuit configurations associated with control systems are included in this evaluation for hot short-induced <u>spurious operation occurrence</u> conditional probability:

1. Single Break (or Contact) Control Circuits
    - Base Case - SOV
    - MOV
    - Medium Voltage Circuit Breaker

2. Double Break (or Contact) Control Circuits
    - Base Case - SOV
    - MOV

The evaluation also includes the hot short-induced <u>spurious operation duration</u> conditional probability for these control circuits.

3.1 Information Available to Proponents

3.1.1 PIRT-Identified Influencing Parameters

The proponents used input from the work of the electrical experts PIRT panel as their key source of information. As documented in Volume 1, the PIRT panel ranked the following parameters as having a HIGH impact on the hot short-induced <u>spurious operation occurrences</u>:

- Circuit Wiring Configuration
    - number of sources, targets, ground/neutral, and their locations
- Cable's Conductor Insulation Material Type
    - for inter-cable hot shorts (TS versus TP)
- Grounding Configurations
    - Cable Grounding Configuration (e.g., ground or drain wire, shield wrap)
    - Armor Grounded versus Ungrounded Circuit (for AC) and Armored versus Unarmored Cable (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 this parameter is important)
- Cable Raceway Fill
    - Bundles (The PIRT panel considered this important even though the panel ranked this factor as having MEDIUM impact).

The PIRT Panel also ranked the following parameters as having a HIGH impact on the likelihoods of <u>spurious operation durations</u>:

- Fire Exposure Conditions
  - flame, plume, hot gas layer
- 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 factor as having MEDIUM impact.)
- Latching Circuit Design (e.g., MOVs)
  - This parameter is related to the design of the specific circuit, and not to any particular aspect of fire-induced circuit failure.

There are influencing parameters other than those listed above, associated with cable installations in plants, which were judged to have minimal effects on the likelihood of spurious operation during a fire. Most of them have not been tested explicitly. In Volume 1, the PIRT panel extensively discussed the effect of these parameters, including power supply and circuit parameters. Given that a cable has been damaged by a fire, the PIRT and the PRA panels judged the following in-plant power supply-circuit configuration parameters to have minimal effect on the likelihoods of hot short-induced spurious operations:

- Conduits versus Tray versus Air Drop Cable Configuration,
- Straight Cable Runs versus Bends or Risers,
- Vertical versus Horizontal Cable Routing,
- Conductor Count in a Cable,
- Cable Jacket Material,
- Specific Position of a Cable Within a Raceway,
- Fire Retardant Coatings, Tray Covers, or Raceway Fire Barrier Systems,
- Base Ampacity Loading Levels, and,
- Cable/Conductor size.

3.1.2 Fire Test Data and Other PIRT Panel Recommendations

The NRC and EPRI have independently and jointly undertaken fire testing of various cable-circuit configurations. Duke Energy also performed similar tests using armored control cables. The PRA panel's overall determination of the conditional probabilities for various control circuit configurations depends primarily on these results and their own expert judgments. Therefore, the following provides a discussion of the test data applicability and related limitations of the estimation of the conditional spurious operation probabilities and the conditional probability values for the duration of spurious operation. Appendix C summarizes this evaluation of these fire-test findings for specific control circuit configurations. Additional information on the NRC's and EPRI's testing can be found in the following reports:

- NUREG/CR-5546, "An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electrical Cables," May 1991 (Ref. 29)

- EPRI TR-1006961, "Spurious Operation of Electrical Circuits Due to Cable-Fires-Results of an Expert Elicitation," May 2002 (Ref. 13)
- NUREG/CR-6776, "Cable Insulation Resistance Measurements Made During Cable-Fire Tests," June 2002 (Ref. 30)
- EPRI TR-1003326, "Characterization of Fire-Induced Circuit Faults: Results of Cable-fire Testing," December 2002 (Ref. 9)
- NUREG/CR-6834, "Circuit Analysis – Failure Mode and Likelihood Analysis," September 2003 (Ref. 31)
- NUREG/CR-6931, "Cable Response to Live Fire (CAROLFIRE)," Vol. 1-3, April 2008 (Ref. 11)
- NUREG/CR-7102, "Kerite Analysis in Thermal Environment of Fire (KATE-Fire): Test Results," December 2011 (Ref. 32)
- NUREG/CR-7100, "Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-Fire) – Test Results," April 2012 (Ref. 12)
- NUREG-2128, "Electrical Cable Test Results and Analysis during Fire Exposure (ELECTRA-FIRE)," September, 2013 (Ref. 17)

All AC tests used a surrogate circuit, known as the surrogate circuit diagnostic unit (SCDU), mimicking an AC MOV motor-starter circuit. These test programs exposed the primarily control cables connected to these surrogate circuits to either a radiant heat source (in the NRC's Small-scale testing - Penlight), or to flaming fire conditions (in the NRC's Intermediate-scale, the EPRI, and Duke Energy testing).

Unlike the AC test configurations in NRC's CAROLFIRE and EPRI/NEI testing, all MOV circuit testing (both AC and DC) in the NRC-sponsored DESIREE-Fire testing used interlocking MOV circuits that had two spurious operation targets[1]. Duke Energy testing also used an interlocking MOV circuit in all its tests. The DC tests performed under DESIREE-Fire included five different circuit types (a 1-inch Valve, a Large Coil, an MOV, an SOV, and circuit breaker). Surrogate circuits were used to test all but the circuit breaker circuit, which used an actual medium voltage circuit breaker with the control cable directly connected to its control circuitry. For these DC circuits, the small SOV, the 1-inch Valve, and the large coil had one spurious operation target while the MOV included two spurious operation targets. The medium voltage circuit breaker had two spurious operation targets, but only one active spurious operation target dependent on the position of the circuit breaker (close/trip).

To support the PIRT panel, the staff from NRC and SNL collected and sorted test data from all available sources (except Duke Energy data). This work is documented in NUREG-2128 (Ref. 17). NUREG-2128 consolidates and analyzes the data from the three major tests of fire-induced circuits and cable failure published between 2001 and 2012. These test programs were (1) EPRI/NEI testing in 2002 (Ref. 9), (2) NRC's CAROLFIRE in 2008 (Ref. 11), and, (3) NRC's DESIREE-Fire in 2012 (Ref. 12). The first two test programs were performed on AC control circuits, while the third test program was undertaken predominantly on DC control circuits. The primary objective of analyzing these test results was to present the data in a factual, coherent format to facilitate the work of the PIRT panel in making informed decisions. The systematic

---

[1] The EPRI tests used three spurious operation targets per each surrogate circuit diagnostic unit (SCDU): two were the same multi-conductor cable similar to all NRC tests, and the third target was located in one of the three single conductor cables that surrounded the multi-conductor cable.

review and analysis of the AC and DC data in light of all influencing parameters that the PIRT panel identified revealed several cases where inter-cable hot shorts were experienced in AC control circuits. The data on the DC tests revealed a failure mode in which multiple conductor shorts to ground from ungrounded circuits and resulted in a spurious operation. The PIRT panel defined this mode as "ground fault equivalent hot short (GFEHS)"[2].

The GFEHS failure mode is possible when conductors short to a ground plane or grounded conductors provided that the circuits involved are ungrounded and use a common power supply. Although the GFEHS phenomenon was postulated in NUREG/CR-6834 (Ref. 30), the DESIREE-Fire testing was the first test program to observe such a phenomenon. As such, the testing was not specifically designed to evaluate the various parameters that could affect the likelihood of such a failure mode. Several factors are judged likely to affect the fire-induced GFEHS failure mode, including the population of cables from the compatible ungrounded power source that are damaged by fire and their fuse sizes. Because of the limited data available on this specific GFEHS failure mode, the PIRT panel recommended future research focusing on the effects and probability of this type of failure mechanism.

Although the GFEHS failure mode was observed only in DC tests, similar results likely would have occurred in the AC testing had it included multiple ungrounded control circuits powered from a common AC power supply. Since all AC tests had only one ungrounded circuit per test, the test set up could not have exhibited the GFEHS mode. In fact, the PIRT panel did not explicitly deliberate this power source configuration until later when the final PIRT tables were reorganized for the PRA panel use. This process reflected the fact that, in most NPPs, the safety-related control circuits typically are designed either with grounded AC or ungrounded DC configurations. A few plants in the United States have safety-related control functions in ungrounded systems with AC power supplied via individual CPTs or a distributed system. The PIRT panel also concluded that all three fire-induced hot short failure modes identified in testing the ungrounded DC control circuits are also applicable to distributed ungrounded AC control circuits.

The test data format in NUREG-2128 and the individual test reports were useful for qualitative discussions but the PRA panel found them to have limited direct applicability for any statistical analysis without significant effort to understand and consistently extract the data from these reports. Available data for several applications such as single-target conductors' circuits, and modeling of MOV control circuit logic also presented an analytical problem. Based on the needs of the PRA panel, the NRC's staff developed a roll-up table of these data sets for applying to different circuits. Appendix D presents this roll-up table.

All proponents were given the roll-up tables. Typically, they did not rely solely on these values in the roll-up tables on which to base their final estimates, but instead used this information to support their final recommendations. In some cases, the proponents started with the roll-up table values and adjusted them accordingly, while, in other cases, a proponent used the information in the roll-up table only as information to check their final estimates. Each proponent's use of the information in the roll-up table varied. In addition, the proponents

---

[2] In PRA applications, the GFEHS failure mode often is identified as multiple shorts to ground (MSG). However, the PIRT panel deliberately chose the term "GFEHS" to separate this mode of fire-induced hot short from other grounding and conductor-to-conductor shorts caused by electrical phenomena other than fire-induced hot shorts.

evaluated the test data as needed to better understand certain influences of various parameters. The parameters evaluated included wiring configuration, circuit grounding, configuration of the circuit protective device, and characteristics of cable failure. Proponents also compared test attributes to the actual in-plant applications. They typically started by understanding the test data, and then applied their individual judgment as to how well the test data represents the conditions in the actual plant.

The roll-up table, developed by the NRC's staff, contains limited test configurations involving armored cables in the three test programs sponsored by the EPRI/NEI and the NRC. In 2006, Duke Energy conducted a proprietary testing program involving armored cables for ungrounded and grounded AC control circuits powered from individual CPTs, and ungrounded DC control circuit configurations. Testing simulated monitoring systems for MOV circuits in a way similar to that used in both EPRI's and the NRC's test programs. In 2007, an NRC staff member observed the testing and documented his observations in a report that was classified as proprietary due to the contents of the report (ADAMS Accession No. ML070740544).

During the deliberations of the PRA panel in Workshops #1 and #2, half of the panel did not have Duke Energy's test results. In January 2013, Duke Energy provided the proprietary test report to EPRI for the exclusive use of the PRA expert elicitation panel.

Proponents #2 and #3 factored these results in their estimates for armored cables. Proponent #4 already had submitted his report to the TI team without considering Duke Energy's findings. Proponent #1 used as much of the Duke Energy's data as possible since he was on the verge of submitting his report to the TI team. The TI team took note of these differences while integrating the proponents' inputs: this was reflected in their choice of the weighing factors used for the proponents' inputs in certain case studies (Table 4-2).

Considering all test results available to the PRA panel, there are cable and power supply configurations of control circuits where limited-to-no test data are available. These are associated with ungrounded AC circuits powered from individual CPTs and include the following:

(a) Intra-cable hot shorts for cables with metal foil shield wrap, and
(b) Inter-cable hot shorts for cables with TS- and TP-insulated conductor.

In addition, there are tests associated with both grounded AC and ungrounded DC circuits wherein the tests were artificially configured to increase the odds of inter-cable hot shorts leading to spurious operations. However, the tests revealed virtually no inter-cable hot short mode of failures, except one in EPRI tests with an atypical cable configuration (i.e., single conductors surrounding a multi-conductor cable). The PRA panel was informed of this and used expert judgments and/or statistical methods to estimate conditional probability.

For developing the duration probability plots, fire exposure test data from all test programs was used. This is discussed in Section 6.

3.1.3 Insights on Data from Cable-Fire Tests

Spurious Operation Probability Estimates

Most proponents of the PRA panel believed that two factors give a modest conservative bias to the data for estimating spurious operation probability. That is, there is a higher likelihood of spurious operation in testing than would be seen with actual in-plant configuration.

Factor 1

A large fraction of the circuit tests used the most conservative of the possible cable-to-circuit wiring configurations (the so-called "Source Centered" configuration). The EPRI/NEI tests evaluated four conductor connection patterns, namely; "Actuation Biased," "Center Ground," "Source Centered," and, "Non-Actuation Biased." Figure 3-1 illustrates these connection patterns as presented in the EPRI/NEI report (Ref. 9). The report shows that the Source Centered wiring configuration engendered approximately a 28% higher likelihood of spurious operation than the average of the other three wiring configurations. Some proponents assessed a difference of 40% between the most likely to the least likely wiring configurations. In reality, the analyst is unlikely to know the actual circuit-to-cable wiring configuration. The PRA panel chose to generalize the quantification by providing a value based on a random conductor arrangement and allow the wiring configuration as an uncertainty factor rather than biasing the median- or mean-value upwards (bounding analysis) to account for the most conservative one. All made some reduction in their final proposed estimates as a result of the wiring configuration, although the reduction factor and methods applied by the proponents varied.

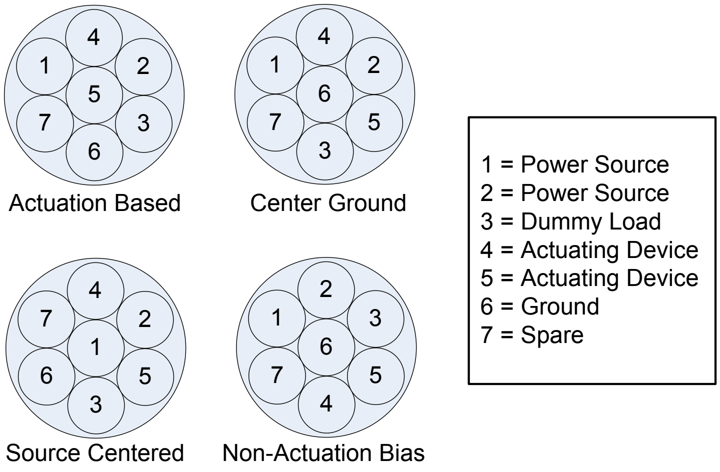


Figure 3-1. Illustration of Conductor Connection Patterns in EPRI/NEI Testing

Factor 2

The second adjustment most proponents made to the test data reflected how spare conductors were left ungrounded in all tests versus the common practice of grounding them in NPPs. In a grounded AC circuit, grounding spare conductors would tend to reduce the likelihood of spurious operation, but increase the likelihood of a fuse clear or a circuit trip because, in a multi-conductor cable, there would be more opportunities for energized conductors to interact with the grounds. Assuming most circuit designs will ground spare conductors; the likelihood of spurious operations would be lower than the test results. The wiring configuration mainly is an issue of the proximity of sources and targets to mitigating conductors (e.g., grounds). Adding more grounded/mitigating conductors mimics changes in wiring configuration. The proponent experts assessed a likelihood reduction factor ranging from 10-to-20%.

Spurious Operation Duration Plots

In developing curves for the likelihood of spurious operation duration, the PRA panel and the TI team believed that the test data used for plotting duration probability plots is more conservative for the early period (i.e., pre-floor) than that would be seen if the complete test data set had been used. This is because the statistical pooling of the data removed both long and short durations of the hot short-induced spurious operations test data. When evaluating the pooled dataset, the PRA panel considered the following:

1. The data for these duration plots does not account for all the influencing parameters with a HIGH impact presented in Section 3.1.1,
2. The method of determining the duration values from plots with multiple hot shorts, such as presented in NRC's roll-up table and in NUREG-2128, and,
3. The exclusion of some results of short- and long-duration tests based on pooled test data-set from NRC's both AC and DC test programs.

Therefore, as discussed in Section 6, the mean Weibull distribution based on the pooled test data is adjusted to account for the differences estimated by the experts between the test configurations and actual in-plant conditions. Further, an uncertainty bound is added to the adjusted mean curve to obtain the final plots of spurious operation duration plots. Finally, floors for AC and DC control circuits are added to account for all tests of long duration (e.g., model the likelihood a hot short would not clear). To make these changes, the Weibull distribution was modified with additional parameters (Section 6 and Appendix C).

3.1.4 Overview of Control Circuit Cases Considered

The PRA panel's evaluation of spurious operation likelihood also included the effect played by the control circuit's power supply and grounding configuration. The type of power supply along with the characteristics of cable construction have an important role in how likely a specific scenario is to experience fire-induced spurious operations. The effect of the configuration of the control circuit power supply also was identified by the PIRT panel.

To support the PRA panel and provide a framework for identifying the phenomena that affect spurious operation likelihood and its duration, the PIRT panel developed tables (Figures 3-5, 3-6, 3-7, and Tables 3-6 and 3-7 in Volume 1) as templates for the PRA panel to populate. At that time, the PIRT panel chose to format the tables to include more cable configurations than what the panel believed the final tables ultimately would encompass. The concept was that either the PRA panel could combine various cells within the table based on the similarity of the derived values or they might decide that a configuration may not be important enough for PRA applications, and could be removed at their discretion. Ultimately, the PRA panel made several modifications to the PIRT panel's templates.

After simplifying the PIRT panel templates in Volume 1, the hot short-induced spurious operation likelihood cases, evaluated by the PRA panel, were categorized using five (5) variables:

1. Circuit Configuration – Single versus Double Break
2. Circuit Cases – SOV, MOV, Circuit Breaker (for single break circuits)
3. Circuit Grounding/Power Supply Type – Grounded AC, Ungrounded AC (powered from individual CPTs), Ungrounded DC (or Ungrounded Distributed AC)
4. Target Cable Construction – Thermoset-insulated Conductor Cable, Thermoplastic-insulated Conductor Cable, Metal Foil Shield Wrap Cable, Armored Cable
5. Conductor Failure Mode – Intra-cable hot short, Inter-cable hot short, GFEHS

The most significant change to the original tables was to modify the TS- and TP-insulated conductor configuration rows. The PRA panel chose to simplify this table's row headings only to indicate the target cable or conductor as being TS-insulated or TP-insulated. Since the circuit analysis typically is based on the target cable rather than the source cable(s), the PRA panel combined both TS→TP[3] and TP→TP in Volume 1 Figures 3-5 through 3-7 into one row as "Thermoplastic-Insulated Conductor Cable." Moreover, the test data available to the PRA panel do not separate this difference in the types of source cable. As such, the PRA panel decided to combine these two rows to one from all the tables where the PIRT panel included it in Volume 1.

The PIRT panel made these distinctions in the template tables to reflect their judgment on the effect that cable insulation has on the likelihood of inter-cable hot-short induced spurious operations for single and double break designs (Table 3-3 of Volume 1). Although the PRA panel agreed with this assessment, they believed that maintaining the table format could confuse the end user, especially for cases other than inter-cable ones. Therefore, the PRA panel chose to rename the "Base Case" row heading in Volume 1 as "Thermoset-Insulated Conductor Cable" and condensed the two rows of the "TP Cable" case to "Thermoplastic-Insulated Conductor cable." The applicability of the results from these two rows are discussed in Section 4 (single break) and Section 5 (double break) to ensure that the PIRT panel's conclusions, documented in Table 3-3 of Volume 1 and its associated text, are maintained.

The second simplification of the PIRT table template was to remove the cable configuration identified as "Cable includes an un-insulated grounded drain wire." Although several cable manufacturers provide control cable products that have a drain wire, this application in currently operating NPPs is very limited. Additionally, the test data on fire-induced spurious operation includes only a few tests wherein a three-conductor (3/C) low-voltage power cable with a drain wire was tested. The PRA panel did not believe that this limited data could accurately represent the actual influence of an un-insulated grounded drain wire on the likelihood of fire-induced spurious operations for control-cable configurations. The panel also believed that given cable damage due to a fire, the presence of a grounded drain wire physically resembles that of all other fire-damaged conductors within a multi-conductor cable. Figures 3-6 and 3-7 of Volume 1 do not include a row for cable with drain wire as in Figure 3-5, since the PIRT panel considered this not applicable because the presence of a drain wire in a cable for ungrounded circuits is

---

[3] TS→TP configuration represents a TS-insulated source conductor hot short with a TP-insulated target conductor.

unlikely. Moreover, for an ungrounded AC circuit involving separate CPTs, a drain wire would likely have little or no effect on spurious operation likelihood.

The third simplification relates to Section 3.3.3 of Volume 1, where the PIRT panel recommended thirteen (13) different control circuit scenarios for single and double break circuit configurations that are vulnerable to hot short-induced spurious operations. As discussed in Section 2.2, they included two separate scenarios for each inter-cable hot short via a ground plane (i.e., GFEHS) representing one within the same raceway and the other between different raceways (Figure 3-4 in Volume 1). The test data from DESIREE-Fire are not explicit enough to differentiate these two scenarios in the probability estimation. Therefore, for the third simplification, the PRA panel combined these two into one hot short-induced spurious operation failure mode case identified in Table 3-1, as "Ground Fault Equivalent" in Column 9.

Table 3-1 presents the matrix of the cable configuration and hot short-induced spurious operation failure modes for the three power-supply/grounding configurations. The PRA experts were asked to offer their best estimates with uncertainty for each of these cells, which are applicable to single break control circuits. Shaded light grey cells in this table represent the PIRT panels' conclusion that such case is an "implausible" event, and cells marked "incredible" are those considered incredible events. The terms "implausible" and "incredible" are defined by the PIRT panel in Section 2.1.3 of Volume 1 and repeated in Section 2.2.2 of this volume. Probabilities for all sub-cases except those classified as "incredible" were estimated by the PRA panel. All columns and rows denoted in the following discussion refer to this table.

Column 3 "Aggregate" probability distributions are derived from Column 1 and 2 distributions using the Boolean "OR" method (Section 2.3.6) assuming that either of these two hot short modes may happen in a fire. Similarly, the values in Column 6 represent an aggregate of those in Column 4 and 5, while Column 10 represents an aggregate of the values in Columns 7, 8, and 9.

Table 3-1 includes intra-cable hot short, inter-cable hot short, and GFEHS-induced spurious operations for four different target cable-configurations, namely, Thermoset-Insulated Conductor Cable, Thermoplastic-insulated Conductor Cable, Metal Foil Shield Wrap Cable, and Armored Cable.

The discussion in Appendix C, presents key information from either the test data or majority of the proponents' judgment for each sub-case (or cell) of this table. Its format presents spurious operation probability distributions for single break control circuits used for SOV (Base Case) and MOV end devices. The following summarizes how the proponents used the test data and expert judgments in assessing the three hot short-induced spurious operation failure modes of control circuits for the SOV Case:

- **Intra-cable Hot Shorts:** The estimates of spurious operation occurrence probability for all sub-cases associated with TS, TP, and Armor Cables under all three power supply categories have significant amount of data from the AC and DC test programs. For the Metal Foil Shield Wrap Cable, however, there is a limited set of data from the CAROLFIRE testing on Japanese cables for the grounded AC and ungrounded DC (or ungrounded distributed AC) power supplies and none for the ungrounded AC (with individual CPTs) power supply.

- **Inter-cable Hot Shorts:** All conductor configurations in the AC and DC test programs exhibited almost no device failure that could be used in the estimation of spurious operation occurrence probability for any sub-case under all three power supply categories; even though the tests were artificially configured to increase the odds of inter-cable hot shorts leading to spurious operations. For TS and TP cables under ungrounded AC (with individual CPTs) there is virtually no test data available. For all data-deficient sub-cases, the proponents mostly used their expert judgment in estimating the failure probability of occurrence for this failure mode.

Table 3-1. Conditional Probability of Spurious Operation – Single Break Control Circuits

Power Supply →		Grounded AC			Ungrounded AC (w/ Individual CPTs)			Ungrounded DC (or Ungrounded Distributed AC)			
Target Cable Configurations		Intra-Cable 1	Inter-Cable 2	Aggregate 3	Intra-Cable 4	Inter-Cable 5	Aggregate 6	Intra-Cable 7	Inter-Cable 8	Ground Fault Equivalent 9	Aggregate 10
Thermoset-Insulated Conductor Cable	1	SB 01_01	SB 01_02	SB 01_01 **+** SB 01_02	SB 01_04	SB 01_05	SB 01_04 **+** SB 01_05	SB 01_07	SB 01_08	SB 01_09	SB 01_07 **+** SB 01_08 **+** SB 01_09
Thermoplastic-Insulated Conductor Cable	2	SB 02_01	SB 02_02	SB 02_01 **+** SB 02_02	SB 02_04	SB 02_05	SB 02_04 **+** SB 02_05	SB 02_07	SB 02_08	SB 02_09	SB 02_07 **+** SB 02_08 **+** SB 02_09
Metal Foil Shield Wrap Cable	3	SB 03_01	Incredible	SB 03_01	SB 03_04	Incredible	SB 03_04	SB 03_07	Incredible	SB 03_09	SB 03_07 **+** SB 03_09
Armored Cable	4	SB 04_01	Incredible	SB 04_01	SB 04_04	Incredible	SB 04_04	SB 04_07	Incredible	SB 04_09	SB 04_07 **+** SB 04_09

Notes: "**+**" represents the Boolean "OR" operator and not a simple sum
"**SB 0X_0Y**" represents Single Break Row X Column Y
Dark Grey shaded cells represent the aggregate
Light Grey shaded cells represent "implausible" cases per the PIRT definition

- **Ground Fault Equivalent Hot Shorts (GFEHSs):** Significant amount of test data is available from the DESIREE-Fire test program for the ungrounded DC (or ungrounded distributed AC) power supply associated with TS and TP Cables and a limited number of hot short-induced spurious operation occurrences for the Metal Foil Shield Wrap Cables and Armor Cable. The proponents used their expert judgment on sub-cases with limited data. For ungrounded AC (with individual CPTs), the test programs did not include this failure mode. However, the PRA panel, after a long deliberation, concluded that the inter-cable hot short failure mode for this power supply encompasses GFEHS failure mode in all tests.

For single break MOV control circuit sub-cases, a "Multiplier" to the SOV probabilities was used and the distribution of this Multiplier for each sub-case was developed using event tree models that utilized the test data for the top event probability input into the models. One proponent recommended a single distribution of the Multiplier for all MOV sub-cases.

Similar to Table 3-1, Table 3-2 presents the double break circuit matrix of the target cable construction and hot short failure mode combination for ungrounded AC or DC control circuit configurations. This table includes all the recommended hot short modes in Tables 3-6 and 3-7 of Volume 1. The light grey cells in this table represent the PIRT panels' conclusion that such case is an "implausible" event. Cells with "incredible" are those considered as such events by the PIRT panel; the probabilities for all cells except those so classified were estimated by the PRA panel. All columns and rows referenced in the discussion below are associated with this table.

For both SOV and MOV control circuit double break cases, no test data was directly used in estimating the probability of occurrence. Instead, either combinations of spurious operation failure modes of single break SOV probability distributions or proponent-recommended distributions were used.

In Section 3.3.3 of Volume 1, the PIRT panel also identified seven double break control circuit configurations out of 13 scenarios that are vulnerable to spurious operation events when their associated cables are damaged by fire. As detailed for single break circuits, the "Ground Fault Equivalent" hot short failure mode in Table 3-2 represents both the scenarios of ground-plane interactions associated with the same raceway or different ones for a double break. This engenders five specific hot short combination modes that the PIRT panel identified.

In Columns 1 through 5 in Table 3-2 include all combinations of intra-cable hot short, inter-cable hot short, and GFEHS failure modes that could occur in a cable-fire. The only combination not addressed involves two concurrent GFEHS failures. As stated in Section 3.4.1.2 of Volume 1, GFEHS in combination with another GFEHS would cause a fuse clear failure; hence it is not a credible failure mode and is not included in Table 3-2.

Cell DB 02_03 (outlined in bold) involves two inter-cable hot short interactions for TS→TP and TP→TP configurations. As discussed in the note under Table 3-3, Volume 1, for a double break configuration, the PIRT panel did not classify as implausible the inter-cable hot short interactions for TP→TP because in the PIRT panel's judgment, the likelihood of this configuration lies between a possible and an implausible classification. On the other hand, the panel classified the scenario with double inter-cable hot short interactions for TS→TP as "implausible." When combined, this cell in Row 2 representing two inter-cable combinations of TP→TP and TS→TP hot short interactions is classified as an "implausible" event. Moreover, we note that both of these interactions have to occur concurrently under compatible power sources.

Similarly, Cell DB 02_05 involves the interaction of one inter-cable hot short and one GFEHS for both TP→TP and TS→TP configurations. The PIRT panel classified the former as a plausible event while the latter is an implausible event (Tables 3-6 and 3-7 of Volume 1). When they are combined, this cell is classified as a plausible event.

Table 3-2. Conditional Probability of Spurious Operation – Double Break Control Circuit Ungrounded AC[4] and DC Power Supply

Target Cable Configuration		Conductor Hot Short Failure Mode Combinations					
		Intra-Cable & Intra-Cable	Intra-Cable & Inter-Cable	Inter-Cable & Inter-Cable	Intra-Cable & Ground Fault Equivalent	Inter-Cable & Ground Fault Equivalent	Aggregate
		1	2	3	4	5	6
Thermoset-Insulated Conductor Cable	1	DB 01_01	DB 01_02	Incredible	DB 01_04	Incredible	DB 01_01 + DB 01_02 + DB 01_04
Thermoplastic-Insulated Conductor Cable	2	DB 02_01	DB 02_02	DB 02_03	DB 02_04	DB 02_05	DB 02_01 + DB 02_02 + DB 02_03 + DB 02_04 + DB 02_05
Metal Foil Shield Wrap Cable	3	DB 03_01	Incredible	Incredible	DB 03_04	Incredible	DB 03_01 + DB 03_04
Armored Cable	4	DB 04_01	Incredible	Incredible	DB 04_04	Incredible	DB 04_01 + DB 04_04

Notes: **"+"** represents the Boolean "OR" operator and not a simple sum
"DB 0X_0Y" represents Double Break Row X Column Y
Dark Grey shaded cells represent the aggregate
Light Grey shaded cells represent "implausible" cases per the PIRT definition

In Section 3.4.1.1 of Volume 1, the PIRT panel states that a conductor within a multi-conductor cable shorting to a grounded conductor (intra-cable hot short) would have the same electrical effect as the same conductor shorting to a grounded raceway, grounded armor, or another grounded medium (other than a conductor). Thus, the question arose as to where to address the intra-cable conductor shorts to grounded conductor(s). To minimize confusion, the PIRT panel recommended that the probability of all intra-cable hot shorts should be considered in the column "Single intra-cable hot short" in Figure 3-7 in Volume 1, and "Intra + Intra cable short" in

---

[4] For ungrounded AC with individual CPTs, Columns 4 and 5 do not apply since the corresponding GFEHS mode is not separately addressed. Rather, in Table 3-2, the inter-cable hot shorts in Columns 2 and 3 include (or represent) the GFEHS mode. More detailed information on this appears in Section 3.1.2 or Section C.1.2 under SB 01_05: Inter-Cable Hot Shorting. However, proponent inputs in Column 4 and Column 5 are combined, respectively, with Column 2 and Column 3. Consequently, DB 03_02 and DB 04_02 no longer are considered "incredible."

Tables 3-6 and 3-7 in Volume 1 for double-break circuits. Thus, a scenario involving an intra-cable hot short between a grounded conductor and another conductor, both within the same cable, should be deemed an intra-cable hot short and not be considered as a GFEHS. Although the circuit's response likely is the same in both, this distinction minimizes the likelihood of any double counting when developing and applying the likelihoods of conditional spurious operation.

For each configuration of AC or DC control circuits, the likelihood values (in Columns marked "Aggregate") correspond to all associated possible and implausible (shaded light grey) failure modes and are calculated using the Boolean "OR" combination of the failure modes of individual hot short-induced spurious operations. Therefore, the probability distributions in Columns 3, 6, and 10 (dark grey) in Table 3-1 and Column 6 (dark grey) in Table 3-2 are not discussed in Appendix C.

For example, assume the scenario under evaluation includes the following:

- TS-insulated target cable
- Multi-conductor with at least one source conductor
- Cable tray raceway type
- Grounded AC circuit
- Other cables within the tray also powered from an AC source.

Then, both intra-cable and inter-cable failure modes are possible. The corresponding value in Row 1 "Thermoset-Insulated Conductor Cable" and Column 3 "Aggregate" derived using a Boolean 'OR' operator on SB 01_01 and SB 01_02, should be used to quantify the conditional likelihood of fire-induced spurious operations.

In developing their estimates the proponents also made the following general assumptions. In those cases of an ungrounded AC power source with individual CPTs, the experts assumed that power is supplied to each circuit from individual ungrounded CPT with each circuit contained in its own multi-conductor cable. Hence, inter-cable spurious operations would occur only if the CPT for one circuit (one source cable) energizes a second circuit (second target cable). However, separate ungrounded CPTs are not considered as compatible power sources. Hence, single hot short between separate CPT circuit cables cannot trigger a spurious operation. For one circuit to power another, both sides of a common CPT must act as sources against the specific target conductors in the target circuit. This requirement significantly reduces the likelihood of direct inter-cable hot shorts leading to spurious operation compared to the grounded AC circuits where only a single inter-cable hot short is needed.

Therefore, for ungrounded AC with individual CPT configuration circuits, it was assumed that one of the two hot shorts may result from a GFEHS event. That is, if one side of the source circuit power supply and one side of the target circuit's end device become grounded, then a single additional inter-cable hot short could cause spurious operation, provided the source circuit's fuses remain intact. Overall, the inter-cable shorting configurations leading to spurious operation are specific and must occur concurrently. Hence, this failure mode would be considered less likely and consequently, the PIRT panel believed that for ungrounded AC with individual CPTs control circuits, the GFEHS mode is the only shorting configuration that has merit for causing this mode to spuriously operate an end device. Concurrent shorts between a specific conductor pair (i.e., inter-cable hot short) on two separate multi-conductor cables seem credible, with a marginal likelihood of happening; the PIRT panel classified this as an "implausible" event. Presently, no known tests have been undertaken exclusively on an ungrounded AC control circuit powered from individual CPTs.

3.2 Single Break Control Circuits

Single break control circuits are defined as designs wherein one side of the actuation device (e.g., coil, motor starter/contactors) directly is connected to either the positive-, negative-, or return-side of the power supply (through protective devices where required). Alternatively, single break control circuits can be considered any wherein the actuation device does not have contacts on both sides of the actuation device (i.e., not of a double break design). Although many circuit designs require having several contacts for particular end-device to actuate, they still may be considered a single break design. Figure 3-2 is an illustration of simplified single break circuit designs for reference and is not meant to be all-inclusive. Appendix C of Volume 1 illustrates and describes several control circuit configurations for single and double break designs.

Within the single break configuration, the proponents were asked for their best estimate conditional probabilities for three circuit types, specifically;

- SOV circuits or circuits with a single spurious operation target
- MOV circuits
- Circuit Breaker (i.e., ungrounded DC control circuit for medium voltage circuit breaker)

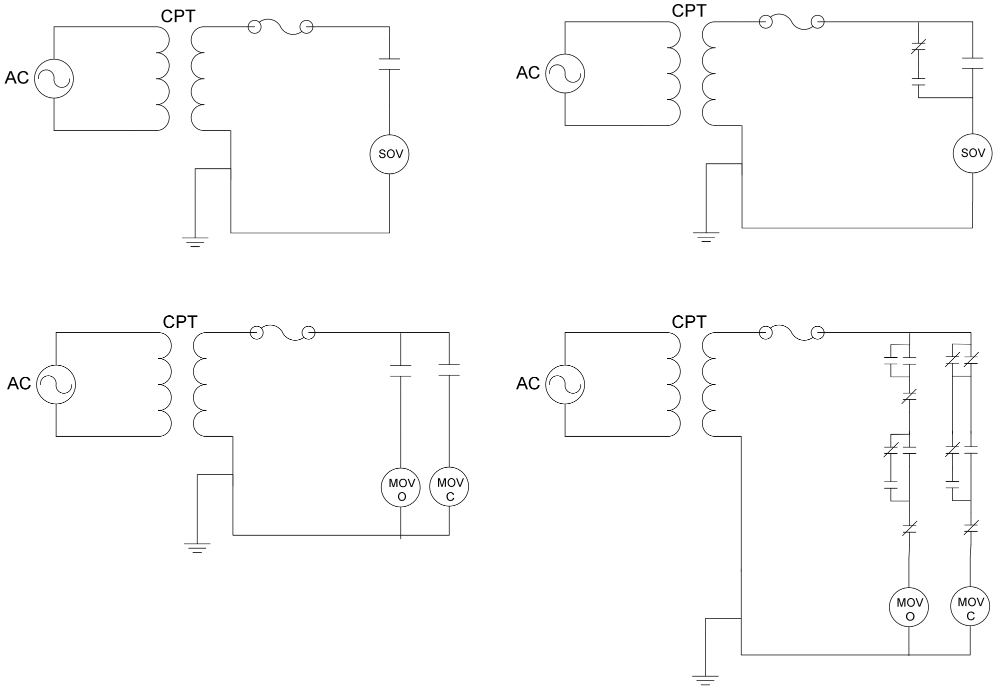


Figure 3-2. Illustration of Example Single Break Control Circuits

Estimates for these three circuit designs were requested due to the circuit design influence on the likelihood of a hot short-induced spurious operation. For example, in an SOV control circuit a single hot short which energizes the SOV coil will result in a spurious operation of an initially de-energized SOV (see top two circuits in Figure 3-2). For an MOV circuit there are two coils, however the MOV is typically either open or closed in the initial state, thus a hot short to only one of the coils will result in a spurious operation (see bottom two circuits in Figure 3-2). Similarly, the control circuit of a medium voltage circuit breaker have trip and close coils, however, only one of these coils can be energized from a fire-induced hot short due to the circuit design.

For the MOV circuit, the proponents ultimately chose to develop event trees using the values of SOV probability as an input and various top-events to modify the SOV (single spurious operation target) value for the likelihood of MOV. For the case of the circuit breaker, the data available from the DESIREE-Fire tests were used, and only one specific case associated with ungrounded DC was considered, including all hot short failure modes.

3.2.1 Approaches Used to Estimate Single Break SOV and MOV Control Circuit Probabilities

The surrogate circuit test data has direct application in determining the likelihood of the spurious operation of motor-operated valve (MOV) control circuits. All of the findings from the AC surrogate circuit tests are based on an MOV circuit that has two spurious operation targets. The results of DC circuits from DESIREE-Fire used MOV and medium voltage circuit breaker control circuit simulators, also with two spurious operation targets. Those tests also encompassed circuits with one spurious operation target; these included the small solenoid operated valve (SOV), 1-inch valve SOV, and the large coil circuit. Therefore, for these cases, each proponent manipulated the data for a single-target single-source circuit. Appendix C has a detailed discussion of the "Base Case – SOV" control circuit configurations; Section 4 contains estimates of the conditional probability distributions.

The MOV control circuit differs from the SOV control circuit, in that there are two active targets, namely, the coils for both the "open" and "close" motor starter's contact sets. In practice, the two are interlocked, mechanically and/or electrically. That is, if one of the two engages, the second is locked-out and cannot engage. Should the first contactor subsequently drop out, the second contactor once again is enabled and may lock-in if energized. This design feature prevents the valve motor from receiving power concurrently from both the open- and closed-motor starter units that, for the example of a three-phase valve motor, would result in phase-to-phase shorting on the MOV's power circuit.

Another feature of an MOV control circuit that differs from an SOV one is that if the former circuit loses power (e.g., due to a fuse blow) the valve motor simply will stop, leaving the valve in whatever position it was in at the time power was lost. Depending on valve's stroke time and the duration of the spurious operation signal, the valve may be left in an intermediate position (i.e., valve position other than fully open or fully closed). In contrast, an SOV or an air-operated valve (AOV) controlled by SOV control circuit(s) will return to its de-energized position when control power is lost typically leaving the valve either fully open or fully closed.

These characteristics raise questions in the PRA context that, to date, have not been factored into known PRA analyses. In a fire PRA, the concern relative to spurious operation of a given

MOV typically focuses on one of two possible outcomes; that is, an MOV may spuriously close thereby closing off a desired flow path, or it may spuriously open creating an undesired flow path (e.g., a diversion path).

To further complicate the situation, there may be some fractional limit to the valve's position where concern begins. That is, an analyst might show that as long as the valve remains at least 50% open, the desired flow path is adequate or, alternatively, as long as the valve remains no more than 20% open, an undesired flow path is not consequential to the PRA. This final factor was not factored into any current analysis known to either panel. The extent to which such considerations can or should be included in Fire PRA circuit analysis is a question that the PIRT panel left to the PRA panel to resolve.

MOVs are infrequently used for modulation, and thus, typically are either closed or open. Hence, a hot short to a conductor associated with the MOV open contactor will cause a spurious opening of a MOV initially in the closed position. However, a hot short to the conductor associated with the close contactor initially will not entail a spurious operation of an MOV in the closed position (it already is closed). The reason for this discussion is that the surrogate circuit (e.g., surrogate circuit diagnostic unit - SCDU) used in testing did not reflect the valve's initial position so that a hot short to either an open or closed contactor would be classified as a hot short-induced spurious operation. In addition, in the EPRI/NEI and CAROLFIRE tests, the electrical- and mechanical-interlocks were removed or not used, such that hot shorts to both open and close contactors on the same MOV could be classified as spurious operations.

In typical designs of MOV circuits, limit switches, torque switches, and selector switches control the direction in which the MOV can operate spuriously. For instance, if the valve is in the closed position, one or both of the close torque and close limit switch contacts are typically open in that portion of the circuit associated with the closing coil of the MOV contactor. Likewise, when the MOV is in the open position, the open-limit switch is open in the portion of the circuit that is associated with the valve's opening One exception to this logic is related to the NRC's Information Notice (IN) 92-18 concern, where a hot short bypasses the limit and torque switches may actuate the valve in the open or closed position. Bypassing these switches could cause the valve assembly to become permanently damaged. Nevertheless, the result of such a hot short-induced spurious operation is uncertain, and may be system-dependent.

These aspects of the testing and actual circuit operation raise the question of how to analyze the test data to represent real-case scenarios. In SSHAC Workshop #1 and #2, two panel members proposed using an event tree that utilizes various split fractions for such events/ conditions as valve response, end position, and IN 92-18 protection. These event trees would use the proponents' estimates of an SOV (e.g., single contact) control circuit to assess the likelihood of an MOV hot short-induced spurious operation. To support the use of these event trees, as discussed during the 1st and 2nd SSHAC Workshops, the MOV data must be analyzed by separately assessing each MOV contactor target conductor for spurious operation. To do this, the MOV data are detailed on a target-specific basis that offers two benefits: First, the MOV is initially either fully closed or fully open and only the hot short-induced spurious operation that would change the valve's position is the failure mode of concern (i.e., only one of the two MOV targets is of interest). Under this approach, the appropriate data set for spurious operations of one contactor is evaluated and then re-analyzed using the same data set for spurious operations as the other contactor, thus doubling the data set and only evaluating one spurious operation target at a time for the MOV data set. Second, this method simplified the complexity of the response of the MOV circuit response, and, more importantly allowed the PRA panel use of the MOV data to support the evaluation of devices that only have one target conductor that can result in a spurious operation.

Three out of four proponents (Proponents #1, #3, and #4) developed their own event tree models and discussed them during the 2nd SSHAC Workshops. Each event tree requires estimates for the probabilities of top events. The tree is then used to arrive at a conditional probability of spurious operation, given fire damage to an MOV-control circuit cable(s). Each model starts with the probability estimates for spurious operation of a single contact (e.g., SOV) and for each sub-case (i.e., cable type-control circuit configurations) with different branch-point assumptions or input based on the test configurations to yield the MOV probability estimates for the spuriously open or spuriously closed failure mode. One proponent used "undesired position" as the final result. The following is a general description of what are the important decision points in the event tree developed by Proponent #3. The event tree developed by Proponent #3 is shown in Figure 3-3. The other proponent's event trees are provided in Appendix C.

Undesired Contactor Conductor Energized

The first probability (identified as "P1" in Figure 3-3) represents likelihood of a hot short to a control cable conductor that is connected to the MOV contactor associated with moving the MOV to an undesired position. This conductor is referred to as the "conductor of concern." This probability is assumed to be the same as the conditional probability of spurious operation of a single contactor control circuit (e.g., an SOV). The up-branch accounts for cases where the mode of circuit failure mode is a fuse clear or any other mode that does not involve energizing the conductor of concern.

Both MOV Contactors Energized

The second probability (identified as "P2" in Figure 3-3) addresses whether both conductors associated with the MOV contactors (forward/reverse or open/close) are energized during the failure of the cable. The up branch accounts for those where only the conductor of concern experiences a hot short-induced spurious operation. Then, it is assumed that the valve travels to its end position and the valve is assumed to fail in this undesired position. The bottom branch accounts for cases where both of the MOV contactors are energized, regardless of the order or of the timing of each hot short. The estimates are based on test data where both contactors can be energized and then adjusted for factors that the proponent felt to differ from the test cases to actuality (e.g., conductor wiring configuration, grounding, cable construction).

IN 92-18 Failure

The third probability (identified as "P3" in Figure 3-3) is associated with the likelihood of conductor shorts causing a bypass of the limit or torque switches, and the MOV drives itself either fully open or fully closed (down branch). The up branch quantifies cases where the failure mode does not cause the torque and limit switches to be bypassed, and, since both MOV contactors are energized, the MOV cycles until the hot short clears. In this case, the final position of the valve position depends on when the hot short abates. The estimates that the proponent proposes for this event in the scenarios were also based on test data (when available), and adjusted for factors that may influence difference between test data and actuality. However, it also was considered that this scenario is highly dependent on the circuit design, and the specific cable being evaluated.

Valve Ends in Desired Position

This decision-point of the event tree (identified as “P4/P5” in Figure 3-3) quantifies the probability of the valve’s end position. The value for the case where IN 92-18 failures could occur (torque or limit switches bypassed) simply assumes that there is a probability (P5) of the MOV contractor being energized first, and the valve strokes to the either the fully open or closed position, or it remains in that position. The first contactor to experience a hot short in combination with the IN 92-18 failure caused the valve to stroke in the direction of the MOV hot-shorted contactor. When the IN 92-18 failure does not occur, the P4 value quantifies the likelihood that the MOV does not cycle to the undesired position. Since this event tree does not consider the duration of a hot short, one proponent proposed that, for all scenarios documented, (1-P4) to be 80% of the time the valve will be in some position other than desired one. Since this aspect of the event tree is so dependent on the valve design, an independent assessment by licensees would offer a more realistic value.

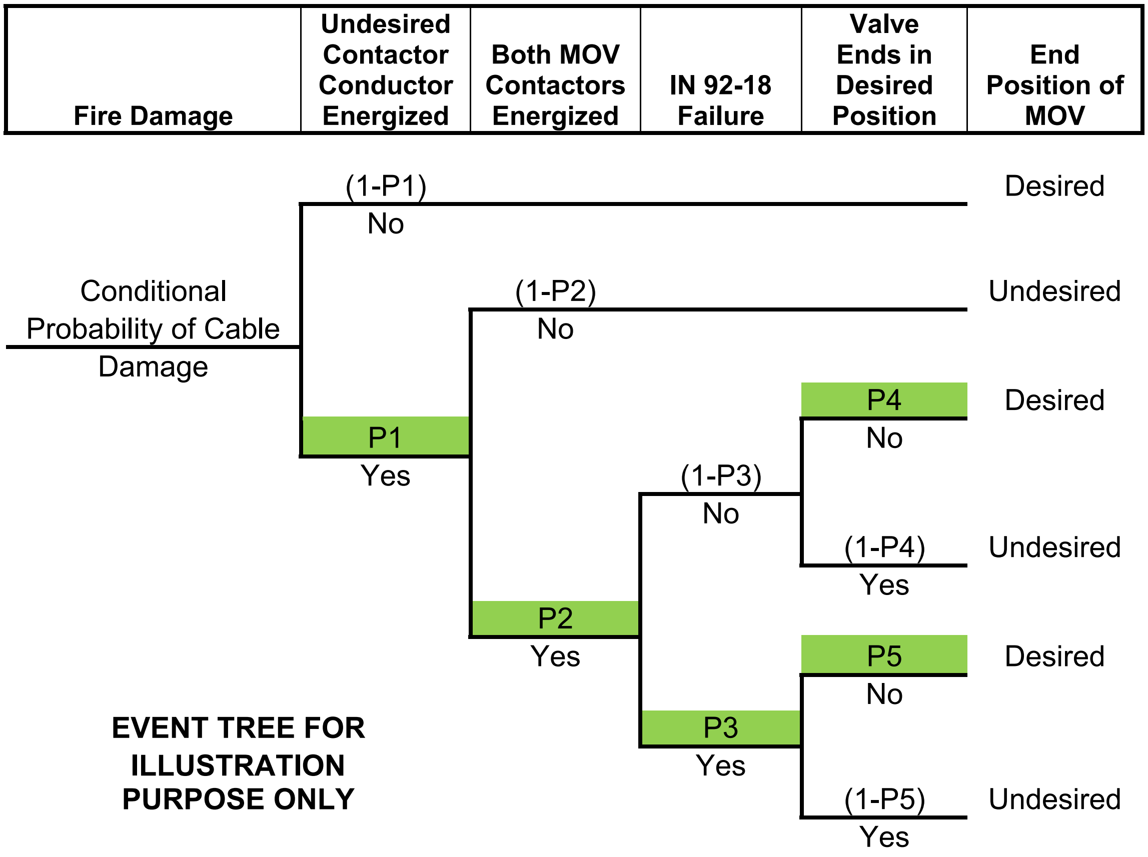


Figure 3-3. Generic Event Tree as Used by Proponent #3

The event-tree models used by the three proponents were similar, but some involved more complex branches to estimate other MOV-failure modes (e.g., failure to open or to close). The

PRA panel discussed each model in detail during their deliberations and finally decided to use a simplified event tree model preserving all the salient features discussed above.

Only Proponent #3 used that simplified model. Although the other two proponents (Proponents #1 and #4) used different event-tree models, their proposed model parameters or the recommended resultant parameter values are consistent with the simplified model. Since each model used the SOV values predicted by the proponent, the TI team developed an approach for combining all three proposed model inputs using the combined SOV values estimated in Section 4 to develop a composite distribution multiplier to the single break SOV conditional probabilities.

3.2.2 Approach Used to Estimate Single Break DC Control Circuits for Medium Voltage Circuit Breaker Probability

Two out of the four proponents analyzed the medium voltage circuit breaker in their reports for ungrounded DC power supply and used the same set of data corresponding to an aggregate case involving all associated hot short failure modes. Proponent #1 started with his estimate of single break (e.g., SOV) failure probability and used various reduction factors to account for biases in test data and circuit configuration applicable to circuit-breaker control circuits. Proponent #3 provided a more detailed analysis of the test data, discussed below.

The control circuit of the medium voltage circuit-breaker is either in the closed or tripped position and so, only a hot short to the trip or to the closed coil will trigger a spurious operation. From the DESIREE-Fire test data, all but one test, Intermediate Scale Test 10, implemented a control cabling scheme wherein the trip- and close-circuit conductors were in separate cables. Table 3-3 tabulates the shorting behavior that occurred in small-scale Penlight and Intermediate Scale medium voltage circuit breaker testing. The results for each test are presented in two parts.

The first part represents the observed test results, identifying the initial position of the breaker followed by the time of the first spurious operation that would cause the breaker to change position and then any subsequent spurious operation that would cause it to return to its initial position. The second part of the table presents the hypothetical response of the circuit, assuming that the breaker initially was placed in the opposite position than what was tested. The hypothetical spurious operation results are based on the real data by analyzing the timing of hot shorts on the spurious operation target conductors that would cause a spurious operation.

The results in Table 3-3 show that the likelihood of a medium voltage circuit breaker control circuit experiencing a spurious operation given cable damage occurred is 81% (29/36). Although the data shows a slightly higher likelihood of spurious operation for TP insulated cables than TS ones, this could not be substantiated based on the limited number of data points and the fact that the other circuit analyses exploring the influence of the insulation material influences did not indicate any differences.

Proponent #3 sorted his results into four bins, specifically,

A. Initial position OPEN, final position OPEN
B. Initial position OPEN, final position CLOSED
C. Initial position CLOSED, final position CLOSED
D. Initial position CLOSED, final position OPEN.

Table 3-3. Circuit Breaker Test Data

Insulation Type	Test #	Observed Test Results			Hypothetical Test Results		
		Breaker's Initial Position	1st S.O. (seconds)	2ND S.O. (seconds)	Breaker's Initial Position	1st S.O. (seconds)	2nd S.O. (seconds)
Thermoset	Pen. 3	OPEN	719	-	CLOSE	667	719
	Pen. 4	OPEN	625	626	CLOSE	589	625
	Pen. 24	OPEN	-	-	CLOSE	2103	-
	Pen. 35	OPEN	1693	-	CLOSE	-	-
	Pen. 42	OPEN	6120	-	CLOSE	6041	6120
	IS 1	OPEN	-	-	CLOSE	1361	
	IS 3	OPEN	1460	-	CLOSE	1363	1460
	IS 4	OPEN	-	-	CLOSE	5237	
	IS C1	CLOSE	410	-	OPEN	-	-
	IS P1	OPEN	508	-	CLOSE	470	508
Thermoplastic	Pen. 10	OPEN	-	-	CLOSE	899	-
	Pen. 29	OPEN	3530	-	CLOSE	3420	3530
	Pen. 32	OPEN	607	620	CLOSE	620	-
	Pen. 39	OPEN	-	-	CLOSE	1678	-
	IS 5	OPEN	1424	-	CLOSE	546	1424
	IS 6	CLOSE	850	1603	OPEN	158	850
	IS 7	CLOSE	1095	-	OPEN	185	1095
	IS C2	CLOSE	334	354	OPEN	354	-

This data was then used to propose a conditional probability for a change in breaker position to an undesired state.

There was no attempt to account for the effects of the anti-pump circuit, the transient nature of the breaker opening and closing, or the duration between spurious operations if multiple spurious operations occurred. **In fact, the anti-pump circuit should not be credited as a means of keeping a breaker tripped for failure modes resulting from fire-induced cable damage.** This is because if the anti-pump circuit worked as designed, the hot short in the closed portion of the circuit would have to be maintained continuously for the duration of the fire transient on the corresponding cable. In actuality, it is highly unlikely that such a hot short would persist on the correct conductors without momentary interruptions, especially for an ungrounded DC. Thus, any perturbation on that portion of the circuit would cause the anti-pump relay to drop out and not maintain the breaker in the open position. The test data also support this conclusion.

Section 4 combines the proposed conditional probability values from both proponents and the final values for medium voltage circuit breaker with an ungrounded DC control circuit.

3.3 Double Break Control Circuits

Figure 3-4 illustrates a design of a "double break" control circuit where two normally open contacts surround the target of interest (SOV). In a double break design, the controls switch opens and closes both the high and the return sides of the circuit. In this example, there is one target end-device of interest, i.e., the SOV, but with a double break design, two hot shorts are required to operate it. One side of the solenoid must short to the high side of a compatible power source and the other side of the solenoid must concurrently short to the return side of that same, or another compatible, power source. Solenoids in these circuits, either AC or DC ones, are not sensitive to the polarity of the energizing power source relative to the two solenoid contacts. Thus, two concurrent hot shorts are required and reversing polarity leads to the same result.

In the case of the circuit illustrated in Figure 3-4, two concurrent hot shorts are needed to form, therefore bypassing both sides of the switch contacts and leading to spurious opening of the valve. Here, the shorts must involve the return-side conductor N shorting to one side of the solenoid (e.g., either to S1 or S2 conductors since either polarity will energize the solenoid) and one of the two high-side source conductors (P or G) shorting to the other side of the solenoid.

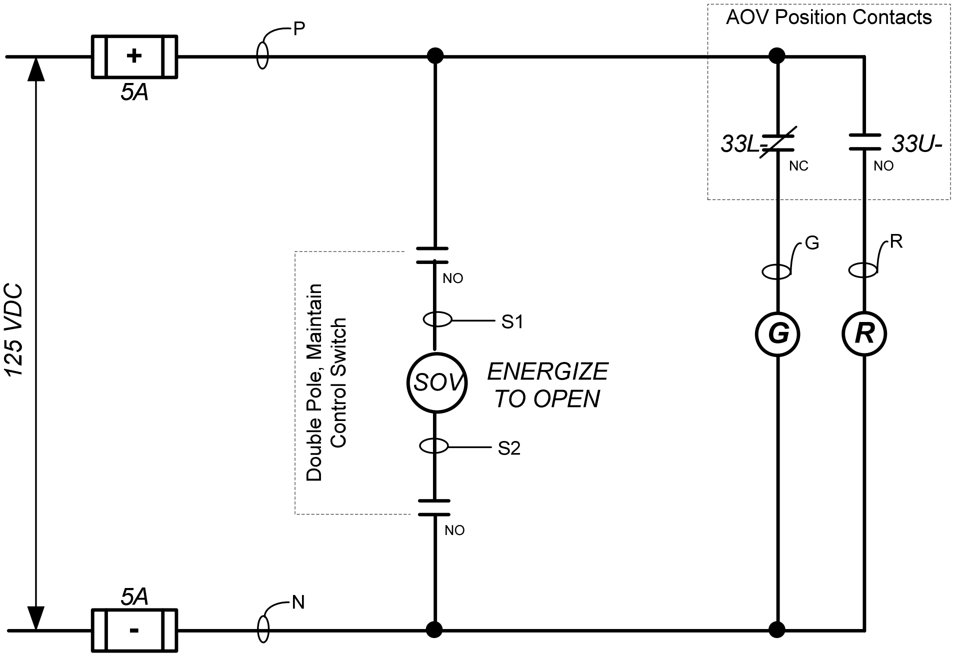


Figure 3-4. Simplified Double Break Control Circuit Design

Figure 3-5 illustrates another variation of a double break design feature sometimes used as a deterministic means to minimize the likelihood of spurious operation. The circuit is disconnected from its source of motive power by manually opening a double-pole disconnect switch positioned immediately downstream from the circuit fuses and the balance of the control circuit. (Note that the same effect could be achieved by removing both circuit fuses).

As shown in Figure 3-5, the target cable of interest contains conductors P and N, but unlike the case discussed in reference to Figure 3-4, the conductors are de-energized relative to the battery bank. Hence, they cannot act as energizing sources. In this design, two external shorts, one to each side of the solenoid (S2 and N) are required to activate it. The two source conductors must be provided from either the same power source (i.e., battery bank) that normally powers the circuit or from a second compatible one (i.e., another DC power source). Note that, as in the first case, it is assumed that AC power sources cannot activate a DC solenoid; but that the relative polarity across the solenoid (i.e., of the shorts to S2 and N) is not important.

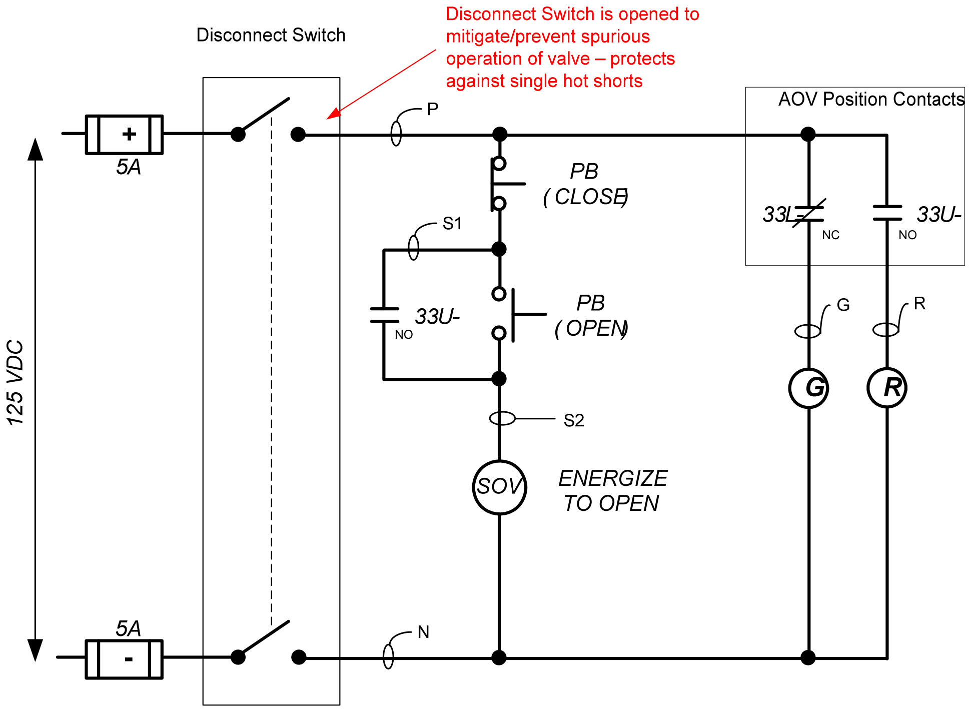


Figure 3-5. Double Break Control Circuit Configuration (Ungrounded DC)

There are two variations on this case: One assumes that the two energizing shorts come from direct cable-to-cable interactions, and the second assumes that one of the two results from GFEHS. Figures 3-8 and 3-9, respectively, of Volume 1 also illustrate double break control circuits for ungrounded AC and DC control circuits. Additional schematics of double break configurations are included in Appendix C of Volume 1.

Three of the four proponents addressed the double break control circuits. Proponent #4 did not include them in his report.

3.3.1 Approach Used to Estimate Double Break Control Circuit Probability

In early panel discussions, a proponent suggested the following: Treat the two hot-short events required to induce a spurious operation in a double break (or contact) control circuit design by simply assuming two independent events of the hot-short type (e.g., combinations of intra-cable hot short, inter-cable hot short and GFEHS). Some panelists suggested that this would ignore dependency issues while others stated that "…given hot shorts forming within a faulting cable, more than one conductor was typically involved in the shorting behavior." Given a hot short to one conductor, hot shorts to additional conductors are not independent events, and so should be assigned a higher probability of occurrence for multiple hot shorts. Therefore, assuming independence would underestimate the probability of spurious operation for the double break designs. However, the proponent who originally proposed them as independent argued that this is an inappropriate interpretation made about the involvement of multiple conductors in most of the cases of cable hot shorting observed in testing. His reasons are discussed below.

> While the prior statements remain true, the above description does not properly interpret the effect as applied to the double break case. To explain further, none of the tests to date have investigated double break designs. In the AC tests, this was the 'high' or 'hot' side of the AC power source (generally a CPT); in the DC tests, this was the 'positive' battery potential. Shorts between the opposite side of the power source (i.e., the 'return', 'neutral' or ground for AC, and the battery negative for DC) and the 'target' conductors would not cause a spurious operation. Such shorts were, in fact, a mitigating effect that would prevent or disrupt a spurious operation by causing a fuse-blow failure after a hot short to the target conductor. In these tests, it was common to see that once the hot short source conductors began shorting to other conductors in the cable, the shorting rarely was limited to just one pair of conductors.
>
> With the double break design, there are two energizing potentials that must come into proper shorting configurations to cause spurious operation (the hot and return sides for AC, and both positive and negative sides for DC). Two independent hot shorts must form concurrently before a spurious operation can occur; namely, a short between one side of the power source and the conductor for one side of the target end-device, and a second separate short between the opposite side of the power source and the opposite side of the target's end device. This is a far different condition from that implied by an earlier statement observing that after one side of the power source has shorted to one side of the target end-device, the same hot short source also is very likely to impact other cable conductors. This would imply that the same side of the power source may well hot short to the conductor associated with the other side of the target end-device, but that this condition would not induce a spurious operation in a double break circuit. However, if one side of energizing power source shorts to several conductors (rather than just one), then a spurious operation might be less likely because a spurious operation requires that the opposing side of the target end-device remains available to receive an energizing hot short from the opposite side of the power source without causing a fuse to blow.
>
> Overall, the dependence implied by the earlier statement actually may imply an inverse dependency with respect to the spurious operation in a double break circuit design. That is, if the first of the two required hot shorts has formed, there is a certain dependent likelihood that the opposite side of the target end device also will short to the same energizing source (i.e., to the same side of the power source). If a subsequent hot short from the opposite side of the power source subsequently formed, a fuse blow failure would occur, not a spurious operation.
>
> Other factors that would play some role in this problem are the duration and timing of the circuit's hot shorts. That is, the timing of the two shorts required to cause a spurious operation event on a double break circuit must overlap. This case is not well represented by the data sets available. For intra-cable based cases, shorts among all conductors do tend to overlap, so duration and timing likely have little effect on cases strictly related to faults within a single cable. For those cases involving external interactions, either grounds or inter-cable shorts, in reality there would likely be many more potential source-cables surrounding the target cable than were present during the

tests. Hence, timing constraints would likely be less restrictive than the data sets nominally indicate. For the purposes of this assessment, neglecting these two factors, timing of circuit damage, and duration of hot shorts, is suggested.

Overall, the PRA panel judged that the value obtained by simply assuming independent hot shorts of the specified type will yield a *moderately conservative* estimate of the spurious operation probability given that this approach ignores the likely *negative* dependency factors described above. However, without testing there is no basis for quantifying that negative dependency and it is unwise to speculate on further reducing these values.

The approach for evaluating a sub-case of the double break control circuit is to treat the two hot short events required to cause a spurious operation in a double break (or contact) control circuit as two conditionally independent events (they are both dependent on the occurrence of fire damage). For example, the community distribution for the intra-cable & intra-cable hot shorts was assessed as the combination of the community distributions for two SOV single break control circuit intra-cable hot shorts because this spurious operation failure mode requires two intra-cable hot shorts.

Given this assessment, the exercise for estimating the probability distributions for most double break sub-cases becomes somewhat direct. As long as the prior single break tables include probability distributions for each of the two individual hot shorting modes considered for a sub-case, the individual modes (e.g., intra-cable plus intra-cable; intra-cable plus GFEHS) were linked under an "AND" gate, and the double-break distribution was obtained by Monte Carlo simulation (see Subsection 2.3.6, "Combining Individual Community Distributions," for a description of the process used for combining probability distributions). Thus, the community distribution for the intra-cable & intra-cable hot shorts for a double break control circuit was assessed by linking under an "AND" gate two SOV single break control circuit intra-cable hot shorts (which are characterized by probability distributions).

For some sub-cases related to the ungrounded AC with CPTs double break control circuits, the proponents provided distribution parameters (i.e., quantiles) for hot short combinations [i.e., intra-cable & inter-cable (column 2) and inter-cable & inter-cable (column 3)] that were used for assessing the final community distributions. These sub-cases included the GFEHS failure mode as part of the inter-cable hot short (i.e., columns 4 and 5 in Table 3-2) in an ungrounded AC with an individual CPTs control circuits. For double break control circuits powered from an ungrounded AC with CPTs the PRA panel merged the data for inter-cable hot short failure mode and the GFEHS failure mode (i.e., columns 2 & 4, and columns 3 & 5). Therefore, the hot short failure mode combination columns in Table 3-2 involving GFEHS are not applicable to these power supply sub-cases (i.e., columns 4 and 5 in Table 3-2 do not apply to this configuration).

Appendix C, presents a detailed discussion of the double break "Base Case – SOV" control circuit configuration. Calculating the conditional probabilities for an MOV control circuit with double break design was not included in the original consideration and hence, was neither deliberated in Workshop #2 nor addressed in the proponents' reports. In the last Workshop #3 attended by both the PIRT and PRA panels, the proponents suggested including the double break design of MOV control circuits in the overall scope of this project. The proponents concluded that a multiplying factor should be used to modify double break control circuit SOV distributions involving intra-cable hot shorts (i.e., Columns 1 and 4) for MOV applications. For all other combinations involving either *inter-cable hot short or GFEHS* failure mode, the double break control circuit SOV values for the single break MOV cases are applicable. However, for an ungrounded AC power source from individual CPTs, the inter-cable hot short and GFEHS failure modes are not separately addressed for single break cases (Table 3-1), but combined within a single column (5).

The PIRT panel stated that they excluded grounded AC control circuits because members were unaware of any applications of double break design for a grounded circuit. Moreover, for a grounded circuit a second hot short is not needed for the circuit to engender a spurious operation. In fact, a hot short plus a ground would blow the fuse. Therefore, the double break design control circuit cases for both SOVs and MOVs are considered only for ungrounded circuits. They specifically are those associated with (1) ungrounded AC (w/individual CPTs) control circuits where one side of the fault is assumed to arise from a fault to ground and (2) ungrounded DC (or ungrounded distributed AC) where a GFEHS situation is involved separate from inter-cable hot shorts.

3.4 Spurious Operation Duration

The PIRT panel recommended developing spurious operation duration tables for exposure conditions to flames, plumes, and hot-gas layer fires for all three specific power-supply configurations, taking into account the effect of fuse size. Although not having a "High Impact" on the spurious operation likelihood, there is evidence that the mode of fire exposure impacts spurious operation duration. Thus, longer duration signals are associated with less intense fire exposure conditions and longer times to cable failure. The PRA panel determined that developing spurious operation duration probabilities based on fire hazard would be difficult to implement primarily due to the difficulty for an analyst in taking credit for shorter spurious operation signal durations based on fire exposure conditions.

Two proponents provided recommendations in their proposals. Proponent #1 estimated the mean durations (with uncertainty bounds) by fitting a Weibull distribution and finally, recommended using the Weibull distribution exclusively for all cases.

Proponent #3 reviewed Section 16, "Hot Short Duration (FAQ 08-0051)" of interim NUREG/CR-6850, Supplement 1, "Fire Probabilistic Risk Assessment Methods Enhancements," (Ref. 15) and stated his estimation of the conditional probability of spurious operation duration for a hot short lasting longer than or equal to time, t, in minutes.

Proponent #3 conservatively modified a data-based Weibull distribution plot to account for his beliefs on the effects of parameters identified by the PIRT panel. In addition, for the DC case, because there were several tests where spurious operations and hot shorts persisted at the time when the test was terminated, this proponent recommended different minimum duration probabilities for AC and DC control circuits. These minimum probability values are called "Floors" for the duration curve.

This particular approach for estimating the length of spurious operation was discussed extensively among the proponents and the TI team members. The processed used for the development of the hot short-induced spurious operation occurrence probability estimation where proponents provided input and the TI team integrated the input systematically, was not used for the duration probability development. In the latter case, the TI team took one of the proponents approach and further developed it with the help of Martin Stutzke (NRC) and feedback from the proponent experts. The TI team decided to develop two plots, one for AC control circuits and another for DC, encompassing all modes of fire exposure.

The PRA panel also made the following suggestions:

- Test data from different fire exposures (i.e., flame, plume, hot gas layer, and radiant heat) should be pooled to form one set for AC control circuits and another for DC control circuits. If the difference between the two is marginal, both sets may be pooled.

- Statistical tests for the poolability of data should be used before combining data sets. As indicated in Proponent #3 report, this has excluded some of very short (i.e., shorter than 1 minute) and very long (i.e., longer than 10 minutes) duration tests from the pooled data set. As noted in their final report (Appendix F), the PPRP recommended against the screening of data purely on statistical grounds.

- Proponent #1 suggested that a Weibull distribution should be fitted to the combined data set. The appropriate adjustments made to this mean (or median) Weibull distribution to account for the effects of all other influencing parameters that the PIRT panel identified, including the in-plant conditions and tests of shorter durations.

- Since there are some very long duration DC test cases, this can be represented by a "floor" to the Weibull distribution that will differ for AC and DC control circuits. (The "floor," so-called because it provides a lower limit for the complementary cumulative probability distribution for duration, is the probability that the spurious operation lasts indefinitely.)

- Appropriate uncertainty bounds should be added to the mean Weibull plots and their floor levels.

To address these suggestions from the PRA panel, a modified Weibull model, known as the "CS Model" was formulated. Development of the CS Model is based off of a technique used by reliability engineers known as "scale-accelerated failure time (SAFT)." It is often used for accelerated testing, but had applicability here as the PRA panel were attempting to model time differences between testing and actual plant fire conditions as they relate to spurious operation duration.

The CS Model provides a mathematical format for adjusting the Weibull distribution. As used in this project, a 'c' value is used to shift the mean Weibull distribution curve, while an 's' value is used to adjust the uncertainty of the Weibull distribution. The 'c' and 's' values do not represent any one physical phenomena, but can be viewed as a tool to model the shape of the distribution. Thus, as used in his project, the proponents pick a value ('c' and 's') based on the shape of the resulting distribution and uncertainty which they fell best represents their informed judgment.

Other factors have not been tested that could lead to spurious operation signals that are not self-mitigating via the common occurrence of clearing of protective devices or by other means. In particular, disrupting the fire (e.g., via suppression) may disturb the progression of damage from fully functional to fully degraded; this disruption can occur at any time. None of the tests of circuit-failure mode tests have explored the effect of extinguishing a fire after initial cable failures occur, but before full cable burn-up is observed. For example, given an external exposure fire, such as a cabinet fire exposing overhead cables, firefighting efforts will focus first on the fire source (i.e., the cabinet). Once the fire is suppressed, the cables likely will self-extinguish (unless a very large-scale cable-fire was allowed to develop). In this scenario, the cables may very well be left in an intermediate damages state; that is, in some conductors the integrity of insulation integrity is lost, while others remain essentially intact, and with the circuit fuses still intact.

It is important to note that the cables in the CAROLFIRE and DESIREE-FIRE tests, which constitute the majority of these results, were exposed to severe thermal conditions, such that the cable would be damaged in 20-30 minutes, a time frame that was felt to be risk-significant during the planning stages of the CAROLFIRE program. In addition, the loading of the cable tray was limited in most cases; had the testing involved a more loaded tray, the time to damage and durations would likely have been extended. So the question that needs to be answered is "How do these exposure conditions correlate to real fires experienced in the plant that are severe enough to cause cable damage?" With the limited number of well-documented fires that have caused cable damage, and the wide variety of fire scenarios has encountered in the plants, this question is not easy to answer.

The spurious operation signal durations should also consider the probability that a spurious operation signal will not clear (i.e., be effectively of infinite duration). In the case of the DC testing in particular, several very long duration signals were observed that the PRA panel decided should not be dismissed. While most of these occurred in the small scale Penlight testing of DESIREE-Fire, the panel determined that they are valid data and should be factored into the guidance on duration. Part of the justification for the "floor" value is that the testing may not accurately represent the events of an actual fire in this regard; some consideration should be given to the potential that spurious operation signals will not self-mitigate.

3.4.1 Approach Used to Estimate Spurious Operation Duration Probability

After several deliberations among the PRA panel, it was concluded that the pooled data set used by Proponent #3 were appropriate to employ in developing the plots of spurious-operation duration. Thus, these plots combine duration data from most of the tests; only the duration data for both AC flame tests and for DC radiant tests are excluded. In addition, other factors affecting duration, as identified by the PIRT panel, were taken into account via a combination of modifying the mean of the Weibull distribution and adding an uncertainty bound to the mean of this distribution. Based on several telephone discussions and a lengthy discussion during the 3rd SSHAC workshop, it was decided to adapt a "CS-Model" of the Weibull distribution developed by Martin Stutzke (see Appendix C).

The method of using this model involves the following steps:

- Model hot short duration as a random variable following a two-piece, discontinuous distribution. (Short durations are modeled using a Weibull distribution; long durations are modeled using a "floor" value, such that the overall complementary cumulative distribution function for the hot short duration never falls below that floor value.)

- Develop the mean value of the duration plot using the pooled test data from the combined AC and DC fire exposure modes suggested by Proponent #3. This portion of the duration plot is common to both AC and DC control circuits and is represented by a Weibull distribution, per the above.

- Adjust the mean value to account for the effect of other influencing factors on duration using the CS Model. This model introduces a scaling factor, denoted by "c" in the equation below. Estimate the value of c.

  $T_{IP}= c\ T_{EX}$

  Where,

  T_{IP} is a random variable denoting duration of hot short during experiment
  T_{EX} is a random variable denoting duration of hot short during actual in-plant fire
  c is the time scaling factor

  $$\text{For c,}\quad R\left(\frac{t}{c}\right) = \exp\left[-\hat{\lambda}\left(\frac{t}{c}\right)^{\hat{\beta}}\right]$$

- Estimate the uncertainty bounds (5% and 95%) using the CS-Model. The model introduces a parameter, denoted by "s". Estimate the value of "s" based on various "s value curves" provided to proponents.

  $$\text{For s,}\ R_{\wp}(t) = \frac{\hat{R}(t)}{\hat{R}(t)+[1-\hat{R}(t)]\ exp\left\{-\frac{sz_{\wp}\sigma_R(t)}{\hat{R}(t)[1-\hat{R}(t)]}\right\}}$$

- To take into account all long duration events observed during tests, estimate the central tendency (median) and uncertainty for the "floors" for AC and DC circuits. Approximate these floor conditional probability estimates developed by each proponent expert using fitted beta distributions (as described in Section 2.3.3) and combined these floor beta distributions using the LOP method (as described in Section 2.3.4).

- Merge the Weibull plot and the floor probability values, along with their uncertainty bounds, to represent the final complementary cumulative distribution functions for the AC and DC circuits. Thus, the two plots for these circuits represent one Weibull distribution period with uncertainty bounds up to the time where the floor values (with uncertainty bounds) intersect the plot. Beyond this intersection point (time in minutes), the floor probability values represent the likelihood of a spurious operation not clearing.

The proponents provided their recommended values for "c" and "s". The final results from the average c- and s-values and the integrated floor-level distribution are also included in Section 6. The proponents' input for the spurious operation duration plots is in each proponent's folder in the compact disk attached to this Volume 2. Details about the development of the modified Weibull "CS-Model" and the duration probability plots are discussed further in Section 6 and Appendix C.

4
CONDITIONAL PROBABILITY OF SPURIOUS OPERATION FOR SINGLE BREAK CONTROL CIRCUITS

This section presents the estimates of the conditional probabilities of hot short-induced spurious operations for single break control circuits.

The community distribution results were calculated via the approach discussed in Section 2.3, "Technical Integration to Obtain Community Distributions," that is, the combination of proponents' input by the Linear Opinion Pooling (LOP) method. There is a brief overview of the structure and process, followed by the conditional probabilities for the following end devices:

1. Solenoid-Operated Valve
2. Motor-Operated Valve
3. Medium Voltage Circuit Breaker

The PIRT panel, in Section 3.1 of Volume 1, concluded that the insulation type (i.e., TS versus TP) and the specific insulation material had *very little effect* on the likelihood of intra-cable hot shorts leading to spurious operation. However, a strong effect is seen on the likelihood of inter-cable hot short-induced spurious operation. Therefore, the community distribution for the Intra(TS&TP) failure mode was obtained as the average of the two community distributions for Intra(TS) and Intra(TP). In general, the average of two probability distributions was obtained by applying the LOP method with equal weight (0.5) for each distribution; see Subsection 2.3.4, "Consolidating Input from Proponents," for a description of this method.

Separate tables are given for Case 1 "SOV" and Case 2 "MOV," which present the conditional probabilities for these types of circuits based on their various attributes (i.e., power supply, grounding configuration, cable construction), and specific hot short failure mode (intra-cable hot short, inter-cable hot short, or GFEHS). Both cases use the format presented in Table 3-1. Case 3 "Medium Voltage Circuit Breaker" is one distribution that bound all three failure modes involving fire-induced hot shorts that result in the spurious operation of an ungrounded DC control circuit for a medium voltage circuit breaker. Case 3 differs from the other cases in that the proponent experts didn't evaluate the parameters individually for the medium voltage circuit breaker case.

Since cables may fail due to any relevant hot short failure modes, each aggregate sub-case in columns 3, 6 and 10 of Tables 4-1 and 4-3 was evaluated as the Boolean OR of the corresponding sub-cases, as discussed in Section 2.3.6. For example, for a combination of target cable configuration (e.g., TS-insulated Conductor Cable) and a particular power supply configuration [e.g., ungrounded DC (or ungrounded distributed AC)], a spurious operation may happen due to any of the possible types of hot short failure modes, viz., intra-cable, inter-cable, or ground fault equivalent. For this example, the Aggregate for this sub-case in an ungrounded

DC (or ungrounded distributed AC) configuration (row 1, column 10 in Tables 4-1 and 4-3) was assessed as follows:

$$\text{Aggregate} = \text{Intra(TS\&TP)} + \text{Inter} + \text{Ground Fault Equivalent}$$

Where,

Aggregate represents the aggregate event,
Intra(TS&TP) means the intra-cable hot short failure mode for the TS- and TP-insulated conductor cables,
Inter signifies the inter-cable hot short failure mode,
Ground Fault Equivalent is the GFEHS failure mode, and,
"+" means sum (i.e., Boolean OR) of the individual failure modes.

The spreadsheets (in the attached compact disk) in Appendix E show the plot, for each individual sub-case, of integrating the individual proponent distributions into a LOP distribution, and the beta distribution that was fitted to the LOP distribution, that is, the final community distribution. For each aggregate sub-case, Appendix E also includes the plot of the beta distribution that was fitted to the quantiles resulting from the combination of several probability distributions, as described above. Subsection 2.3.5, "Deriving a Parametric Community Distribution," gives a brief description of the approach for fitting a beta distribution.

4.1 SOV Single Break Control Circuits

All four proponents provided input to this case study. The SOV case is considered as the "Base Case." The estimation of conditional probabilities (i.e., given cable damage) for it follows the SSHAC process using the LOP method of combining expert input.

Table 4-1 contains the results of applying the process outlined in Section 2.3. Each sub-case includes five characteristics of the beta distribution (i.e., the community distribution): The two distribution parameters (alpha and beta), the 5th percentile, the mean, and the 95th percentile (in that order). As discussed above, the community distributions for the TS- and TP-insulated target conductors were averaged for the intra-cable hot short failure mode for all three power supply control circuits. Therefore, the conditional probability distribution parameters in the first two rows for TS- and TP-insulated conductor cables for the *intra-cable* hot short failure mode are the same (see rows 1 and 2 probabilities for columns 1, 4, and 7 in Table 4-1).

Table 4-1. Conditional Probability of Spurious Operation: SOV Single Break-Control Circuits

Power Supply →			Grounded AC			Ungrounded AC (w/ Individual CPTs)			Ungrounded DC (or Ungrounded Distributed AC)			
			Conductor Hot Short Failure Mode									
Target Cable Configuration		Beta Distribution Characteristics	Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	Ground Fault Equivalent	Aggregate
			1	2	3	4	5	6	7	8	9	10
Thermoset-Insulated Conductor Cable	1	Alpha	8.54	0.36	8.79	4.73	0.60	4.74	10.16	0.32	2.27	12.76
		Beta	11.74	35.25	11.81	2.69	613.31	2.69	11.70	50.01	11.45	10.18
		5%	*2.5E-01*	*4.6E-06*	*2.6E-01*	*3.4E-01*	*8.9E-06*	*3.4E-01*	*2.9E-01*	*1.2E-06*	*3.8E-02*	*3.9E-01*
		Mean	**4.2E-01**	**1.0E-02**	**4.3E-01**	**6.4E-01**	**9.7E-04**	**6.4E-01**	**4.6E-01**	**6.3E-03**	**1.7E-01**	**5.6E-01**
		95%	*6.0E-01*	*4.3E-02*	*6.1E-01*	*8.9E-01*	*3.5E-03*	*8.9E-01*	*6.4E-01*	*2.8E-02*	*3.5E-01*	*7.2E-01*
Thermoplastic-Insulated Conductor Cable	2	Alpha	8.54	0.85	9.19	4.73	0.27	4.86	10.16	0.92	1.83	12.66
		Beta	11.74	32.67	11.90	2.69	17.16	2.71	11.70	44.19	10.36	10.19
		5%	*2.5E-01*	*8.6E-04*	*2.7E-01*	*3.4E-01*	*5.2E-07*	*3.5E-01*	*2.9E-01*	*8.7E-04*	*2.6E-02*	*3.8E-01*
		Mean	**4.2E-01**	**2.5E-02**	**4.4E-01**	**6.4E-01**	**1.5E-02**	**6.4E-01**	**4.6E-01**	**2.0E-02**	**1.5E-01**	**5.5E-01**
		95%	*6.0E-01*	*7.9E-02*	*6.1E-01*	*8.9E-01*	*7.2E-02*	*8.9E-01*	*6.4E-01*	*6.2E-02*	*3.4E-01*	*7.2E-01*
Metal Foil Shield Wrap Cable	3	Alpha	1.22	Incredible	1.22	2.63	Incredible	2.63	2.54	Incredible	1.97	4.68
		Beta	3.77		3.77	2.24		2.24	2.79		4.54	2.69
		5%	*2.5E-02*		*2.5E-02*	*1.9E-01*		*1.9E-01*	*1.6E-01*		*6.7E-02*	*3.4E-01*
		Mean	**2.4E-01**		**2.4E-01**	**5.4E-01**		**5.4E-01**	**4.8E-01**		**3.0E-01**	**6.3E-01**
		95%	*5.9E-01*		*5.9E-01*	*8.7E-01*		*8.7E-01*	*8.1E-01*		*6.1E-01*	*8.9E-01*
Armored Cable	4	Alpha	0.22	Incredible	0.22	4.00	Incredible	4.00	9.82	Incredible	2.77	14.63
		Beta	4.52		4.52	4.93		4.93	3.59		2.97	2.34
		5%	*2.3E-07*		*2.3E-07*	*1.9E-01*		*1.9E-01*	*5.2E-01*		*1.7E-01*	*7.1E-01*
		Mean	**4.7E-02**		**4.7E-02**	**4.5E-01**		**4.5E-01**	**7.3E-01**		**4.8E-01**	**8.6E-01**
		95%	*2.4E-01*		*2.4E-01*	*7.1E-01*		*7.1E-01*	*9.0E-01*		*8.0E-01*	*9.7E-01*

As detailed in Section 2.3.4, the TI team assigned equal weights to the distributions of individual proponents in almost all sub-cases when applying the LOP method. In only four sub-cases of single break SOV circuits were different weights assigned. Table 4-2 shows the weights used for these sub-cases and the TI team justifications for selecting them. The weights were discussed and finalized with each proponent during the SSHAC Workshop #3.

Table 4-2. Bases for Assignment of Weights to Proponents in Four Sub-cases

Sub-Case[1]	Proponent's Weight				Bases for Assigning Weights
	1	2	3	4	
SB 01_02	0.1	0.2	0.5	0.2	1. The TI team's confidence in the individual proponent's representation of this sub-case. 2. The weights were adjusted according to the TI team's interpretation of the PIRT's recommendation for "implausible" in Volume 1.
SB 01_08	0.38	0.12	0.38	0.12	1. The TI team's confidence in the individual proponent's representation of this sub-case. 2. The weights were adjusted according to the TI team's interpretation of the PIRT's recommendation for "implausible" in Volume 1.
SB 04_01	0.2	0.35	0.35	0.1	1. Proponents 2 and 3 were considered to better capture the information available, specifically the proprietary test data from Duke Energy on armored-control cable testing (Proprietary). 2. Proponent 1 was considered to have less knowledge about this sub-case than proponents 2 and 3. 3. Proponent 4 did not use the data from Duke Energy.
SB 04_09	0.2	0.4	0.4	0.0	1. The TI team gave lower weight to Proponent 1 than to Proponents 2 and 3 because his data set did not include the information from Duke Energy. 2. The TI team gave a weighting of 0 to Proponent 4 because the data set used was not correct for this case.

4.2 MOV Single Break Control Circuits

As discussed in Section 3, the proponents developed event trees using SOV estimates as the starting point of the tree to develop MOV likelihood of occurrence estimates. However, each proponent used a different logic structure, and the TI team could not identify a practical way of

---

[1] Refer to Table 3-1 in Section 3 of this report.

consolidating the structures into a "unified" event tree. Nevertheless, a commonality between the logic structures lays the following basic formulation:

> For each sub-case (or cell) of the conditional probability table for the single break MOV control circuits,
>
> $$P\ (MOV) = P\ (SOV) * MOV\ Multiplier^{2}$$
>
> Where,
>
> P (X) is the probability of an event X.
>
> P (MOV) is the conditional probability of spurious operation of single break MOV control circuits. Values of P (MOV) are given in Table 4-3.
>
> P (SOV) is the conditional probability of spurious operation of single break SOV control circuits. Values of P (SOV) are given in Table 4-1.
>
> "MOV Multiplier" is a factor developed from the aggregation of the proponent estimates obtained from their event-tree models.
>
> * denotes the product of random variables.

All the probabilities in the previous equation depend on the conditions established by each sub-case, that is, a particular combination of target-cable configuration (e.g., Thermoset-insulated conductors) and a type of hot short failure mode (e.g., intra-cable hot short) in a power supply-grounding configuration (e.g., a grounded AC).

Since the P (SOV) was evaluated in Section 4.1 for each sub-case, this section focuses on assessing the "MOV Multiplier" for each of them. The assessment entailed two main steps:

Step 1: Determining the MOV Multiplier (i.e., a beta distribution) from each proponent's (Proponents #1, #3, and #4) input for each sub-case.

The MOV Multiplier for each sub-case was evaluated for each of the three proponents, as follows (Recommended by the TI team):

Evaluation of Proponent #1's Individual Distributions

Proponent #1 offered three quantiles for one MOV multiplier for all sub-cases. A beta distribution was fitted to each of the seven combinations of the quantiles, and he selected the beta distribution (44.03, 19.06) from them. This distribution was used for Proponent #1's MOV multiplier for all sub-cases.

---

[2] MOV Multiplier is a statistical distribution (i.e., a beta distribution) function.

Evaluation of Proponent #3 and #4's Individual Distributions

Section 3.2.1, "Approaches Used to Estimate Single Break SOV and MOV Control Circuit Probabilities," shows the event-tree-like logic structure that Proponent #3 used in Figure 3-3, and gives a detailed description of this model. The first event, "Undesired Contactor Conductor Energized" (identified as "P1" in Figure 3-3) corresponds to the event Single Break-SOV. Hence, the approach to assess this proponent's MOV multiplier was to evaluate the three sequences of this structure leading to the outcome "Undesired End Position of MOV," conditional on this event Single Break-SOV happening for each sub-case. This model was implemented and evaluated using the code SAPHIRE 7 for Windows (Ref. 28), as described generically in Section 2.3.6 under "Combining Individual Community Distributions." The outcome of this process was Proponent #3's MOV multiplier in the form of a beta distribution for each individual sub-case of MOV single break control circuit.

Proponent #4 also developed an event-tree logic structure, but structured differently from the one that Proponent #3 used. Application of the same process used for Proponent #3 on the input provided by Proponent #4 resulted in an MOV multiplier for Proponent #4 in the form of a beta distribution for each individual MOV sub-case.

Step 2: Aggregating the three Beta Distributions (representing proponents' MOV Multipliers) using the LOP method to obtain the Community Distribution for the MOV multiplier for each sub-case.

The MOV multipliers for each sub-case were obtained by aggregating the three proponents' beta distributions using the LOP method to obtain the community distribution for the overall "MOV Multiplier" for the sub-case.

Finally, for each sub-case, the P (MOV) was evaluated as the product of P (SOV) and "MOV Multiplier", according to the above equation. This operation involved the product of two random variables obtained in terms of two beta distributions.

Table 4-3 gives the resultant P (MOV) for each sub-case of a single break circuit, that is, the values therein are the conditional probability values for an MOV control circuit with a single break design and includes five characteristics of the beta distribution (i.e., the community distribution): The two distribution parameters (alpha and beta), the 5th percentile, the mean, and the 95th percentile (in that order). Similar to the SOV control circuits, the community distributions for the TS- and TP-insulated target conductors were averaged for the intra-cable hot short failure mode for all three power supply control circuits for the MOV results. Therefore, the conditional probability distribution parameters in the first two rows for TS- and TP-insulated conductor cables for the *intra-cable* hot short failure mode are the same (see rows 1 and 2 probabilities for columns 1, 4, and 7 in Table 4-3).

Table 4-3. Conditional Probability of Spurious Operation: MOV Single Break Control Circuits

Power Supply →			Grounded AC			Ungrounded AC (w/ Individual CPTs)			Ungrounded DC (or Ungrounded Distributed AC)			
Target Cable Configuration		Beta Distribution Characteristics	Conductor Hot Short Failure Mode									
			Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	Ground Fault Equivalent	Aggregate
			1	2	3	4	5	6	7	8	9	10
Thermoset-Insulated Conductor Cable	1	Alpha	5.55	0.36	5.80	4.81	0.58	4.81	5.53	0.32	1.93	7.65
		Beta	14.98	40.31	15.16	7.69	687.61	7.68	12.03	56.43	14.97	11.63
		5%	*1.3E-01*	*4.1E-06*	*1.3E-01*	*1.8E-01*	*7.1E-06*	*1.8E-01*	*1.5E-01*	*1.0E-06*	*2.1E-02*	*2.2E-01*
		Mean	**2.7E-01**	**8.8E-03**	**2.8E-01**	**3.8E-01**	**8.5E-04**	**3.9E-01**	**3.1E-01**	**5.6E-03**	**1.1E-01**	**4.0E-01**
		95%	*4.4E-01*	*3.8E-02*	*4.5E-01*	*6.1E-01*	*3.1E-03*	*6.1E-01*	*5.0E-01*	*2.5E-02*	*2.6E-01*	*5.8E-01*
Thermoplastic-Insulated Conductor Cable	2	Alpha	5.55	0.84	6.20	4.81	0.27	5.02	5.53	0.91	1.50	7.58
		Beta	14.98	37.19	15.43	7.69	19.75	7.75	12.03	49.25	13.25	11.55
		5%	*1.3E-01*	*7.2E-04*	*1.4E-01*	*1.8E-01*	*4.5E-07*	*1.9E-01*	*1.5E-01*	*7.4E-04*	*1.3E-02*	*2.2E-01*
		Mean	**2.7E-01**	**2.2E-02**	**2.9E-01**	**3.8E-01**	**1.3E-02**	**3.9E-01**	**3.1E-01**	**1.8E-02**	**1.0E-01**	**4.0E-01**
		95%	*4.4E-01*	*7.0E-02*	*4.5E-01*	*6.1E-01*	*6.3E-02*	*6.2E-01*	*5.0E-01*	*5.6E-02*	*2.5E-01*	*5.8E-01*
Metal Foil Shield Wrap Cable	3	Alpha	1.20	Incredible	1.20	3.64	Incredible	3.64	2.62	Incredible	2.11	4.85
		Beta	6.15		6.15	6.15		6.15	5.95		7.41	5.72
		5%	*1.5E-02*		*1.5E-02*	*1.5E-01*		*1.5E-01*	*8.9E-02*		*4.9E-02*	*2.2E-01*
		Mean	**1.6E-01**		**1.6E-01**	**3.7E-01**		**3.7E-01**	**3.1E-01**		**2.2E-01**	**4.6E-01**
		95%	*4.2E-01*		*4.2E-01*	*6.3E-01*		*6.3E-01*	*5.8E-01*		*4.6E-01*	*7.1E-01*
Armored Cable	4	Alpha	0.21	Incredible	0.21	3.76	Incredible	3.76	7.52	Incredible	3.10	10.97
		Beta	5.94		5.94	10.05		10.05	9.24		7.72	7.12
		5%	*6.7E-08*		*6.7E-08*	*1.0E-01*		*1.0E-01*	*2.6E-01*		*9.5E-02*	*4.2E-01*
		Mean	**3.4E-02**		**3.4E-02**	**2.7E-01**		**2.7E-01**	**4.5E-01**		**2.9E-01**	**6.1E-01**
		95%	*1.7E-01*		*1.7E-01*	*4.8E-01*		*4.8E-01*	*6.5E-01*		*5.2E-01*	*7.8E-01*

4.3 Single Break Ungrounded DC Control Circuits for Medium Voltage Circuit Breaker

For the medium voltage circuit breaker case, only one generic distribution was developed. This estimation is based on two proponents' inputs using the DC fire-test data as discussed in Section 3.2.2 for the circuit breaker from the DESIREE-Fire testing. Two proponents provided input for this case which was subsequently fit to a beta distribution. These two distributions were combined using equal weights when applying the LOP method. The results are shown in Figure 4-1. Table 4-4 presents the resulting community distribution Beta (5.54, 8.47). These results are applicable to all circuit failure modes (i.e., "aggregate") for ungrounded DC medium voltage circuit breaker control circuit.

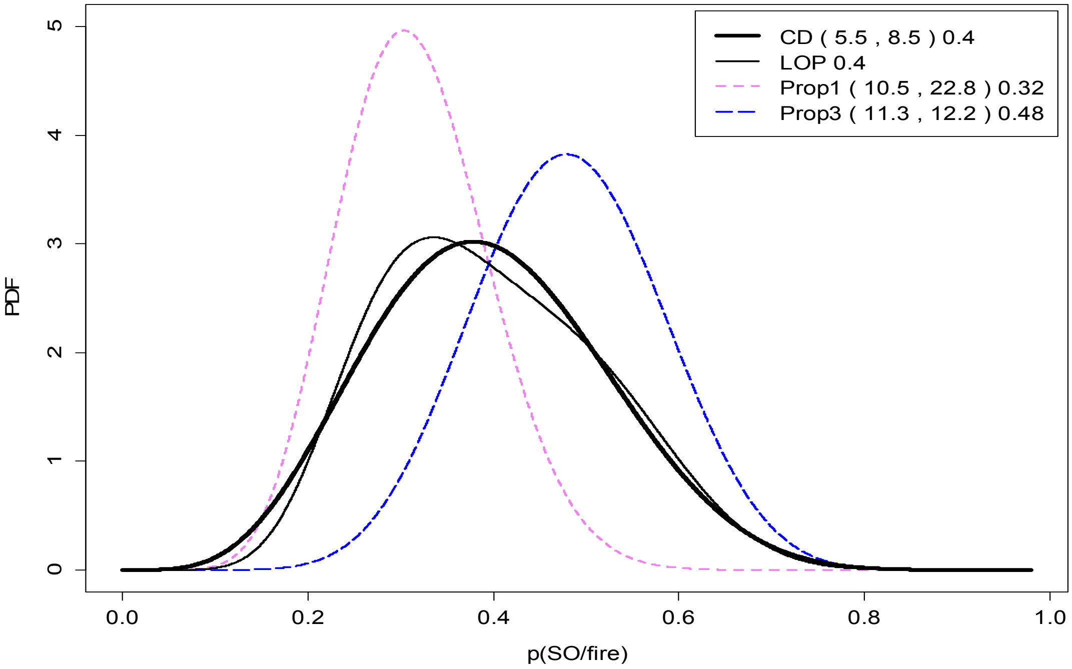


Figure 4-1. Community Distribution for Circuit Breakers Using LOP of Inputs from Proponents 1 and 3

CD in the legend represents the Community Distribution.

Table 4-4. Conditional Probability of Spurious Operation: Ungrounded DC Control Circuits for Medium Voltage Circuit Breaker

Characteristics of Beta Distribution	Probability Value
Alpha	5.54
Beta	8.47
5%	*2.0E-01*
Mean	**4.0E-01**
95%	*6.1E-01*

Thus, the conditional probability estimate in Table 4-4 represents the aggregate as this estimate was developed assuming that the data includes all three individual hot short-induced spurious operation failure modes (i.e., intra-cable hot short, inter-cable hot short, and GFEHS). Since these individual failure modes were not developed for the circuit breaker case, the PRA panel recommended that for inter-cable hot short and GFEHS failure modes the corresponding SOV values (Table 4-1) should be used to quantify the circuit breaker conditional spurious operation probability for the respective failure mode (inter-cable hot short or GFEHS). The PRA panel also recommended using the aggregate value in Table 4-4 for the medium voltage circuit breaker intra-cable failure mode[3].

---

[3] Note that the aggregate value in Table 4-4 for a circuit breaker was evaluated using the SSHAC process that led to developing the community distribution. For other sub-cases (i.e., intra-cable, inter-cable, and ground fault equivalent hot shorts), the conditional probability values are based on the panel's recommendation (i.e., consensus).

5
CONDITIONAL PROBABILITY OF SPURIOUS OPERATION FOR DOUBLE BREAK CONTROL CIRCUITS

This section presents the estimates of the conditional probabilities of hot short-induced spurious operations for double break control circuits. Hot short-induced spurious operation for double break control circuits is assumed to require two concurrent fire-induced failure modes to actuate an end device (e.g., SOV, MOV). The conditional probability tables in this section include five characteristics of the community distribution [i.e., a beta distribution]: The two parameters (alpha and beta); the 5th percentile; the mean; and the 95th percentile (in that order). Appendix E details the findings for each sub-case.

The procedures used in estimating the conditional probabilities for spurious operation of double break control circuits are described for the following two end devices:

1. Solenoid-Operated Valve
2. Motor-Operated Valve

The above two double break control circuit cases for the SOV and MOV are associated with ungrounded circuits, namely, ungrounded AC (with individual CPTs) and ungrounded DC (or ungrounded distributed AC). Both cases were assessed for the same four target-cable configurations as was done for single break control circuits: 1. Thermoset-insulated conductor cable; 2. Thermoplastic-insulated conductor cable; 3. Metal-foil shield wrap cable; and, 4. Armored cable.

5.1 SOV Double Break Control Circuits

The TI team used the same approach discussed in Section 3.3.1 for deriving the double break spurious operation conditional probability distributions for SOV circuits. That is, corresponding SB-SOV values were assumed to be independent and combined as such, using the single break distributions in Table 4-1 for the SOV base-case.

5.1.1 Ungrounded AC (with Individual CPTs)

Double break SOV control circuits powered from individual CPTs in an ungrounded AC configuration are susceptible to the following failure modes;

- Intra-cable & Intra-cable hot shorts (Column 1),
- Intra-cable & Inter-cable hot shorts (Column 2), and,
- Inter-cable & Inter-cable hot shorts (Column 3).

CONDITIONAL PROBABILITY OF SPURIOUS OPERATION FOR DOUBLE BREAK CONTROL CIRCUITS

The intra-cable hot short & GFEHS and the inter-cable hot short & GFEHS (columns 4 and 5 of Table 3-2) are not applicable failure modes to the Ungrounded AC (with individual CPTs) control circuits.

Table 5-1 presents the estimated conditional probability distribution community distributions for double break SOV control circuits powered from an Ungrounded AC with individual CPTs power supply.

Table 5-1. Conditional Probability of Spurious Operation: Double Break Control Circuits for Ungrounded AC (w/ individual CPTs)
Base Case – SOV

Target Cable Configuration		Beta Distribution Characteristic	Conductor Hot Short Failure Mode Combinations			
			Intra-Cable & Intra-Cable	Intra-Cable & Inter-Cable	Inter-Cable & Inter-Cable	Aggregate
			1	2	3	4
Thermoset-Insulated Conductor Cable	1	Alpha	2.12	0.68	Incredible	2.58
		Beta	2.78	9.83		2.92
		5%	*1.2E-01*	*1.1E-03*		*1.5E-01*
		Mean	**4.3E-01**	**6.5E-02**		**4.7E-01**
		95%	*7.8E-01*	*2.1E-01*		*8.0E-01*
Thermoplastic-Insulated Conductor Cable	2	Alpha	2.12	0.34	0.48	2.52
		Beta	2.78	3.85	89.92	2.71
		5%	*1.2E-01*	*3.2E-05*	*1.6E-05*	*1.6E-01*
		Mean	**4.3E-01**	**8.2E-02**	**5.3E-03**	**4.8E-01**
		95%	*7.8E-01*	*3.5E-01*	*2.1E-02*	*8.1E-01*
Metal Foil Shield Wrap Cable	3	Alpha	1.18	0.88	Incredible	1.86
		Beta	2.35	6.43		2.64
		5%	*3.6E-02*	*5.0E-03*		*9.4E-02*
		Mean	**3.3E-01**	**1.2E-01**		**4.1E-01**
		95%	*7.5E-01*	*3.5E-01*		*7.8E-01*
Armored Cable	4	Alpha	1.56	0.86	Incredible	2.44
		Beta	5.34	4.42		4.50
		5%	*3.4E-02*	*6.8E-03*		*1.0E-01*
		Mean	**2.3E-01**	**1.6E-01**		**3.5E-01**
		95%	*5.1E-01*	*4.6E-01*		*6.5E-01*

Note: Inter-cable hot shorts are assumed to involve GFEHS failure modes.

The following describes the approach for evaluating each of the conductor hot short failure mode combinations in columns 1-3.

Intra-cable & Intra-cable Hot Shorts (Column 1 of Table 5-1)

This failure mode was assessed as the product of the community distributions for two SOV single break control circuit intra-cable hot shorts given in Table 4-1.

Intra-cable & Inter-cable Hot Shorts (Column 2 of Table 5-1)

The proponents suggested using their actual input values (in lieu of the single break community distributions in Table 4-1) for this combination of hot short failure modes. The TI team agreed with this approach and followed a three-step process described below:

1. Proponents #1 and #3 both provided distributions (i.e., quantiles) for the intra-cable & inter-cable hot shorts, and the intra-cable & ground fault equivalent hot shorts. The distribution for each proponent was evaluated as the sum of his distributions for the intra-cable & inter-cable hot shorts (column 2), and the intra-cable & ground fault equivalent hot shorts (column 4) given in his input table.

2. Proponent #2 considered that inter-cable hot shorts that mimic the fault mode of GFEHSs are encompassed under the intra & inter cable hot shorts, so accordingly he did not offer input for the combination, intra-cable hot short & GFEHS failure modes. Hence, as he suggested, his intra-cable & inter-cable hot short-induced spurious operation occurrence distribution was selected (which was derived as the product of his distributions for SOV single break intra-cable and inter-cable hot short failure modes).

3. The community distribution for each sub-case in column 2 was obtained by applying the LOP method and then fitting a beta distribution.

Inter-cable & Inter-cable Hot Shorts (Column 3 of Table 5-1)

This type of hot short is considered incredible for the sub-cases of TS-insulated conductor target cable, metal-foil shield wrap target cable, and armored target cable[1]. Accordingly, it was evaluated only for the TP-insulated conductor target cable. The overall approach consisted of adding the proponent's inputs for the double break distributions for the inter-cable & inter-cable hot shorts (column 3), and the inter-cable & ground fault equivalent hot shorts (column 5). Specifically, the proponent expert process was used as follows:

1. Proponent #1 considered that the inter-cable & inter-cable failure mode is incredible, and gave a distribution (i.e., quantiles) only for the inter-cable & ground fault equivalent hot shorts. It was used by this proponent in aggregating the all proponents' input, described in step 4 below.

2. Proponent #2 offered a distribution (i.e., quantiles) for the inter-cable & ground fault equivalent hot shorts that are the same as that he gave for the SOV single break inter-cable hot short. For the inter-cable & inter-cable failure mode, he suggested using the product of this distribution with itself; however, the resulting distribution then would have

---

[1] PIRT panel, as documented in Volume 1 of NUREG/CR-7150, concluded that the likelihood of two inter-cable hot shorts occurring for these cable configurations is incredible.

a mean that is over two orders-of-magnitude less than the mean of the individual distribution, so its contribution was considered negligible compared to that from the latter distribution. Accordingly, he used his distribution for the inter-cable & ground fault equivalent hot shorts (i.e., his distribution for the SOV single break inter-cable hot shorts) in aggregating all the proponents' inputs, described in step 4 below.

3. The distribution for the inter-cable & inter-cable hot short for Proponent #3 was evaluated as the sum of his distributions for the inter-cable & inter-cable hot shorts (column 3) and the inter-cable & ground fault equivalent hot shorts (column 5) given in his input table.

4. The community distribution was obtained by integrating, via the LOP method, the distributions from Proponents 1, 2, and 3, obtained in the previous three steps and then fitting a beta distribution.

5.1.2 Ungrounded DC (or Ungrounded Distributed AC)

The conductor hot-shorting failure modes of interest are those in Table 3-2, namely,

- Intra-cable & Intra-cable hot shorts (Column 1),
- Intra-cable & Inter-cable hot shorts (Column 2),
- Inter-cable & Inter-cable hot shorts (Column 3),
- Intra-cable & Ground Fault Equivalent hot shorts (Column 4), and,
- Inter-cable & Ground Fault Equivalent hot shorts (Column 5).

The community distribution of each sub-case was assessed as the product of the corresponding community distributions of the SOV single break control circuits (Table 4-1) for control circuits. Table 5-2 presents the spurious operation conditional probabilities for the SOV control circuits for an ungrounded DC (or ungrounded distributed AC) double break circuits.

Since cables may fail due to any combination of hot short failure modes, each aggregate sub-case in column 6 of Table 5-2 was assessed as the Boolean OR of the corresponding preceding columns 1 through 5.

Table 5-2. Conditional Probability of Spurious Operation: Double Break Control Circuits Ungrounded DC (or Ungrounded Distributed AC)
BASE CASE – SOV

Target Cable Configuration		Beta Distribution Characteristics	Conductor Hot Short Failure Mode Combinations					
			Intra-Cable & Intra-Cable	Intra-Cable & Inter-Cable	Inter-Cable & Inter-Cable	Intra-Cable & Ground Fault Equivalent	Inter-Cable & Ground Fault Equivalent	Aggregate
			1	2	3	4	5	6
Thermoset-Insulated Conductor Cable	1	Alpha	3.90	0.32	Incredible	2.21	Incredible	4.66
		Beta	13.36	109.19		26.64		11.64
		5%	*8.5E-02*	*5.1E-07*		*1.6E-02*		*1.2E-01*
		Mean	**2.3E-01**	**2.9E-03**		**7.7E-02**		**2.9E-01**
		95%	*4.0E-01*	*1.3E-02*		*1.7E-01*		*4.8E-01*
Thermoplastic-Insulated Conductor Cable	2	Alpha	3.90	0.87	0.30	1.80	0.60	4.67
		Beta	13.36	90.66	352.91	24.12	193.16	11.56
		5%	*8.5E-02*	*3.4E-04*	*9.7E-08*	*1.1E-02*	*2.8E-05*	*1.2E-01*
		Mean	**2.3E-01**	**9.5E-03**	**8.6E-04**	**7.0E-02**	**3.1E-03**	**2.9E-01**
		95%	*4.0E-01*	*3.0E-02*	*3.9E-03*	*1.7E-01*	*1.1E-02*	*4.8E-01*
Metal Foil Shield Wrap Cable	3	Alpha	1.06	Incredible	Incredible	1.53	Incredible	1.48
		Beta	2.92			9.16		2.63
		5%	*2.1E-02*			*1.9E-02*		*5.7E-02*
		Mean	**2.7E-01**			**1.4E-01**		**3.6E-01**
		95%	*6.5E-01*			*3.4E-01*		*7.5E-01*
Armored Cable	4	Alpha	4.45	Incredible	Incredible	3.04	Incredible	6.07
		Beta	3.65			5.55		2.60
		5%	*2.7E-01*			*1.2E-01*		*4.3E-01*
		Mean	**5.5E-01**			**3.5E-01**		**7.0E-01**
		95%	*8.1E-01*			*6.3E-01*		*9.1E-01*

5.2 MOV Double Break Control Circuits

For MOV circuits with a double break design, the TI team used an “MOV Multiplier” approach similar to the single break control circuits. However, the derivation of this MOV multiplier was different from that used for single break control circuits. As noted previously, this input from the proponent for this case was not included in the initial request. It was only during Workshop #3 that the PRA panel agreed to develop a spurious operation likelihood of occurrence estimate for this case. It is the PRA panel’s belief that this case is not common, but does exist in a small number NPP circuit designs. It should be noted that the estimates for this case do not follow the SSHAC Level 2 process. The specifics of the approach used are described below.

The MOV multiplier and the process used for MOV double break control circuits were those suggested by members of the PIRT and PRA panels during SSHAC Workshop #3. Members from both panels (PIRT and PRA) agreed to use the single “MOV Multiplier” applied to all double break sub-cases as suggested by Proponent #1 for single break sub-cases.

Proponent #1 offered three quantiles for a single MOV multiplier for all sub-cases. This MOV multiplier is represented as a beta distribution (Beta (44.03, 19.06)). This “MOV Multiplier” was used for all sub-cases involving MOV double break control circuits with both ungrounded AC (with individual CPTs) and ungrounded DC (or ungrounded distributed AC) cases.

5.2.1 Ungrounded AC (with Individual CPTs)

The failure modes of conductor shorting of interest for MOV double break control circuits are the same as those for the SOV double control circuits, assuming both have the same power supply configuration (i.e., ungrounded AC (with individual CPTs)). The following process, as suggested by both panel members during Workshop #3, was applied:

1. The community distribution of the intra-cable & intra-cable failure mode (column 1 of Table 5-3) was assessed as the product of the community distribution of the SOV double break control circuits for intra-cable & intra-cable hot shorts in Table 5-1, and Proponent #1’s single distribution of his “MOV Multiplier.”[2]

2. The community distribution of each of the intra-cable & inter-cable hot shorts (column 2 of Table 5-3), and inter-cable & inter-cable hot shorts (column 3 of Table 5-3) sub-cases was considered to be approximated by the corresponding community distributions of SOV double break control circuits in Table 5-1.

Table 5-3 presents the estimations of the conditional probabilities for double break MOV control circuits. Each aggregate sub-case in column 4 of Table 5-3 was determined as the sum of the community distributions of the corresponding sub-cases in the preceding columns (i.e., 1, 2, and 3).

---

[2] This case was developed during Workshop #3. Because of this, other proponent experts didn’t have sufficient time or resources to complete the detailed analysis for the double break MOV case. During Workshop #3 the proponents agreed that the MOV multiplier suggested by Proponent #1 was adequate for this case on a consensus basis.

Table 5-3. Conditional Probability of Spurious Operation: Double Break Control Circuits for Ungrounded AC (w/ individual CPTs)
Motor-Operated Valve

Target Cable Configuration		Beta Distribution Characteristics	Conductor Hot Short Failure Mode Combinations			
			Intra-Cable & Intra-Cable	Intra-Cable & Inter-Cable	Inter-Cable & Inter-Cable	Aggregate
			1	2	3	4
Thermoset-Insulated Conductor Cable	1	Alpha	2.96	0.68	Incredible	3.28
		Beta	6.84	9.83		6.10
		5%	*9.8E-02*	*1.1E-03*		*1.3E-01*
		Mean	**3.0E-01**	**6.5E-02**		**3.5E-01**
		95%	*5.5E-01*	*2.1E-01*		*6.1E-01*
Thermoplastic-Insulated Conductor Cable	2	Alpha	2.96	0.34	0.48	2.96
		Beta	6.84	3.85	89.92	5.17
		5%	*9.8E-02*	*3.2E-05*	*1.6E-05*	*1.2E-01*
		Mean	**3.0E-01**	**8.2E-02**	**5.3E-03**	**3.6E-01**
		95%	*5.5E-01*	*3.5E-01*	*2.1E-02*	*6.5E-01*
Metal Foil Shield Wrap Cable	3	Alpha	1.53	0.88	Incredible	2.24
		Beta	5.03	6.43		4.59
		5%	*3.5E-02*	*5.0E-03*		*8.4E-02*
		Mean	**2.3E-01**	**1.2E-01**		**3.3E-01**
		95%	*5.3E-01*	*3.5E-01*		*6.3E-01*
Armored Cable	4	Alpha	1.72	0.86	Incredible	2.40
		Beta	9.20	4.42		5.77
		5%	*2.6E-02*	*6.8E-03*		*7.9E-02*
		Mean	**1.6E-01**	**1.6E-01**		**2.9E-01**
		95%	*3.6E-01*	*4.6E-01*		*5.7E-01*

Note: Inter-cable hot shorts are assumed to involve GFEHS failure modes.

5.2.2 Ungrounded DC (or Ungrounded Distributed AC)

The failure modes of conductor shorting of interest for MOV double break control circuits are the same as those for the SOV double control circuits, assuming both have the same power supply configuration (i.e., ungrounded DC (or ungrounded distributed AC)). The following process, as suggested by both panel members during Workshop #3, was used:

1. The intra-cable & intra-cable failure mode (column 1 of Table 5-4) was assessed as the product of the community distribution of the ungrounded DC (or ungrounded distributed AC) SOV double break control circuit intra-cable & intra-cable hot shorts in Table 5-2, and Proponent #1's single distribution of his "MOV Multiplier."

2. Similarly, the intra-cable & ground fault equivalent hot short failure mode (column 4 of Table 5-4) was evaluated as the product of the community distribution of the ungrounded DC (or ungrounded distributed AC) SOV double break control circuit intra-cable & ground fault equivalent hot shorts in Table 5-2 and Proponent #1's single distribution of his "MOV Multiplier."

3. The community distribution of each of intra-cable & inter-cable hot shorts (column 2 of Table 5-4), inter-cable & inter-cable hot shorts (column 3 of Table 5-4), and inter-cable & ground fault equivalent hot shorts (column 5 of Table 5-4) was approximated by the corresponding community distributions of ungrounded DC (or ungrounded distributed AC) SOV double break control circuit in Table 5-2.

Table 5-4 shows the estimations of the double break control circuit for the MOV. Since any combination of hot short failure modes may cause the cables to fail, each aggregate sub-case in column 6 of Table 5-4 was evaluated as the sum of the community distributions of the corresponding preceding columns, 1 through 5.

Table 5-4. Conditional Probability Of Spurious Operation: Double Break Control Circuits Ungrounded DC (or Ungrounded Distributed AC) Motor-Operated Valve

Target Cable Configuration		Beta Distribution Characteristics	Conductor Hot Short Failure Mode Combinations					
			Intra-Cable & Intra-Cable	Intra-Cable & Inter-Cable	Inter-Cable & Inter-Cable	Intra-Cable & Ground Fault Equivalent	Inter-Cable & Ground Fault Equivalent	Aggregate
			1	2	3	4	5	6
Thermoset-Insulated Conductor Cable	1	Alpha	4.11	0.32	Incredible	2.21	Incredible	4.83
		Beta	21.86	109.19		38.98		18.74
		5%	*5.9E-02*	*5.1E-07*		*1.1E-02*		*8.6E-02*
		Mean	**1.6E-01**	**2.9E-03**		**5.4E-02**		**2.0E-01**
		95%	*2.9E-01*	*1.3E-02*		*1.2E-01*		*3.5E-01*
Thermoplastic-Insulated Conductor Cable	2	Alpha	4.11	0.87	0.30	1.81	0.60	4.88
		Beta	21.86	90.66	352.91	35.42	193.16	18.48
		5%	*5.9E-02*	*3.4E-04*	*9.7E-08*	*7.9E-03*	*2.8E-05*	*8.9E-02*
		Mean	**1.6E-01**	**9.5E-03**	**8.6E-04**	**4.9E-02**	**3.1E-03**	**2.1E-01**
		95%	*2.9E-01*	*3.0E-02*	*3.9E-03*	*1.2E-01*	*1.1E-02*	*3.6E-01*
Metal Foil Shield Wrap Cable	3	Alpha	1.19	Incredible	Incredible	1.58	Incredible	1.61
		Beta	5.17			14.13		4.50
		5%	*1.7E-02*			*1.4E-02*		*4.3E-02*
		Mean	**1.9E-01**			**1.0E-01**		**2.6E-01**
		95%	*4.7E-01*			*2.4E-01*		*5.8E-01*
Armored Cable	4	Alpha	6.53	Incredible	Incredible	3.46	Incredible	7.18
		Beta	10.50			10.47		6.31
		5%	*2.0E-01*			*8.7E-02*		*3.1E-01*
		Mean	**3.8E-01**			**2.5E-01**		**5.3E-01**
		95%	*5.8E-01*			*4.5E-01*		*7.5E-01*

6
CONDITIONAL PROBABILITY OF SPURIOUS OPERATION DURATION FOR CONTROL CIRCUITS

Testing has shown that the duration of most hot short-induced spurious operations were typically finite in duration, and relatively short. As such, modeling the duration of hot short-induced spurious operations may enhance the reality of the fire PRA model. Based on the available data, this section presents the results on the estimated conditional probability of duration of hot short-induced spurious operation.

6.1 Test Data and CS-Model of Weibull Distribution

The TI team determined that a simplified model, presented by Proponent #3, was technically adequate to quantify the likelihood of the duration of spurious operation. This approach evaluated the various bins of duration data by using Kolmogorov-Smirnov (k-s) statistical tests and developed a single data-pool. The k-s test affords a distribution-independent comparison of two data sets and rejects the null hypothesis (i.e., the distributions are the same) depending on the number of data points in the data sets and the deviations between the sets. Table 6-1 lists the data bins assessed.

Table 6-1. Pooling of Test Data for Spurious Operation Duration

For AC Test Data	For DC Test Data
+ Grounded AC Hot Gas Layer Thermoset	+ Ungrounded DC Flame Thermoset
+ Grounded AC Hot Gas Layer Thermoplastic	+ Ungrounded DC Flame Thermoplastic
+ Ungrounded AC Hot Gas Layer Thermoset	+ Ungrounded DC Hot Gas Layer Thermoset
+ Ungrounded AC Hot Gas Layer Thermoplastic	+ Ungrounded DC Hot Gas Layer Thermoplastic
+ Grounded AC Plume Thermoset	+ Ungrounded DC Plume Thermoset
+ Grounded AC Plume Thermoplastic	+ Ungrounded DC Plume Thermoplastic
+ Ungrounded AC Plume Thermoset	
+ Ungrounded AC Plume Thermoplastic	
- Grounded AC Flame Thermoset	- Ungrounded DC Radiant Thermoset
- Grounded AC Flame Thermoplastic	- Ungrounded DC Radiant Thermoplastic
- Ungrounded AC Flame Thermoset	
- Ungrounded AC Flame Thermoplastic	

"+" represents data sets included in the pooled data set
"-" represents data sets not included in the pooled data set

The k-s tests showed that for the AC test data, all could be pooled except the flame exposure condition. The k-s tests of the DC data also revealed that all but the radiant thermal conditions could be combined. Further, a k-s test, conducted on the AC and the DC data pools confirmed that the two pools could be grouped into one. The PRA panel noted that the k-s test run to develop the pooled dataset removed approximately five (5) spurious operation durations longer than eight (8) minutes. Additionally, several very short duration (<1 minute) test data points were also removed. The proponent experts were informed of the removed data, especially the long duration data points. These data points were used to inform the proponent experts such that their duration floor estimates were informed from the test data and didn't rely solely on the pooled k-s dataset. In the list of bins above, the "+" symbol represents data bins that are in the pooled data set, while the "-" symbol represents those data bins that were <u>NOT</u> included in the pooled data set. A Weibull distribution was then fit to the pooled data set (Figure 6-1).

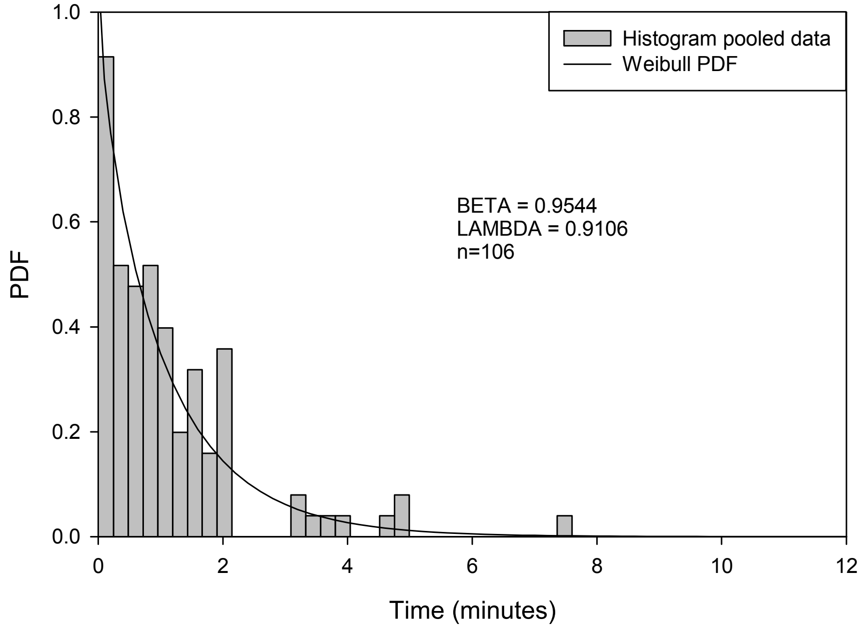


Figure 6-1. Historgram and Weibull Fit to Data

Since the original model developed by Proponent #3 was based on both test data and expert judgment, the TI team asked other proponents to provide input to reflect their judgment in calibrating this model and to offer estimates of uncertainty. To assure that the proponent input was evaluated consistently, Martin Stutzke, an NRC Senior PRA Technology Specialist, developed a "CS-Model" of the Weibull distribution that consolidates the input of individual proponents into distribution curves for the AC and DC circuits. Details of the development of this CS-model are documented in Appendix Section C.3.

6.2 Proponent Input and Results of Assessing Duration of Spurious Operation

To develop the spurious operation duration probability estimates, the proponents were asked to estimate 'c' and 's' values of the CS-model as well as quantiles representing the probability distributions of the floors for the AC and DC duration curves.

The c-value shifts the distribution to the right and intrinsically widens uncertainty, while accounting for the effect of the influencing parameters identified by the PIRT panel. The average of the experts' input resulted in a 'c-value' of 1.4[1]. The s-value, on the other hand, directly widens the uncertainty. The inputs of the PRA panel experts set the s-value equal to 1.9[2]. Applying these values in the CS-Model generated the modified Weibull distribution plot.

For the floor values, the experts were asked to provide the central tendency (median) and uncertainty estimates (quantiles). Using the LOP method, the results from the expert elicitation on the distribution curve floors for AC and DC control circuits are shown in Figures 6-2 and 6-3, respectively. The numerical values characterizing the floor value community distributions are listed in Table 6-2.

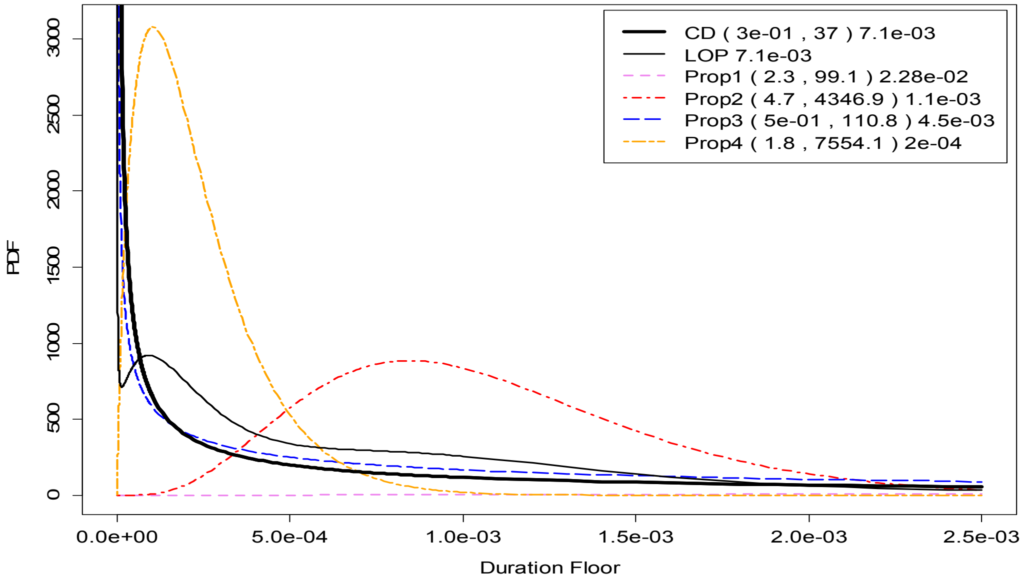


Figure 6-2. Community Distribution for AC Duration Floor

---

[1] For c-value, proponents recommended the following values: Proponent 1 – 1.2; Proponent 2 – 1.0; Proponent 3 – 2.2 for DC (and 2.5 for AC); Proponent 4 – 1.2.

[2] For s-value, proponents recommended the following values: Proponent 1 – 2.0; Proponent 2 – 2.0; Proponent 3 – 2.0 for DC (and 2.5 for AC); Proponent 4 – 1.5.

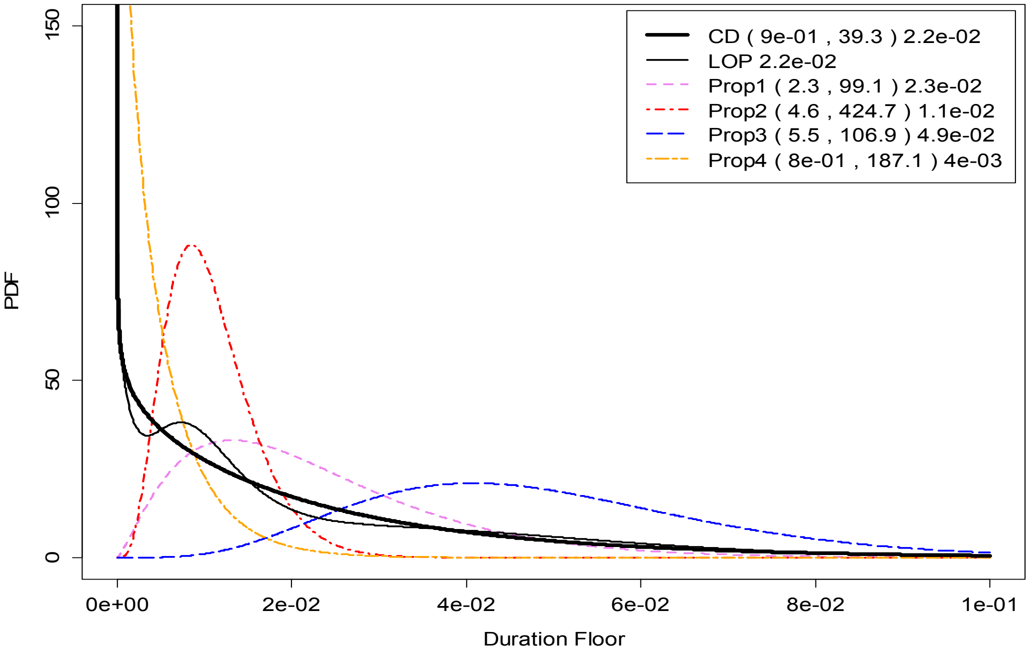


Figure 6-3. Community Distribution for DC Duration Floor

Table 6-2. Duration Conditional Probability Floors with Uncertainties

Beta Distribution Parameter	AC Control Circuits	DC Control Circuits
Alpha	0.27	0.88
Beta	36.99	39.28
5th	*2.4E-07*	*8.2E-04*
Mean	**7.1E-03**	**2.2E-02**
95th	*3.4E-02*	*6.8E-02*

This modified Weibull distribution plot and the floor probability values, along with their uncertainty bounds, are merged together to represent the final plots for the AC and DC control circuits. Thus, the two plots for these circuits represent one Weibull distribution with uncertainty bounds up to the time where the floor values (with uncertainty bounds) intersect the modified Weibull distribution plot. Beyond this intersection point (time in minutes), the floor probability values represent the likelihood of a spurious operation not clearing. Figure 6-4 for AC and Figure 6-5 for DC illustrate these duration plots for control circuits. Table 6-3 shows the tabulated values from the distribution curves at 1 minute intervals.

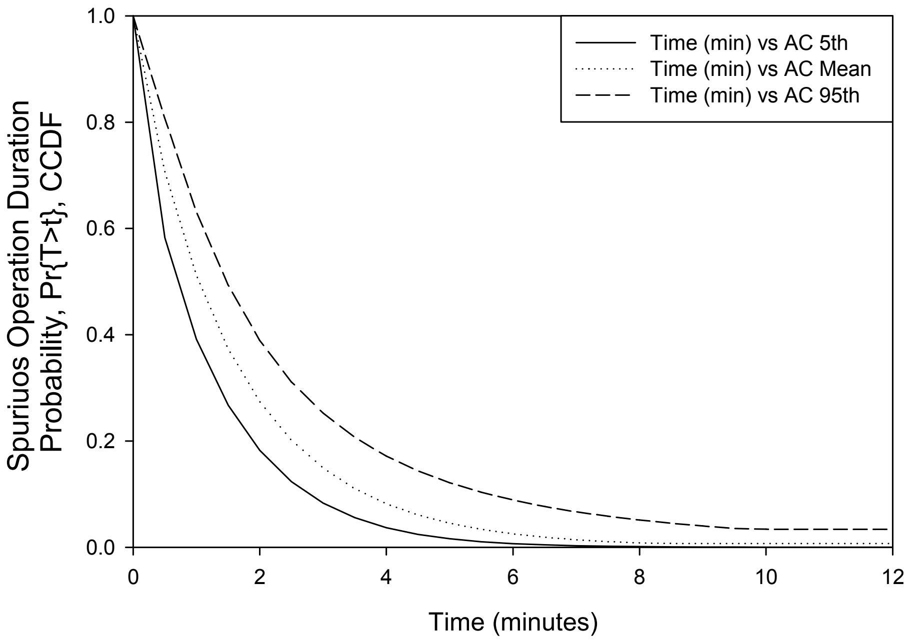


Figure 6-4. AC Control Circuit Spurious Operation Duration Conditional Probability Curve

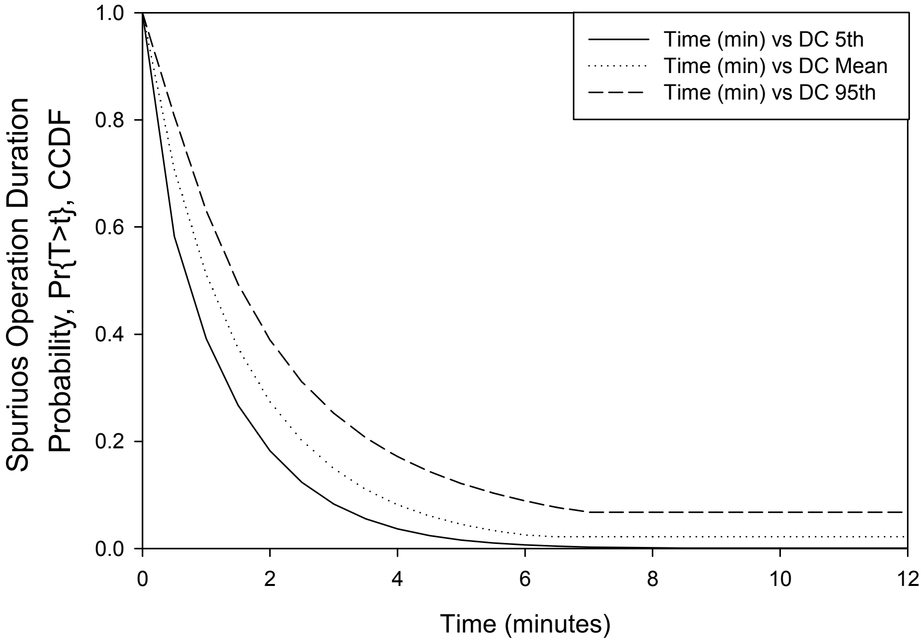


Figure 6-5. DC Control Circuit Spurious Operation Duration Conditional Probability Curve

Table 6-3. Tabulated Spurious Operation Duration Conditional Probability Values for AC and DC Control Circuits

AC Pr{T>t} CCDF			Time (minutes)	DC Pr{T>t} CCDF		
5th	Mean	95th		5th	Mean	95th
1.0	1.0	1.0	0	1.0	1.0	1.0
3.91E-01	5.12E-01	6.31E-01	1	3.91E-01	5.12E-01	6.31E-01
1.82E-01	2.74E-01	3.90E-01	2	1.82E-01	2.74E-01	3.90E-01
8.31E-02	1.49E-01	2.52E-01	3	8.31E-02	1.49E-01	2.52E-01
3.68E-02	8.17E-02	1.71E-01	4	3.68E-02	8.17E-02	1.71E-01
1.59E-02	4.51E-02	1.21E-01	5	1.59E-02	4.51E-02	1.21E-01
6.76E-03	2.51E-02	8.86E-02	6	6.76E-03	2.51E-02	8.86E-02
2.82E-03	1.40E-02	6.65E-02	7	2.82E-03	2.20E-02	6.80E-02
1.16E-03	7.85E-03	5.10E-02	8	1.16E-03	↓	↓
4.74E-04	7.10E-03	3.98E-02	9	8.20E-04	↓	↓
1.91E-04	↓	3.40E-02	10	↓	↓	↓
7.64E-05	↓	↓	11	↓	↓	↓
3.03E-05	↓	↓	12	↓	↓	↓
1.19E-05	↓	↓	13	↓	↓	↓
4.67E-06	↓	↓	14	↓	↓	↓
1.82E-06	↓	↓	15	↓	↓	↓
7.03E-07	↓	↓	16	↓	↓	↓
2.71E-07	↓	↓	17	↓	↓	↓
2.40E-07	↓	↓	18	↓	↓	↓
↓	↓	↓	19	↓	↓	↓
↓	↓	↓	20	↓	↓	↓
2.40E-07	7.10E-03	3.40E-02	>20	8.20E-04	2.20E-02	6.80E-02

The PPRP provided feedback on the development and use of this model throughout the SSHAC Workshops and discussions where these estimates were developed. As discussed in their report (Appendix F), the PPRP believes that the estimated duration curves for spurious operation may underestimate the uncertainty in the region of the curve where the Weibull models these likelihood estimates (i.e., pre-floor region). This is a result of the CS-Model using scalar values for ‘c’ and ‘s’ rather than distributions.

The PPRP point is important, however, two points need to be clarified. First, the ‘c’ and ‘s’ values are not meant to model any specific physical quantity. They are parameters that were used to adjust the shape of the mean Weibull distribution curve (‘c’ value) along with the 5th and 95th percentile uncertainty distributions (‘s’ value). In application of the model, the proponents were given plots with numerous ‘c’ value distributions to choose from which they believed best represents their beliefs. Likewise, once the average ‘c’ value was identified, another plot with numerous ‘s’ values was provided to the proponents to help them select the uncertainty bounds that best represents their knowledge. The second point is the understanding that a majority of the application of the spurious operation duration distribution will use the floor values. That is, the values that were based on proponent input and application of the LOP method to derive the floor community distributions for both AC and DC circuits.

7

GUIDANCE FOR USING CONDITIONAL PROBABILITY OF SPURIOUS OPERATION FOR CONTROL CIRCUITS[1]

Conducting a fire PRA for an NPP requires analyzing fire-induced circuit failures. One such failure involves the hot short-induced spurious operation of end devices in control circuits. One task of the fire PRA analysis includes a “Circuit Failure Mode Likelihood Analysis” (Task 10). Section 10 in Volume 2 of NUREG/CR-6850, EPRI 1011989, “Fire PRA Methodology for Nuclear Power Facilities,” (Ref. 14) offers such a method for analyzing this likelihood.

The method in NUREG/CR-6850 for analyzing the likelihood of the circuit failure mode offers two options (Option #1 and Option #2) for assigning estimates of the likelihood of hot short-induced spurious operation to be used in fire PRA. Option #1, “Failure Mode Probability Estimate Table,” is used for most circuit analyses scenarios. It consists of five look-up tables which contain likelihood estimates for several configurations. Option #2, “Computational Probability Estimates,” is an alternative method generally used when the look-up tables cannot be applied. It consists of formulas developed by applying a reverse-engineering technique to the best fit of the EPRI/NEI fire-test data (Ref. 9). The approach considers various circuit and cable parameters that could affect the likelihood of hot short-induced spurious operations due to fire damage in electrical cables.

The information in this report on the conditional probability estimates is based on a larger data base involving several test programs (including the EPRI/NEI testing). Therefore, the conditional probabilities herein supersede the values in NUREG/CR-6850 (Ref. 14) and in its Supplement 1 (Ref. 15). This section provides an overview of an approach for conducting a circuit failure mode likelihood analysis, a summary of pertinent information, and recommended guidance for using the conditional probabilities developed in this report. It should be noted that this guidance was developed outside of the SSHAC process, but received feedback from both the PRA and PIRT panel members. As documented earlier in this report, this guidance does not represent regulatory requirements.

7.1 Overview of Approach

This section offers guidance for applying the results of the conditional probabilities of spurious operations in single and double break control circuits summarized in Sections 4 and 5, as well as those of the duration of spurious operation given in Section 6. The guidance is similar to the approach in Section 10 of NUREG/CR-6850 (Ref. 14), with the stipulation that Step 2 (Select Analysis Approach) will use the methodology described herein. Additionally, new guidance is offered for applying the conditional probabilities of spurious operation duration to the fire PRA. NUREG/CR-6850, Supplement 1 (Ref. 15) currently addresses duration only for AC circuits based on a limited test data set.

---

[1] Methods and information included in this section was developed by the PRA panel members on a consensus basis, and therefore, should be construed as outside the scope of the SSHAC expert elicitation process.

The general approach for applying the results of this report to a circuit analysis includes the following steps detailed in Section 7.3:

1. Compile prerequisite information, including the results of "Detailed Circuit Failure Analysis," (Task 9 in NUREG/CR-6850) and the important cable and configuration attributes. If the duration of spurious operation is to be credited, the circuit analysis should determine the final component state once the cable conductors are grounded (other than the GFEHS that could be recovered) or the circuit fuse clears (Sections 7.3.1 and 7.3.2).

2. Analyze the likelihood of circuit failure from the tables in Sections 4 or 5 (Section 7.3.3).

3. In applying values for the duration of spurious operation, determine the time available, so that if the spurious operation is terminated, the system will successfully perform its safety function (Section 7.3.4).

4. Calculate the probability of duration of spurious operation (Section 7.3.4).

5. Apply the probabilities of circuit failure and duration to the fire PRA plant response model (Section 7.3.5).

6. Document the analyses of these probabilities in the fire PRA (Section 7.3.6).

7. Document the uncertainty in the analysis (Section 7.3.6).

Note that using conservative assumptions in applying each step can reduce the overall PRA effort: (1) For example, applying the probabilities of the duration of spurious operation may be limited to only scenarios involving significant spurious operation in the fire PRA. (2) It may be less effort to credit spurious operation duration/termination than undertake the detailed circuit analysis needed to apply circuit-failure likelihoods; therefore, an analyst may choose to use circuit failure probabilities of 1.0 as a starting point in the fire PRA (for selected circuits). Regardless of the analytical approach, a sufficient level of circuit analysis needs to be done such that there is confidence that the undesired spurious operation is caused by a hot short and that the ultimate grounding of the affected conductors will result in the component passively returning to the desired (pre-spurious) state. Recommendations presented in Section 7.3 should also be considered when developing a technically sound analytical approach. Any simplifications and conservatisms in the assumptions and/or analysis should be documented.

7.2 PRA Panel's Expert Elicitation Results

As covered in this Volume 2 of NUREG/CR-7150, the following recommendations of the PRA panel are applicable to Fire PRA. *The section numbers below refer to **Volume 2**.* This guidance is applicable to control circuits only.

- The tables in Sections 4 and 5 should replace the conditional probability tables for Option #1 in NUREG/CR-6850; these tables include two major circuit designs of control systems:

1. Single Break (or Contact) Control Circuits
    a. Base Case – SOV (Table 4-1)
    b. MOV (Table 4-3)
    c. Medium Voltage Circuit Breaker (Table 4-4)

2. Double Break (or Contact) Control Circuits
    a. Base Case – SOV (Tables 5-1 and 5-2)
    b. MOV (Tables 5-3 and 5-4)

- Option #2 and its technical basis in Appendix J of NUREG/CR-6850 (Ref. 14) should not be used since it does not offer an adequate method for quantifying the likelihood of hot short-induced spurious operation. It was based on a limited test data obtained from, and an engineering evaluation conducted on the results from the EPRI/NEI testing. Additionally, Option #2 was never validated to quantify the uncertainties associated with applying it. Considering the substantial additional data from the NRC, EPRI, and Duke Energy sponsored tests, the electrical expert PIRT results, and the level of refinement in the tables developed by the PRA panel that are as documented in this report, the panel does not endorse the continued use of Option #2 in NUREG/CR-6850 (Ref. 14).

- The plot of the probability of spurious operation duration in Figure 6-4 for AC control circuits (data listed in Table 6-3) should replace the plot of AC duration (Figure 16-1 and Table 16-1) for FAQ 08-0051 in Section 16 of Supplement 1 to NUREG/CR-6850 (Ref. 15). In addition, Figure 6-5 for DC control circuits (data listed in Table 6-3) now provides the plot for DC duration.

- Aggregate values are given for every case where all potential hot short-induced failure modes are applicable. Unlike the current method in NUREG/CR-6850, the new estimates of the PRA expert elicitations are explicit parametric distributions. The aggregate row in the probability tables represents the summation from using these parametric distributions for all applicable modes of hot short failure. Therefore, unless it is demonstrated that a cable under evaluation is only susceptible to a single failure mode, the aggregate values given herein should be used to represent the conditional probability of fire-induced spurious operation to an end device under evaluation.[2]

7.3 PRA Panel Recommended Guidance for Using the Conditional Probability Tables and Duration Plots

This section is a revision of NUREG/CR-6850, Section 10.5, “Procedure,” which analyzes the circuits located within a plant’s fire area or compartment. This procedure assesses the likelihood of specific cable-failure modes that could negate the functionality of components credited in a fire PRA. The resulting probability estimates are documented for various possible

---

[2] Ungrounded DC (or ungrounded distributed AC) control circuits are subject to three possible hot short failure modes. The Aggregate column provides the conditional probability when all three hot short modes are applicable. When two out of these three hot short modes are applicable; the combined conditional probability of the two hot short failure modes must use their sum.

hot short cable failure modes caused by fire damage. This procedure is applied to PRA scenarios where the configuration of interest reasonably conforms to, or is bounded by, the various circuit configurations included in this Volume 2.

The duration data in this report *does not apply* to shorts-to-ground (other than GFEHS failure mode)[3] or open circuits that de-energize a cable, triggering a component repositioning. These events are not considered recoverable by the short-to-ground clearing (there was no evidence in the testing to show this could occur). The application of spurious operation conditional probabilities or their durations should only be applied to circuit types covered in this report. In addition, neither the likelihood of hot short-induced spurious operation nor the duration probability results apply directly to instrument cables.

7.3.1 Assumptions

- Requisite cable and configuration attributes are available or can be determined as part of the analysis.

- The normally operating position or condition of equipment at the onset of the fire must be determined. Where a component's status is indeterminate or could change as a result of expected plant conditions, the analyst should assume the worst-case initial conditions, consistent with the detailed circuit analysis.

- Users of this procedure are knowledgeable and are experienced in designing circuits, analysis methods, and estimating probability.

7.3.2 Compile and Evaluate Prerequisite Information and Data

This step ensures that prerequisite information and data are available before beginning the analyses of the likelihood of circuit failure modes.

- Confirm that a detailed circuit failure analysis was completed and documented for the control circuit end device of interest (i.e., SOV, MOV, and Circuit Breaker).

- Confirm that analysis has covered or conducted additional circuit failure analysis on failure modes not covered in NUREG/CR-6850, but identified by the PIRT panel in Volume 1 of this report as being possible or implausible, such as GFEHS.

- Collect data on attributes of target cable and its configuration, including the following:

    - Single break or Double break control circuit design,
    - Cable's construction attributes (i.e., insulation material [TS or TP], robust metal shield wrap, armor),
    - Type of power source (i.e., AC or DC),
    - Circuit Grounding Condition (i.e., grounded or ungrounded),

---

[3] Shorts to ground that de-energize a cable (without any possibility of a recovery) are different from that for GFEHS failure mode, which provide a surrogate path to energize conductors for a short duration in certain circuit configurations.

- Applicable fire-induced circuit hot short failure modes (i.e., Intra-cable, Inter-cable, Ground fault equivalent), and,
- Identify whether multiple hot shorts (i.e., a combination of concurrent hot short failure modes) are required.

7.3.3 Perform Circuit Failure Mode Likelihood Analysis

This step conducts the likelihood analysis to decide which table in Sections 4 and 5 of this Volume 2 is best suited for conducting the evaluation, and then determines the appropriate estimate to use for the particular scenario. The approach has the following steps:

Step 1: Determine the appropriate table to use based on

i. Circuit Design (Single Break or Double Break)
ii. Circuit Type (SOV, MOV, Circuit Breaker)

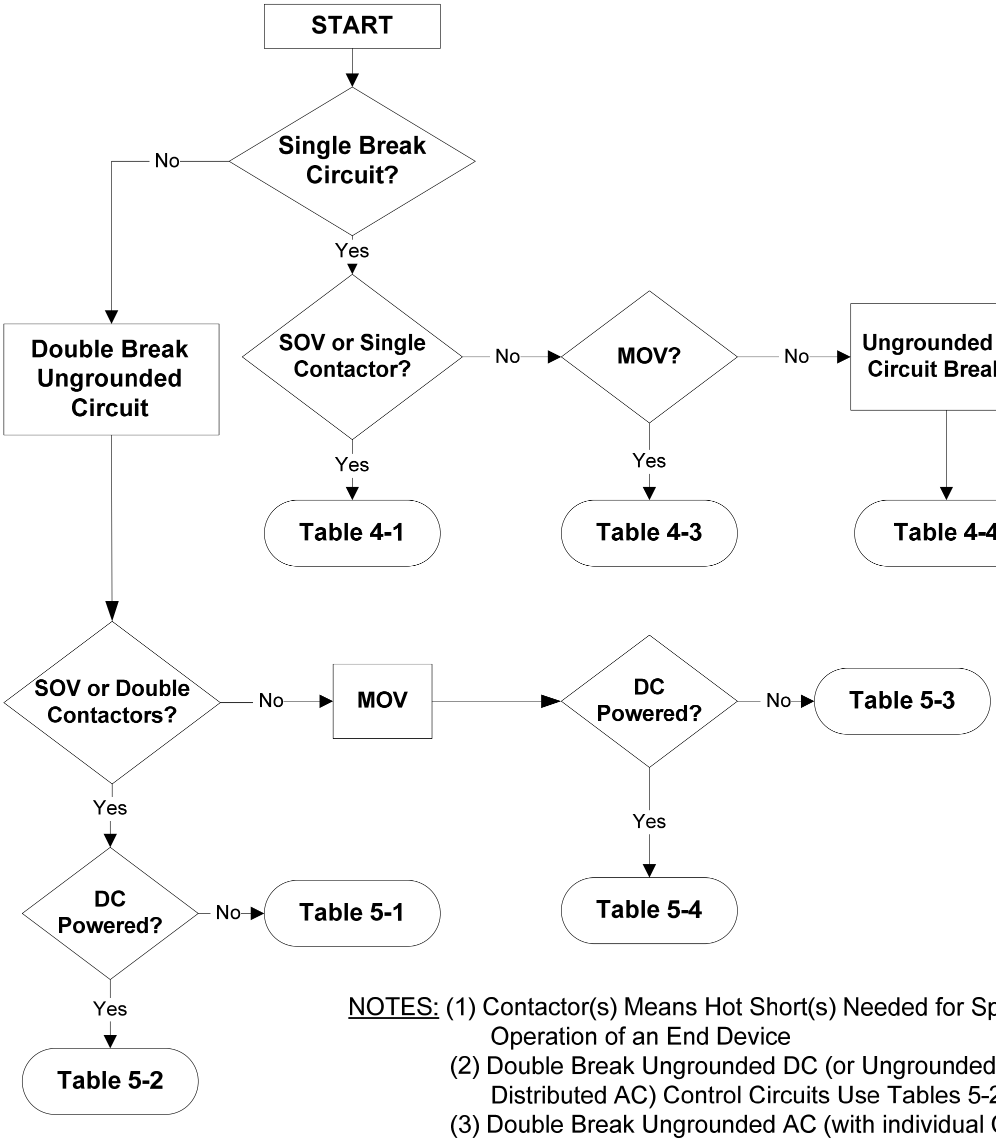
Step 2: Determine the proper value to use from the table selected in Step 1 based on

i. Cable Insulation Type (Thermoset or Thermoplastic)
ii. Special cable construction attributes, if any (e.g., Metal foil Shield Wrap or Armored)
iii. Power Supply and Grounding Configuration
iv. Hot Short Failure Mode(s) of Concern
v. Appropriate Estimate of Conditional Probability Estimate

Step 1 identifies the appropriate table to use from Sections 4 and 5 of this report. All values for circuits with a single break design appear those in tables in Section 4, while all values for double break design appear in Section 5. Figure 7-1 is a flowchart for identifying them.

Having identified the table, the analyst can use the information from Steps 2.i through 2.v to determine the cell containing the needed conditional probabilities for the particular scenario. Steps 2.i and 2.ii identify the applicable row in the table. *If the cable has armor, or a robust metal-foil shield wrap, the corresponding row should be selected regardless of insulation type (i.e., TS or TP) of its conductors*. For example, if a 7/C 12 AWG XLPE insulated/CSPE jacketed cable with square lock steel armor is being evaluated, the “Armored Cable” row should be used regardless of the fact that it is a Thermoset-insulated cable. Next, Step 2.iii and Step 2.iv support the identification of the appropriate column. Step 2.iii “Power supply and Grounding configuration” narrows the appropriate columns down to a subset of columns. Once the subset of the column is identified, the exact one to use can be selected. In most cases, all failure modes are applicable and the analyst selects the “aggregate” column. However, occasionally, only one or two failure modes are applicable. If so, the analyst should identify the failure modes and justify not using the aggregate column. Once the appropriate row and column are identified, in Step 2.v the appropriate values (typically the mean or, if performing a distributional analysis, the corresponding beta distribution parameters) in the corresponding cell can be used in estimating the conditional hot short-induced spurious operation probability.

Each of the conditional probabilities in Sections 4 and 5 above also have uncertainty quantities. These quantities should be used when performing a fire PRA uncertainty analysis.



NOTES: (1) Contactor(s) Means Hot Short(s) Needed for Spurious Operation of an End Device
(2) Double Break Ungrounded DC (or Ungrounded Distributed AC) Control Circuits Use Tables 5-2 and 5-4
(3) Double Break Ungrounded AC (with individual CPTs) Control Circuits Use Tables 5-1 and 5-3

Figure 7-1. Flowchart Showing Process Used to Determine Appropriate Spurious Operation Table

7.3.3.1 Specific Guidance on Use of Spurious Operation Tables

The PRA panel also made the following recommendations when using the results of Section 4 and 5.

1. The “Aggregate” estimate should be used unless a detailed circuit analysis is completed to justify the use of a specific hot short failure mode for the target conductor of interest.

That is, justification should be provided for excluding a failure mode from the quantification analysis.

2. For cables constructed with a robust metal foil shield wrap cables or armor cable; the respective rows labeled “Metal Foil Shield Wrap” or “Armored Cable” of the applicable table (Tables 4-1, 4-3, 5-1 or 5-4) should be used regardless of the cables insulation material type. For example, an armored TS insulated cable should use the applicable estimate documented in row 4 “Armored Cable” rather than the estimate documented in Row 1 “Thermoset-Insulated Conductor Cable.” This is based on PIRT panel’s finding that the effect of a ground plane outweighs that of the cable’s conductor insulating material on the fire-induced hot short failure modes in control circuits.

3. For medium voltage circuit breaker case, the estimate documented in Table 4-4 represents the aggregate as this estimate was developed assuming all failure modes (i.e., intra-cable hot short, inter-cable hot short, and GFEHS). Since individual failure modes were not developed for this case, the PRA panel recommends that for inter-cable hot short and GFEHS failure modes the corresponding SOV values (Table 4-1) should be used to quantify the circuit breaker conditional spurious operation probability for the respective failure mode. The PRA panel also recommends using the aggregate value in Table 4-4 for the medium voltage circuit breaker intra-cable failure mode.

7.3.4 Spurious Operation Duration Analysis

With a few exceptions, primarily involving DC circuits where the hot shorts never clear, testing has shown that fire-induced spurious operations typically do not persist for long times. Thus, the analysis of the length of spurious operation attempts to quantify the likelihood that a hot short-induced spurious operation will last for more than a specified amount of time (necessary for PRA-component failure). The specific amount of time depends on the system and its components and typically requires some type of analysis (e.g., thermal hydraulic) to determine the time available for a hot short-induced spurious operation to clear before failure of the safety function occurs.

As a caution to the analyst, using the probability of duration of a spurious operation in a fire PRA can be a time- and resource-consuming process, as this involves the performance of engineering calculations to determine the length of time the spurious operation must persist to ensure failure of a safety function. The analyst should determine if such an analysis is suitable for that particular scenario. The application of duration probability to a spurious operation typically is not required to complete a circuit failure likelihood analysis.

In many instances, if a flow diversion or other system response that causes equipment functional failure is terminated (spurious operation clears) within a predetermined time, there will be minimal or no adverse consequences from it. In the case of valves, one of the most common issues is the spurious opening of a pressurizer power-operated relief valve (PORV) in a pressurized water reactor (PWR) plant, which results in a LOCA. If the PORV LOCA is terminated within a specified time, core damage is avoided altogether.

In general, MOVs fail as-is when the hot short-induced spurious operation clears, while many of the SOVs/AOVs return to a fail-safe position once this spurious operation clears. Thus, only circuits that return to their desired position upon clearing of a spurious operation should be analyzed and credited for duration. Valves that transfer to the undesired position and remain so should not receive any credit for the duration time, which only is relevant if they transfer, not for how long (since they do not “recover”). This should be confirmed before applying the recovery event for hot short-induced spurious operation duration. Therefore, application of a probability that the hot short causing the spurious event will “self-clear” within the appropriate time window can result in a lower assessment of the frequency of core damage. In this report the terms “recovery event” and “self-clear” are synonymous with each other and represent the occurrence of a hot short-induced spurious operation terminating due to a protective device (fuse) clearing as a result of fire damage.

Duration curves have been provided in Section 6 that assesses the likelihood of a spurious event clearing. To use these curves, a defendable success criterion is needed, i.e., how much time is available to return the component or circuit to its fail-safe position before the adverse effects are manifested.

Analyzing the probability of safety system functional failure due to a fire-induced spurious operation entails three steps, namely;

1. Determine the time available (for the component or system under evaluation),
2. Analyze the spurious operation duration, and,
3. Document that analysis.

The conditional probability of failure can be illustrated in the following formula. Were a hot short induced spurious operation has occurred; the probability of failure is equal to the probability of a spurious operation duration lasting longer than the time available to recover the safety system.

$$P\{\text{failure}\} = P\{\text{spurious operation duration} > \text{time available}\}$$

7.3.4.1 Determine the Time Available

The time available is defined as the time between the calculated occurrence of fire damage and the time to recover the safety function. Thus, the time available is based on the time between fire damage occurring and the minimum time the spurious operation needs to clear to recover the function. This may be the time when core damage occurs; the time for an operator to perform a recovery action; the time when a safety function is fully recovered; the time to fail a safe shutdown function; or some other defined state. Clearing of a hot short-induced spurious operation involves removal of the hot short, which typically involved a fuse clear in the fire-damaged circuit. Regardless of the state, the time available must be determined.

The success criteria for determining the available time may need to include a thermal-hydraulic analysis similar to that performed for determining other success criteria in a fire PRA accident-sequence. The documentation of this analysis should be equivalent to that of the previously analyzed success criteria. For multiple spurious operations (MSOs), the success criteria should also consider if one MSO clearing will recover safe shutdown function, or if more than one (or all) SOs in the MSO scenario need to be cleared. For example, with most main steam-isolation valves (MSIVs) an MSO (2 spurious operations) could result in the MSIV failing to close. Generally clearing either of the spurious operations (hot shorts) will result in the MSIV closing and isolation of the steam line (assuming fail-closed MSIVs).

Regardless of the success or failure state used to determine the time available, an “adequate analysis” must be performed and documented to identify the time available.

7.3.4.2 Perform the Spurious Operation Duration Analysis

The probability that the spurious operation will self-clear is calculated by using the time available calculated in Section 7.3.4.1 to derive a probability from the duration curves in Section 6. This probability is referred to in the section below as “conditional duration probability.” The estimated duration probability must not be lower than the recommended minimum probability. In determining the conditional duration probability for self-clearing the spurious operation (or MSOs), the following should be applied:

1. When a single circuit failure or hot short can result in single- or multiple-spurious operations (e.g., multiple components operating as a result of a single hot short), then the dependencies should be modeled in the PRA. Typically, this involves applying the same basic event name both to the spurious operation and the conditional duration probability.

2. For MSOs, since only a limited number of tests were performed and analyzed for this report, with a limited analysis of dependencies between spurious operation events or duration; the dependency between the duration of events is not fully known and is highly uncertain. Consequently, limited credit is recommended for the MSO conditional duration probabilities, based on the following rules[4]:

    a. If the MSOs result from damage to the same cable, only one conditional duration probability is recommended [i.e., the second spurious operation is assumed to not self-clear (non-clearance probability is set to be 1.0)].

        - Analysis of the circuits with multiple targets in the same cable (e.g., two MOV coils) shows that in a majority of cases, both targets were energized simultaneously. Additionally, the targets were energized and de-energized at the same or similar times in most cases. As a result, a conservative approach (setting the second conditional duration non-clearance probability to 1.0) is recommended.

        - The above is considered conservative for trunk cables with significantly more than the 12 conductors present in the cables on which the tests were based. It is likely that for trunk cables with more than 12 conductors (e.g., 37 conductors), the durations may be somewhat independent.

    b. For MSOs occurring due to fire in separate cables, (for both AC and DC circuits) the application of conditional duration probabilities for MSO’s should be limited to a joint minimum value of 1.0 E-05. This limitation on the application of conditional duration probabilities is being recommended due to several scenario dependent variables that

---

[4] The rules described here were developed by the PRA panel outside of any formal SSHAC Workshop. Therefore, development of these rules does not have the same rigor as the material documented in the rest of the report.

may influence dependencies among MSO's with regard to spurious operation duration.

- Given all of the views expressed by the proponents on several conference calls, the TI team could not reach a consensus opinion on a method to quantitatively bound these dependencies. Therefore, Item 2.b represents a compromise between the feedback received from the proponents and the views expressed among the TI team members. However, the TI team did agree on the minimum value of 1.0 E-05 as applied to duration probabilities for MSO scenarios. One TI team member's views which differed from the approach outlined above is described below.

> "The Expert Elicitation focused on single SOs in estimating both occurrence and duration exceedance probabilities. At least one proponent considered the potential dependence among the duration exceedance probabilities as mentioned in Appendix H, and concluded some degree of dependence existed. To accommodate this, the floor of 1E-5 on joint duration exceedance probabilities for MSOs has been recommended, with which I agree. Not really examined was the potential for similar dependence among the occurrence probabilities themselves, even if not as evident to the PIRT Panel or the proponents. To accommodate this possibility as well, I recommended the imposition of a floor on BOTH the joint occurrence AND duration exceedance probabilities, suggesting a numerical value of 1E-8 as discussed in Appendix H, but willing to consider lower values. No other member of the TI team was comfortable with this, hence my differing opinion."

Additional technical discussion on this TI team member's views and recommendations are documented in Section H.1 of Appendix H. The appendix also includes the technical views discussed by the proponents on this subject area.

3. For double break failures (e.g., the two hot shorts required to engender a single spurious operation), the above rules also apply. If the spurious operation requires two separate cable failures, then the application of two conditional duration probability values is acceptable based on item 2 discussed above. However, if a single cable is involved, only a single conditional duration probability is recommended.

The above guidance is recommended for spurious operation duration only, and is not applicable to the spurious operation conditional probabilities, which may be treated as independent.

As noted in Section 6, the conditional probabilities of duration are not separated for intra-cable, inter-cable, or aggregate spurious operation events. Therefore, regardless of the cable failure that occurs, the conditional duration probabilities are applicable to any spurious operation caused by hot short events. The conditional duration probability values are not applicable to spurious operations resulting from shorts either to ground (other than GFEHS failure mode) or to open circuits.

The resulting spurious operation duration probability values applied to the fire PRA should also include the estimated uncertainty bounds given in Section 6.

7.3.4.3 Document the Spurious Operation Duration Analysis

Documentation of the duration analysis should include the supporting documentation for the following three areas:

1. The safe-shutdown function is restored, given the spurious operation clears.
2. The timing analysis is described in Section 7.3.4.1.
3. The duration probability analysis is described in Section 7.3.4.2.

Documentation for restoring the safe-shutdown function should consider the circuit-specific impact on the component, as well as the circuit-specific impact for clearing of each hot short.

For example, even for an SOV that returns to its fail-safe position, the spurious operation of an auxiliary- or actuation-circuit may result in a seal-in of the valve. When the hot short on the auxiliary circuit clears, the valve may remain as-is. However, clearing of a hot short on the main control switch circuit most likely would result in the SOV returning to its fail-safe position; since power would be removed from the seal-in circuit when the circuit clears. This example demonstrates that, when the component returns to a fail-safe position (restoring safe shutdown function); not all circuits, when cleared, result in the recovery of the component and function.

7.3.5 Apply the Circuit Failure Probabilities and Duration Probabilities

Application of the circuit failure probabilities and duration recovery events would depend on the method used for quantifying the fire PRA model. In general, there are two approaches that are possible. A common approach is the use of a database substitution method, where the spurious operation probability is substituted for the random failure event such as “valve fails to remain closed” or similar. This substitution process may or may not result in a new name for the existing basic event (in some fire PRAs, the event is renamed with a “SO” at the end or similar). The second approach is to add the spurious operation event in the system fault trees prior to the fire PRA solution process. For these spurious operation events, the modeling or solution process must ensure the spurious operation event is applied only to fires where the control circuit is damaged by the fire.

In either approach, the probability calculated in Section 7.3.4.2 above is used as the best estimate probability for either the substituted event or event added to the system fault tree.

Similarly, adding credit for the limited duration for the spurious operation can be performed by either modifying the spurious operation probability above, or through use of a separate conditional duration probability value to the model. Addition of a separate event can be performed through the fire PRA recovery file, or directly into the fire PRA fault trees.

Application of the duration recovery event should be applied to the model considering the rules discussed in Section 7.3.4 above (e.g., multiple events from the same cable, and limiting the application of recoveries to a minimum floor value of 1.0 E-05). An example fault tree modeling spurious operation of SRVs in a plant PRA is shown Figure 7-2.

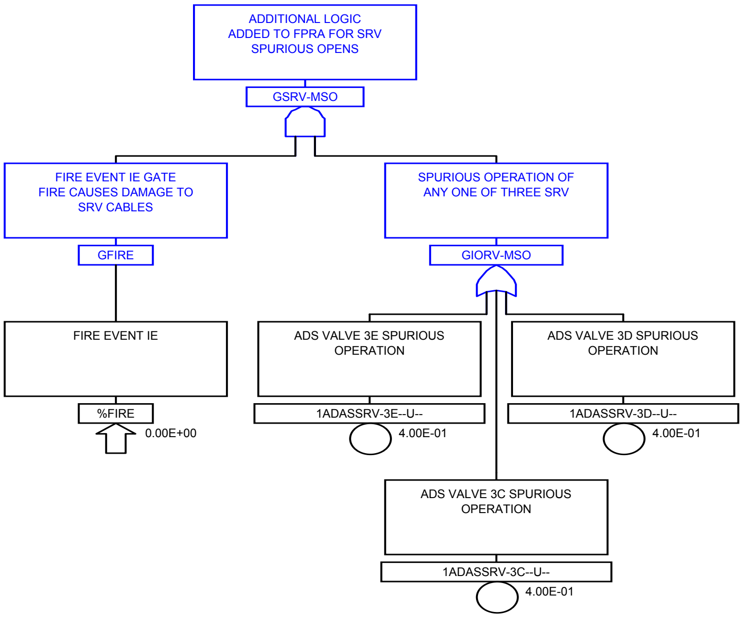


Figure 7-2. Fault-Tree Modeling of Spurious Operation of SRVs – Example 1

Assuming that each SRV in the above example is spuriously operated by fire damage of separate cables, the conditional duration probability event can be applied to each of the SRV spurious operation basic events in the model. This is shown in Figure 7-3.

Note in the above example that if all of the three SRVs were involved in an MSO scenario (e.g., gate GIORV-MSO was an AND gate), then the combined duration probabilities need to be evaluated to ensure it doesn't fall below the floor value of 1.0 E-05. In the modified case above where all three SRVs were to be involved in an MSO scenario (2.2E-02)^3 = 1.06E-05 is greater than 1.0 E-05 and thus no limitation on the duration recovery credit is needed for this example.

In the fire PRA, the concept of conservation of probability can be applied. Specifically, if a single cable can cause a component to have competing failure modes, only one can occur in a given scenario. If the probability of a valve spuriously opening is 0.4, then the probability that the valve fails to open would be the complement or 1-0.4 = 0.6.

Another example of a conservation of probability would involve multiple PORV or safety relief valve (SRV) openings. Assuming two PORVs for a given plant, the probability of two PORVs spuriously opening would be the probability of spurious operation, P (SO), squared. For a single PORV opening, however, the probability of one and only one specific PORV opening out of two PORVs is then equal to P(SO) * [1-P(SO)].

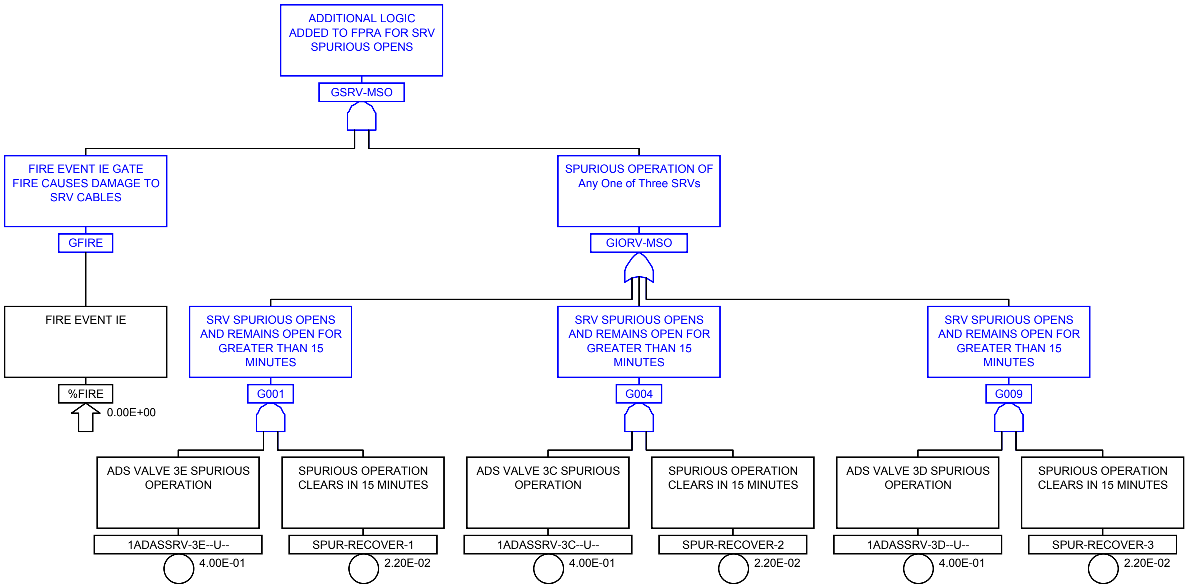


Figure 7-3. Fault-Tree Modeling of Spurious Operation of SRVs – Example 2

7.3.6 Document the Analysis and Uncertainty

The analysis of circuit failure and its duration should be performed in accordance with the fire PRA plan similar to that discussed in NUREG/CR-6850, Section 10.5.4. During this process, the uncertainty values also are developed, and should be documented as an integral part of the analysis. The standard State-of-Knowledge-Correlation (SOKC) employed when the underlying failure data are based on common data sets needs to be evaluated and any increase in the mean value relative to the point or best estimate reported (along with the uncertainty range).

Documentation should also include a discussion on the assumptions used in the analysis as well as the sources of uncertainty introduced after exploring circuit failure and duration.

7.4 PRA Panel Recommendations on Other Cable Configurations

From the results detailed in Volume 1 and discussions during the PRA expert elicitation workshops, several cable configurations are not covered explicitly in the information presented above. To support fire PRA application and provide the current state of knowledge on these specific cable configurations, the PRA panel makes the following recommendations for panel wiring, trunk cables, and instrumentation cable. These recommendations are made based on a consensus of the PRA panel and not by the use of the SSHAC process.

Panel Wiring

There are no test data for evaluating the likelihood of hot short-induced spurious operations for panel wiring. A hot short in the panel wiring’s conductor bundles within a cabinet could behave similarly to any of the failure modes of an electrical cable (i.e., intra-cable, inter-cable, or

GFEHS) depending upon the proximity of the conductors to the fire and the tightness of their bundles. The conditional probability of hot short-induced spurious operation most likely is affected by the configuration and tightness of the conductor bundles, along with the proximity of source and target cables. Considering the lack of applicable test data and the potential risk importance of panel wiring, the PRA panel recommends using **aggregate** values in the tables in Sections 4 and 5.

Trunk Cables

Duke Energy conducted a few tests using armored trunk cables. Because of the many conductors in a trunk cable, the PIRT panel noted that the greater availability of target and source conductor interaction could affect the spurious operation above that seen in Duke Energy's tests. In addition, each trunk cable contains multiple circuits (Duke Energy had four circuits in a 37/C trunk cable) and the analysis should treat each circuit independently. While this may be plausible, there is a large uncertainty due to the limited test data and the applicability to armored trunk cables. Because of this dearth of data, the PRA panel recommends using the **aggregate** values to quantify trunk cable conditional spurious operation estimates. Per the documentation found in Volume 1, trunk cables are commonly classified as cables containing greater than 12 conductors.

Instrument Cables

These low voltage circuits typically comprise instrument-signal cables for monitoring, protection systems, or control valve circuits. Shielded twisted-pair signal cables commonly are used for these applications. The spurious operation of instrument circuits can result in a circuit-fault mode wherein the circuit's instruments may give false indications or readings without initiating an operational mode or a movement of the indicating light or process equipment. We also note that the probability results for control circuits in this Volume 2 are based on the PIRT panel's definition of circuit-fault mode. Thus, 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. Therefore, the PRA panel concluded that the **spurious operation conditional probability tables provided in Sections 4 and 5 and spurious operation duration probability in Section 6 should not be used for instrument circuits**. Based on the current state of knowledge, the panel recommends that the analyses assume that the instrument cable fails in the worse-case state for the individual scenario involved, and assigns a 1.0 or 0 depending on state (Task 9 of NUREG/CR-6850).

8
SUMMARY AND CONCLUSIONS

The objective of this expert elicitation was to develop best estimates for the conditional probability occurrence of hot short-induced spurious operation phenomena in various control circuit configurations used in nuclear power plants. The durations of those phenomena where the length of its persistence could affect the circuit function of the component or device also was considered. These phenomena include fire-induced intra-cable hot short, inter-cable hot short and GFEHS failure modes of cables and potentially can cause spurious operation in various end devices (e.g., SOV, MOV, and circuit breaker). The spurious operation here is defined as 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.

To achieve this objective, the PRA panel used an enhanced Level 2 expert elicitation process defined by the NRC's SSHAC (Ref. 21). Its primary reasons were to minimize, if not eliminate, the technical and procedural biases that might have evolved out of the elicitation process and to preserve, as much as technically possible, each proponent's recommended methods and estimated values while developing the final intended to represent a larger technical community. Accordingly, the objective of this project was to generate a representation of the informed scientific community's view of each particular probability of occurrence and duration of spurious operation conditional on fire damage.

Unlike the current method in Section 10.5.3.1, Option 1, item 3 of the NUREG/CR-6850 (Ref. 14), the probability estimates here are parametric distributions (beta distributions). Thus, where more than one fire-induced hot short failure mode is applicable, we used the combination of the probability distributions for each applicable failure mode. The aggregate columns in the conditional probability result tables in Sections 4 and 5, and Tables 8-1 and 8-2 represent this calculation for all applicable hot short failure modes under the given power supply-grounding configuration.

The control circuit cases for hot short-induced spurious operation evaluated by the PRA panel were categorized in Volume 1 using the following five (5) circuit variables:

1. Circuit Configurations – Single Break, Double Break
2. Circuit Type Cases – SOV, MOV, Medium Voltage Circuit Breaker
3. Circuit Grounding/Power Supply Types – Grounded AC, Ungrounded AC (with Individual CPTs), Ungrounded DC (or Ungrounded Distributed AC)
4. Target Cable Constructions – TS-insulated Conductor Cable, TP-insulated Conductor Cable, Metal Foil Shield Wrap Cable, Armored Cable
5. Conductor Failure Modes – Intra-cable hot short, Inter-cable hot short, GFEHS

These five variables resulted in developing spurious operation conditional probability tables for the following two control circuit configurations, namely;

1. Single Break (or Contact) Control Circuits
    a. Base Case - SOV

    b. MOV
    c. Medium Voltage Circuit Breaker

2. Double Break (or Contact) Control Circuits (for ungrounded circuits)
    a. Base Case - SOV
    b. MOV

The evaluation of conditional probability of the duration hot short-induced spurious operation associated with these control circuits included two likelihood plots; one for AC power supply, and the other for DC.

With the fire-induced hot short failure modes and an understanding of the predominant cable-circuit configurations and phenomena that could cause spurious operation of these above end devices, the proponent experts were asked to:

1. Estimate the conditional probabilities of hot short-induced spurious operations for specific control circuits due to fire damage to electrical cables, and,

2. Estimate the likelihood of various durations of hot short-induced spurious operations due to fire damage to electrical cables.

The NRC staff developed a roll-up table containing fire test data from EPRI/NEI (Ref. 9), NRC's CAROLFIRE (Ref. 11) and DESIREE-Fire (Ref. 12) test programs (Appendix D). Also, the Duke Energy testing on armor cables (Proprietary) was available to proponents. They used these test data from the NRC's roll-up table or directly from the source documents published by EPRI, NRC, and Duke Energy. Typically, they did not base their final estimates solely on the roll-up table values, but instead used this information to support their final recommendations. In some cases, the proponents started with these table values and adjusted them accordingly, while, in other cases, a proponent only used the information in the roll-up table to check their final estimates.

The TI team assessed the proponents' inputs and developed an integrating process that was used to calculate the conditional probability distribution for all single break and double break cases. In addition to training the experts in the PRA panel, this entailed the following calculation steps:

1. Receiving Input from Proponents
2. Fitting and Feedback from Proponents
3. Consolidating Input from Proponents
4. Deriving a Parametric Community Distribution
5. Combining Individual Community Distributions

The steps generally were carried out in the order listed. However, in practice, two main reasons made this an iterative process:

1. The SSHAC process encourages interactions between the resource experts, proponent experts, the TI team, and the PPRP during and between the workshops; and sometimes the outcomes thereof required revising certain steps.

2. The many sub-cases, along with the complexity and number of issues addressed

required refining some of the steps, or modifying the approach to resolve challenges that initially were not evident.

Conditional Probabilities of Spurious Operation

Single Break Control Circuits

Table 8-1 summarizes “mean conditional probabilities” of spurious operation for single break control circuits of SOV, MOV and circuit breaker end devices. *A complete description of these conditional probability distributions is included in Section 4 of this report.* As shown in the table, there are 34 sub-cases each for the SOV and MOV control circuits. Only one sub-case (representing both TS and TP cable) is analyzed for the circuit breaker based on the DESIREE-Fire test data for ungrounded DC control circuit for medium voltage circuit breaker. The PRA panel recommends that for the intra-cable hot short failure mode the aggregate value for the circuit breaker should apply. However, for inter-cable hot short and GFEHS failure modes one should use the corresponding SOV values.

Table 8-1. Summary of Mean Conditional Probability of Spurious Operation For Single Break Control Circuits

Power Supply →			Grounded AC			Ungrounded AC (w/ Individual CPTs)			Ungrounded DC (or Ungrounded Distributed AC)			
Target Cable Configuration		Device Type	Conductor Hot Short Failure Mode									
			Intra-Cable 1	Inter-Cable 2	Aggregate 3	Intra-Cable 4	Inter-Cable 5	Aggregate 6	Intra-Cable 7	Inter-Cable 8	Ground Fault Equivalent 9	Aggregate 10
Thermoset-Insulated Conductor Cable	1	SOV	0.42	0.01	0.43	0.64	9.7E-04	0.64	0.46	6.3E-03	0.17	0.56
		MOV	0.27	8.8E-03	0.28	0.38	8.5E-04	0.39	0.31	5.6E-03	0.11	0.40
		Circuit Breaker							0.40	6.3E-03	0.17	0.40
Thermoplastic-Insulated Conductor Cable	2	SOV	0.42	0.025	0.44	0.64	0.015	0.64	0.46	0.02	0.15	0.55
		MOV	0.27	0.022	0.29	0.38	0.013	0.39	0.31	0.018	0.10	0.40
		Circuit Breaker							0.40	0.02	0.15	0.40
Metal Foil Shield Wrap Cable	3	SOV	0.24	Incredible◊	0.24	0.54	Incredible◊	0.54	0.48	Incredible◊	0.30	0.63
		MOV	0.16		0.16	0.37		0.37	0.31		0.22	0.46
Armored Cable	4	SOV	0.047	Incredible◊	0.047	0.45	Incredible◊	0.45	0.73	Incredible◊	0.48	0.86
		MOV	0.034		0.034	0.27		0.27	0.45		0.29	0.61

◊ “Incredible” represents a sub-case where no numerical estimates were developed because it is believed that the event will not occur.

In addition, the conditional probability values for metal foil shield wrap and armored cables should be used regardless of their conductor insulating material type (i.e., TS or TP).

Double Break Control Circuits

Table 8-2 summarizes the “mean conditional probability” of spurious operation for double break control circuits for SOV and MOV end devices. This table is applicable to control circuits powered from an ungrounded AC (with individual CPTs) and ungrounded DC (or ungrounded distributed AC). *A complete description of these conditional probability distributions is included in Section 5 of this report.* There are 13 sub-cases each for SOV and MOV circuits for ungrounded AC (with individual CPTs) and 16 sub-cases each for ungrounded DC (or ungrounded distributed AC) control circuit configurations.

Table 8-2. Summary of Mean Conditional Probability of Spurious Operation For Ungrounded Double Break Control Circuits

Target Cable Configuration		Power Supply Configuration	Device Type	Combinations of Conductor Hot Short Failure Modes					
				Intra-Cable & Intra-Cable	Intra-Cable & Inter-Cable	Inter-Cable & Inter-Cable	Intra-Cable & Ground Fault Equivalent	Inter-Cable & Ground Fault Equivalent	Aggregate
				1	2	3	4	5	6
Thermoset-Insulated Conductor Cable	1	AC w/CPTs	SOV	0.43	0.065	Incredible◊			0.47
			MOV	0.30	0.065				0.35
		DC (AC w/o CPTs)*	SOV	0.23	2.9E-03		0.077	Incredible◊	0.29
			MOV	0.16	2.9E-03		0.054		0.20
Thermoplastic-Insulated Conductor Cable	2	AC w/CPTs	SOV	0.43	0.082	5.3E-03			0.48
			MOV	0.30	0.082	5.3E-03			0.36
		DC (AC w/o CPTs)*	SOV	0.23	9.5E-03	8.6E-04	0.07	3.1E-03	0.29
			MOV	0.16	9.5E-03	8.6E-04	0.049	3.1E-03	0.21
Metal Foil Shield Wrap Cable	3	AC w/CPTs	SOV	0.33	0.12	Incredible◊			0.41
			MOV	0.23	0.12				0.33
		DC (AC w/o CPTs)*	SOV	0.27	Incredible◊		0.14	Incredible◊	0.36
			MOV	0.19			0.10		0.26
Armored Cable	4	AC w/CPTs	SOV	0.23	0.16	Incredible◊			0.35
			MOV	0.16	0.16				0.29
		DC (AC w/o CPTs)*	SOV	0.55	Incredible◊		0.35	Incredible◊	0.70
			MOV	0.38			0.25		0.53

* DC (AC w/o CPTs) represents ungrounded DC (or ungrounded distributed AC) power supply configuration.

◊ “Incredible” represents a sub-case where no numerical estimates were developed because it is believed that the event will not occur.

As for the single break circuits, the conditional probability values for metal foil shield wrap and armored cables should be used for the double break circuits regardless of their conductor insulating material type (i.e., TS or TP).

Conditional Probabilities of Duration of Spurious Operation

Figure 8-1 includes the spurious operation duration plots of the "mean conditional probability" for the AC and DC control circuits. Each plot represents the Weibull distribution up to the time (in minutes) where the floor value intersects the Weibull plot. Beyond this intersection, the floor probability values represent the likelihood of a hot short-induced spurious operation not clearing. The floors are different for AC and DC control circuit configurations. *A complete description of these conditional probability distributions is included in Section 6 of this report.* The mean conditional probability value of the AC floor at 9 minutes is 0.0071 and that of the DC floor at 7 minutes is 0.022.

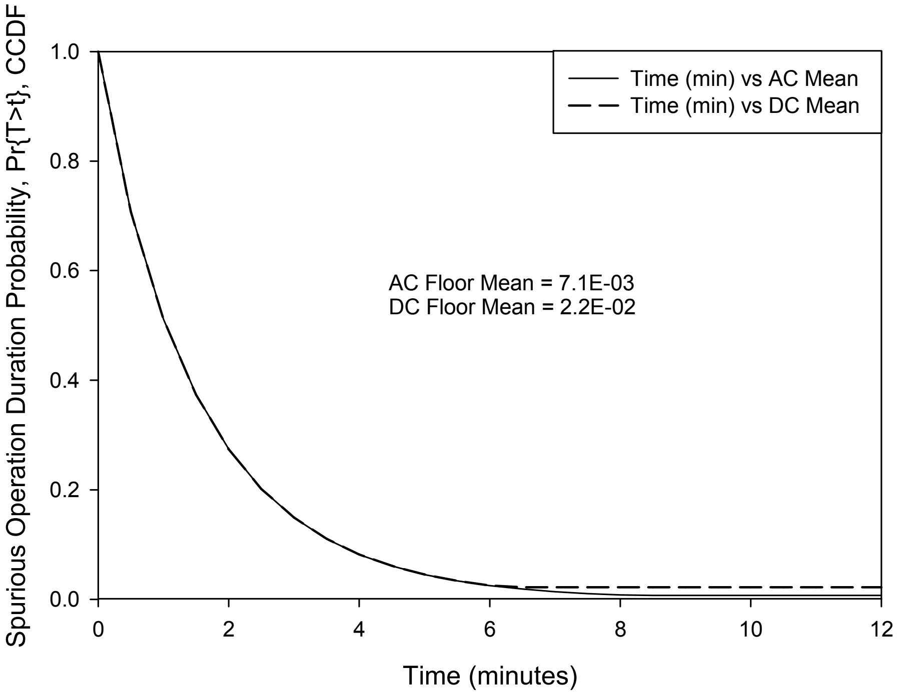


Figure 8-1. AC and DC Spurious Operation Duration Mean Conditional Probability Plots

The PRA panel recommends the following fire PRA applications for the control circuits:

- Section 10.5, Revising the "Procedure," for both Option #1 and Option # 2 in NUREG/CR-6850 to include the findings from both the PIRT panel's and PRA panel's expert elicitations.
    - For Option #1, the conditional probability tables in Section 10 (Tables 10-1 through 10-5) should be replaced by the tables in Sections 4 and 5 of this Volume 2.

  - Option #2 should not be used since it was based on reverse engineering of the EPRI/NEI test data. The current state-of-knowledge and available test data (EPRI/NEI, NRC's CAROLFIRE, NRC's DESIREE-Fire, and Duke Energy's) cannot validate its use.

- Section 16, "Hot Short Duration (FAQ 08-0051)" of NUREG/CR-6850, Supplement 1, "Fire Probabilistic Risk Assessment Methods Enhancements," should be replaced with conditional probability plots for duration of the spurious operation for AC and DC control circuits discussed in Section 6.

- Section 7 of this Volume 2 offers guidance in applying the spurious operation conditional probability tables, the spurious operation duration plots, and related issues that should be considered in analyzing the fire PRA circuit.

In conclusion, this work represents the current state-of-the-art knowledge and methods for quantifying the conditional probabilities of hot short-induced spurious operation occurrence and its duration of control circuit end devices due to fire damage of cables.

Identification of Future Research

During the course of the work, several areas for additional future research have been identified. Section 7 of Volume 1, to NUREG/CR-7150 identifies several areas where additional work could benefit industry, stakeholders and the NRC. During the PIRT exercise, several issues were not addressed specifically, but either passed on to the expert elicitation panel to solve (if possible) or was intended to be addressed by industry and the NRC. This included:

- Quantification of instrumentation circuit failure mode likelihoods,
- Use risk-insights to inform revision of qualitative classification, and
  - quantitative insights could be used to inform the qualitative classification of two inter-cable thermoplastic hot shorts to resolve the NOTE to Table 3-3 of Volume 1
- Classification of systems and circuits as "high consequence."

The results of this Volume 2, indicate that the current method for quantifying instrumentation circuit risk has not advanced since the issuance of NUREG/CR-6850 (EPRI 1011989). Thus, the panel restates the need to advance the knowledge of fire-induced circuit failure for instrumentation circuits and the associated fire PRA modeling of such failures.

During the course of the expert elicitation exercise, there was reluctance from the experts to use risk-insights to make qualitative judgments that would modify the work previously completed by the PIRT panel. Although nothing was identified that contradicts the acceptability of the PIRT results, the PRA panel members believe that use of the risk-insights from this quantification effort could help enhance the classification of several qualitative judgments made by the PIRT panel.

9
REFERENCES

1. 10 CFR 50.48 (Title 10 of the Code of Federal Regulations, Part 50, Section 50.48), “Fire Protection.”

2. 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities.”

3. 10 CFR Part 52, “Licenses, Certifications, and Approval for Nuclear Power Plants.”

4. Appendix A to 10 CFR Part 50, “General Design Criteria for Nuclear Power Plants,” GDC 3, “Fire Protection.”

5. Appendix R to 10 CFR Part 50, “Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979.”

6. NFPA 805, “Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants,” 2001 Edition, National Fire Protection Association, Quincy, MA.

7. NUREG -0050, “Recommendations Related to Browns Ferry Fire; Report by Special Review Group,” February 1976.

8. Information Notice 99-17, “Problems Associated with Post-Fire Safe-Shutdown Circuit Analysis,” June 3, 1999.

9. EPRI 1003326, “Characterization of Fire-Induced Circuit Faults: Results of Cable-fire Testing,” Electric Power Research Institute, Palo Alto, California, December 2002.

10. Regulatory Issue Summary 2004-03, “Risk-Informed Approach for Post-Fire Safe-Shutdown Circuit Inspections,” Revision 1, December 29, 2004.

11. NUREG/CR-6931, “Cable Responses to Live Fire (CAROLFIRE),” SAND2007-600/V1, V2, and NISTIR 7472 Vol. 3, April 2008.

12. NUREG/CR-7100, “Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-Fire) - Test Results,” SAND2012-0323P, April 2012.

13. EPRI 1006961, “Spurious Operation of Electrical Circuits Due to Cable-fires – Results of an Expert Elicitation” Electric Power Research Institute, Palo Alto, California, May 2002.

14. NUREG/CR-6850 and EPRI 1011989, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities,” Volumes 1 and 2, September 2005.

15. NUREG/CR-6850, Supplement 1, “Fire Probabilistic Risk Assessment Methods Enhancements,” Supplement to NUREG/CR-6850, EPRI 1019259, September 2010.

16. NUREG/CR-7150 and EPRI 1026424, “Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE) - *Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure*,” BNL-NUREG-98204-2012, Volume 1, October 2012.

17. NUREG-2128, “Electrical Cable Test Results and Analysis during Fire Exposure (ELECTRA-FIRE) – A consolidation of the three major fire-induced circuit and cable failure experiments performed between 2001 and 2011,” September 2013.

18. NUREG/CR-4106, “Application of SLIM-MAUD: A Test of an Interactive Computer-Based Method for Organizing Expert Assessment of Human Performance and Reliability,” BNL-NUREG-51828, Volumes 1 and 2, September 1985.

19. NUREG/CR-5411, “Elicitation and Use of Expert Judgment in Performance Assessment for High-Level Radioactive Waste Repositories,” SAND89-1821, May 1990.

20. NUREG-1150, “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants,” Volumes 1, 2, and 3, December 1990.

21. NUREG/CR-6372, “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts,” Volumes 1 and 2, April 1997.

22. NUREG-1829, “Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process,” Volumes 1 and 2, April 2008.

23. ASME/ANS RA-Sa–2009, “Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications,” Addenda to ASME/ANS RA-S–2008, 2009.

24. NRC Regulatory Guide 1.208, “A Performance-Based Approach to define the Site-Specific Earthquake Ground Motion,” March 2007.

25. NUREG-2117, “Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies,” Revision 1, April 2012.

26. O’Hagan, A., Buck, C.E., Daneshkhah, A., Eiser, J.R., et al., “Uncertain Judgements: Eliciting Experts’ Probabilities,” John Wiley & Sons, 2006.

27. Belgorodski, N., Greiner, M., Tolksdorf, K., and Schueller, K., “rrriskDistributions: Fitting distributions to given data or known quantiles,” R package version 1.8. September 26, 2012. URL http://cran.r-project.org/web/packages/rriskDistributions/index.html.

28. Wood, S.T., Smith, C. L., Kvarfordt, K. J., and Beck, S.T., “Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE),” NUREG/CR-6952, September 2008.

29. NUREG/CR-5546, “An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electrical Cables,” May 1991.

30. NUREG/CR-6776, “Cable Insulation Resistance Measurements Made During Cable-fire Tests,” June 2002.

31. NUREG/CR-6834, “Circuit Analysis – Failure Mode and Likelihood Analysis,” September 2003.

32. NUREG/CR-7102, “Kerite Analysis in Thermal Environment of Fire (KATE-Fire): Test Results,” December 2011.

APPENDIX A
PANELIST AND FACILITATOR RESUMES

Robert Cavedo, Jr., Constellation Energy

Summary of Qualifications

My professional work experience spans a twenty-four year career working as a Reliability Engineer for the Constellation Energy Group (CEG). My current role as a principal engineer can best be described as the technical lead in PRA for the CEG Fleet.

Education

B.S. Nuclear Engineering – December, 1989
University of Maryland – College Park, MD
Graduate studies include course work in Reliability Engineering and Software Engineering

Professional Experience

Constellation Energy Group
Baltimore, MD

Principal Reliability Engineer
Sept. 2006 to Present
Lead PRA Engineer for Constellation transition to Risk-Informed Fire protection using NFPA-805Transition requires risk-informed change analysis of multiple spurious actuations and required manual actions. Analysis involves the performance of a Fire PRA for all Constellation sites using the new Fire PRA methods in NUREG/CR-6850. Provided PRA support for NRC Triennial Fire Inspections and Self Assessments, including Fire PRA and SDP review of issues raised during the inspections. Member of the NEI NFPA805 PRA Task Force. Calvert technical lead in converting RISKMAN into CAFTA which includes some model upgrades in support of EOOS usage and Regulatory Guide 1.200 compliance.

PRA Consultant May 2004 to Sept. 2006
Perform Significance Determination Process (SDP) for numerous issues within the fleet. The technical lead on the Calvert Cliff DG AOT extension request. This included significant model upgrades to support of 14-day AOT. Provided training to plant personnel related to the first Component Design Basis Inspection. Developed the Calvert Cliffs Integrated Leak Rate Testing (ILRT) AOT extension. Developed the Ginna Mitigating System Performance Indicators. Participated in numerous Emergency Response Drills as the Technical Analyst.

Senior Reliability Engineer Feb. 1995 to April 2004
Perform risk analyses on major modifications. Perform system analyses as needed. Provide training to Reliability Engineers within our group as part of the qualification process. Continue to improve the Calvert Cliffs Nuclear Power Plant (CCNPP) Risk Model. Review the CCNPP on-

line risk assessment process. Maintain and improve the on-line risk assessment software. Participate in NRC inspections and related meetings. Developed the plan for the Fire Portion of the Individual Plant Examination of External Events (IPEEE). Created the Fire portion of the IPEEE plant model. Provided technical expertise in the development of the Seismic and Wind portion of the IPEEE plant model developments. Coordinate and evaluate the efforts of contractors as they assist our unit. Developed the Performance Indicators for the Nuclear Regulatory Commission (NRC) mandated Maintenance Rule. Performed the Severe Accident Mitigation Alternative (SAMA) analysis for the CCNPP License Renewal Effort. Participated in the Fort Calhoun, Milestone, Palo Verde, and ANO Station Combustion Engineering Owners Group Peer Review. Was the system analyst technical lead in the first RG.1200 pilot peer review at SONGS. Participated in the Watts Bar Westinghouse Owners Group Peer Review. PRA representative for the Pressurized Thermal Shock Code of Federal Change working group.

Reliability Engineer May 1992 to Feb. 1995
Perform risk analyses for the Individual Plant Examination (IPE). The analyses performed included: Safety Injection System, Auxiliary Feedwater System, Component Cooling Water System, Containment Spray System, Containment Air Cooler System, and other analyses as needed. Developed the method and software for the CCNPP On-line Risk Assessment Process. Created the CCNPP Risk Model submitted in the IPE. Attended Users Group meetings associated with the Software used to quantify the CCNPP Risk Model. Provided training sessions on statistics and systems analyses methods to work group members. Tested, trained and qualified each member of our unit in the Risk Assessment Area. Provided required training to all technical staff members at the CCNPP in the areas of risk assessment and the results of our IPE.

Associate Reliability Engineer Jan. 1990 to May 1992
Developed the format, including tools and procedures, used to perform risk analyses in the Reliability Engineering Unit. Created the failure database used within system analyses and the plant model. Performed IPE related risk analyses on the Salt Water System, the Service Water System and the 4 kV System.

Summer Student Strategic Engineering Department May 1989 to November 1989
Performed elementary risk analyses on the Salt Water and Service Water Systems. Assisted with the plant condition-monitoring program.

Summer Student Technical Services Engineering Department May 1988 to August 1988
Wrote several programs including programs used to monitor xenon reactivity and boron concentrations found in the core and reactor coolant system. Performed elementary reactivity analyses.

National Institute of Standards and Technology, Gaithersburg, MD
Research Assistant Materials Department June 1987 to January 1988
Developed a program, which acoustically evaluated the ultrasonic wave forms used to predict the point at which certain materials become super conductive.

Daniel Funk, Hughes Associates, Inc.

Summary

Mr. Funk is Manager of the Engineering Analysis Section within the Power Systems Division of Hughes Associates, Inc. In this capacity he directs technical and business operations for the Section. The Engineering Analysis Section provides consulting services to the nuclear power industry, specializing in all aspects of analysis relating plant response to fire, safe shutdown capability, and risk-informed analysis. 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

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*
Hughes Associates, Inc.

Mr. Funk joined Hughes Associates, Inc. in November 2011 as a Senior Technical Consultant and Manager of the Engineering 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. Mr. Funk's expertise and experience includes both traditional deterministic fire safe shutdown analysis and fire probabilistic analysis.

Appendix R and NFPA 805:

- Over his career Mr. Funk has participated in or managed Appendix R and NFPA 805 deterministic safe shutdown analysis activities for many nuclear plants, including Southern Nuclear Fleet (Vogtle, Hatch, Farley), Entergy (Palisades, Waterford 3, River Bend, Grand Gulf, Pilgrim, Indian Point 2/3), Progress Entergy (Harris, Brunswick, Robinson), PSE&G (Salem, Hope Creek), Diablo Canyon, SONGS, Columbia Station, Point Beach, Palo Verde, Duane Arnold, Turkey Point, Browns Ferry, VC Summer, Limerick, Milestone, and Nine Mile Point.
- 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.
- Providing direction and technical consulting to utilities for major projects involving NFPA 805 transition and implementation, multiple spurious operation analysis, and fire-induced circuit failure issues.
- 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.
- Principle author for several EPRI projects involving surveillance and calibration reduction efforts for fire protection equipment, emergency lighting and instrumentation (EPRI Reports 1006756, 106154, 106752-R2, and 100249-R1).
- Conduct fire risk assessments for electrical process equipment as part of U.S. and European Union equipment safety certifications.

Fire PRA:

- Over the past 10 years Mr. Funk has participated in numerous key activities for Fire PRA, including research, analytical methods development, and application. His specific areas of expertise are PRA circuit analysis, associated circuits, spurious operations likelihood analysis (including MSO), Fire PRA equipment selection, and Fire PRA data management.
- Mr. Funk has participated in PRA activities for EPRI, NEI, and numerous nuclear plants, including Southern Nuclear Fleet (Vogtle, Hatch, Farley), Entergy (Palisades, Waterford 3), Progress Entergy (Harris, Brunswick, Robinson), Diablo Canyon, SONGS, Palo Verde, Turkey Point, Browns Ferry, VC Summer, Milestone, and Nine Mile Point.
- Industry representative for joint NRC/EPRI expert panel for assessment of fire-induced circuit failures (Electrical PIRT Panel and Fire PRA Panel). These two panels are

  developing the circuit analysis failure modes and spurious operation probabilities that are to be used in future Fire PRA analysis.
  - Co-author of NUREG 6850, with primary responsibility for development of advanced analytical methods for the analysis of fire-induced circuit failures. Primary author for Task 3, Task 9, Task 10, and related appendices.
  - Participated in three Fire PRA peer reviews as lead for cable selection and circuit failure supporting requirements.
  - Principal instructor for on-going EPRI/NRC Fire PRA course. Instruct the circuit analysis module.
  - Currently supporting six plants with NFPA 805 RAI responses for Fire PRA issues pertaining to circuit analysis, failure probability sensitivity studies, model continuity issues for interlocks, and spurious operations.
  - Active participant in industry and NRC fire-induced circuit failure tests, including EPRI/NEI, CAROL-FIRE, and DESIREE-FIRE. These tests serve as the basis for industry and regulatory guidance for Fire PRA circuit analysis.
  - 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).
- 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.

Publications

- NUREG/CR-7150, *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*, October 2012.
- *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
- Air Force Manual 32-1181, *Design Standards for Facilities Interior Electrical Systems*
- 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 (IPASS)*, 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

Ray Gallucci, NRC

Licensed Professional Engineer (since 1985) specializing in applied research and problem-solving through risk, reliability, safety and maintainability analyses and probabilistic and statistical modeling. Doctorate in Nuclear Engineering and Science with extensive experience in the government regulatory arena and the commercial power industry. Innate ability to complete projects within tight deadlines. Intuitive decision-maker willing to try new approaches. Skilled technical writer.

Selected Accomplishments

- Analyzed and resolved over 100 nuclear industry safety issues in six months to clear the backlog at the US Nuclear Regulatory Commission (NRC).
- Have served as first and only prime technical lead for Fire Probabilistic Risk Analysis (PRA) in Fire Protection Branch of the USNRC's Office of Nuclear Reactor Regulation, including technical lead for Fire PRA for pilot plant program to transition commercial reactors from deterministic to performance-based, risk-informed fire protection licensing bases.
- Created predictive models to extend the operating lives of 10 electric generating plants built and serviced by Asea-Brown Boveri Combustion-Engineering, Inc.
- Demonstrated that the risk to the public from cross-country shipment of radioactive waste from Three-Mile Island would be less than natural background radiation (for the US Department of Energy [DOE]).
- Served as a Peer Reviewer of the landmark US NRC Procedures Guide for PRA and authored the Regulatory Analysis Technical Evaluation Handbook.
- Proved the acceptability of statistically-based instrument set points for all Asea-Brown Boveri Combustion-Engineering nuclear utilities, saving them costly hardware upgrade expenses.
- Quantified the improvements in health and safety to the public and worker resulting from environmental restoration and security consolidation at the US DOE Hanford Site.
- Characterized the spectrum of potential accidents (nuclear and explosive detonations, fires, transportation) in Hazard and Safety Analysis Reports for nuclear weapon dismantlement at the US DOE Pantex Plant.
- Served on Technical Review Committee of the Westinghouse Owners Group Risk Management Subcommittee and as PRA Representative for RE Ginna Maintenance Rule (10CFR50.65) Expert Panel.
- Used analytical techniques to demonstrate frequency for catastrophic external flooding at RE Ginna fell below regulatory acceptable threshold, saving costly hardware upgrade expenses without compromising public safety.
- Published and presented numerous technical conference and journal articles (publication list available upon request).
- Won the J. Erik Jonsson Prize as valedictorian at Rensselaer Polytechnic Institute, Troy, New York.
- Received seven “Leading Edge” Awards for extraordinary contributions at Ginna Nuclear Plant.
- Received five Annual Performance Awards since joining the US NRC (2005-2009).
- Secretary (2006), Vice-Chair (2007) and Chair (2008) of the American Nuclear Society's Nuclear Installations Safety Division Program Committee (Member since 2002).

- Hold L-level security clearance. Held an Unescorted Access security clearance to Ginna Nuclear Plant from the US NRC. Held both L- and Q-level security clearances while employed for contractors to the US DOE.

Professional Experience

Senior Fire Probabilistic Risk Analysis Engineer
US Nuclear Regulatory Commission, Rockville, MD
Senior Probabilistic Safety Analysis Engineer 2003 - present

Rochester Gas & Electric Corp., RE Ginna Nuclear Plant, Rochester,
New York. 1997 - 2003
Senior Research Scientist/Engineer
Battelle-Columbus Operations @ Pantex Plant, Amarillo, Texas 1997 - 2003

Battelle Pacific Northwest National Laboratories, Richland, Washington 1991 - 1997
Principal Engineer

Asea-Brown Boveri Combustion-Engineering, Inc., Windsor, Connecticut 1984 - 1991
Research Engineer

Battelle Pacific Northwest National Laboratories, Richland, Washington 1980 - 1984

Education

Ph.D., Nuclear Engineering and Science, 1980
M.Eng., Nuclear Engineering and Science, 1976
B.S., Nuclear Engineering and Science, 1975
Rensselaer Polytechnic Institute, Troy, New York

Memberships

Society for Risk Analysis
American Nuclear Society

Dennis Henneke, GE Hitachi Nuclear Energy

Current Title: Consulting Engineer, Risk and Reliability (PRA)

Nuclear Experience: 31 Years

Education

MS, Nuclear Engineering, University of Florida, 1982
BS, Nuclear Engineering, University of Florida, 1981

Advanced Training and Certification

Professional Engineer (PE) License, State of North Carolina, 2002
Six Sigma Green Belt Training
Project Management Training

Experience

GENERAL ELECTRIC COMPANY – 6 YEARS
Consulting Engineer - GEH Nuclear Engineering

- Chairman, Joint ANS/ASME Fire PRA Writing Group developing the Fire PRA Standard, 2001-2013.
- Peer Review Team Lead for most BWROG Fire PRA Peer Reviews and numerous Internal Events and Flooding PRA Peer Reviews against Regulatory Guide 1.200 and the ASME PRA Standard.
- Vice Chair for ASME/ANS JCNRM overseeing all PRA standard development and maintenance activities.
- Technical Program Chair, PSA 2011 (www.psa2011.org), March 13-17, Wilmington NC. Conference was attended by approximately 300 PRA/PSA experts from approximately 35 countries.
- IAEA Support for International Workshops on Risk-Informed Decision Making (RIDM). Support includes 1 week-long workshop per year on RIDM, and publication of an IAEA report on issues discussed during the workshops. Presentations include a wide variety of risk applications, include methods on risk monitor development and use.
- Member ASME CNRM supporting development and updating of the ASME Internal Events PRA Standard and development of the Advanced Light Water Reactor Standard. Member, ANS RISC Committee overseeing the development of all ANS PRA Standards including Shutdown PRA, External Events PRA, Level II and Level III.
- Development of the BWR Owner’s Group and NEI guidance on Fire PRA Peer Review (NEI 07-12).
- Fire PRA Support for three US BWR utilities in support of Fire PRA development under NFPA 805. Support includes methodology development and review of existing Fire PRA interim results.
- Co-Author, NUREG/CR-6850, Supplement 1; EPRI TR-1019259, December 2009. Report includes new Fire PRA methods developed under the NFPA 805 FAQ process. Author of 5 of the FAQs published in Supplement 1.

- Development of the BWR Owner's Group and NEI guidance on response to the NRC Generic Letter on Circuit Analysis for non-NFPA 805 plants (NEI 00-01, Revisions 0, 1 and 2 – Coauthor of each).
- Lead for Fire PRA training courses in Spain and Wilmington, NC in 2009. FPRA methods include NUREG/CR-6850, recent advances, and FPRA Standard overview.
- Lead for ABWR PRA development for new ABWR reactors. Supporting activities for COL submittal for South Texas ABWR.
- PRA Support for ESBWR PRA Licensing, including Aircraft and Security Assessments, Fire PRA, and Human Factors Engineering.
- PRA support for PRISM Sodium Cooled Reactor.
- QRA support for Global Laser Enrichment Licensing and Global Nuclear Fuels Facility Integrated Safety Assessments (ISAs).

DUKE POWER COMPANY - 6 YEARS
Senior Engineer - PRA Section

Senior Engineer, Probabilistic Risk Assessment (PRA) Section supporting Duke Power's three nuclear sites, McGuire, Oconee, and Catawba Nuclear Stations. Responsibilities include interface responsibility with the three Duke Power sites as well as national and international organizations for the following technical areas:

- Lead PRA Engineer for Duke Power transition to Risk-Informed Fire protection using NFPA-805. This process began in early 2005 with Duke's Oconee Nuclear Plant. Transition requires risk-informed change analysis of multiple spurious actuations and required manual actions. Analysis involves the performance of a Fire PRA for all three Duke sites using the new Fire PRA methods in NUREG/CR-6850.
- Provided PRA support for all three plant's NRC Triennial Fire Inspections and Self Assessments, including Fire PRA and SDP review of issues raised during the inspections.
- American Nuclear Society: Chairman, Fire PRA Standard Writing Group. As chairman, responsible for coordination and development of the ANS Fire PRA Standard, due to be complete in late 2006. Member of the ANS RISC committee, which oversees and approves all ANS PRA standards.
- Session organizer and presenter, ANS Utility Working Conference, August 2004, Amelia Island, Florida, and presenter for 2005. Both presentations were on Risk-Informed, Performance-Based Fire Protection. Track Organizer for PRA track at 2006 meeting, scheduled for August 2006.
- American Society of Mechanical Engineers (ASME): Member of the Joint ANS/ASME PRA Standards integration committee, formed in late 2004. This committee is tasked with integrated all level 1 PRA standards into a single PRA standard.
- Nuclear Energy Institute: Member of three advisory committees, including the Circuit Analysis Task Force, Fire Protection Rule Making Task Force and the newly formed NFPA-805 working group. Committees are responsible for recommending revisions to the Fire Protection regulations and development of industry guidance on Risk-Informed Fire Protection. Developed Report NEI-00-01, guidance on analysis of circuit failures for Nuclear Plants. PRA Lead Engineer for McGuire Circuit Analysis Pilot project, which is one of two pilot applications of NEI-00-01. Lead PSA Engineer for Pilot Application of NEI Implementation Guide for NFPA-805 at the McGuire Nuclear Plant, documented in EPRI Report TR-1001442. Reviewer for NEI Implementation Guide on Risk-Informed Fire Protection, NEI-04-02. Participated in the development of an NEI Self-Assessment Guide

on Fire-Induced Multiple Spurious Operation, NEI-04-06. Have presented at the last 4 NEI Fire Protection Information Forum. In 2005, presentations include a presentation on the Duke transition to NFPA-805, and use of Fire SDP Zone of Influence tables for issue resolution.

- IAEA: Support in the development of technical report “Peer Review of PSA Applications,” Instructor for Advanced PSA applications training (4 courses), and support IAEA mission work in PSA for Bulgarian and Russian Nuclear Sites. Scheduled as an instructor for the IAEA training in Shanghai, China, June 2006.
- EPRI: Peer reviewer for the development of the revised Fire PRA method (2003-2005), co-developed by EPRI and the NRC (NUREG/CR-6850). Attended Fire PRA Training on the new methods, June 2005. Presenter in the EPRI Configuration Risk Management Forum (CRMF) discussing shutdown PRA.
- Project Manager in the development of a Shutdown PSA for all three Duke Power sites. Developing Shutdown PSA for Oconee Plant based on Framatome generic shutdown guidance.
- Coordinating Training for new PRA engineers. Training includes 19 basic modules of training based on the draft EPRI guidance on PRA qualifications and training. Provided Internal Training to Site Fire Protection Staff on Fire Significance Determination Process and Fire PRA. Provided Fire PRA and Circuit Analysis Training to Duke Power PRA Staff.

SOUTHERN CALIFORNIA EDISON – 3 YEARS
Senior Engineer - PRA Group

Senior Engineer in the San Onofre Nuclear Generating Stations (SONGS) Units 2/3 PRA Group. Focus areas included activities to ensure SONGs lead the industry in PSA and Risk-Informed Activities:

- Co-winner of the 2000 William R. Gould Award for Engineering and Operational Excellence at Southern California Edison.
- Co-winner of the 2000 Top Industry Practice (TIP) Vendor Award, presented by the Nuclear Energy Institute (NEI) for PRA work on extending the SONGS Diesel Allowed Outage Time from 3 to 14 days.
- Lead Engineer for the Risk-Informed Technical Specification project. SONGS is the industry lead plant for this NEI sponsored project, which included participation from all owners’ groups, EPRI, and NEI. Performed analysis in support of End State Optimization task, Mode restraints task, and 3.0.3 relaxation task. Developed a transition mode model in support of End State task, and integrated this model into the SONGS 2/3 Safety Monitor.
- Vice-Chairperson of the Safety Monitor User’s Group. Lead PRA Engineer for development and use of the SONGS Shutdown Safety Monitor. The Shutdown Safety Monitor has been used for the last 2 plant outages for both SONGS Units 2 & 3 for outage planning, and is being used by plant staff for the most recent outages to meet the Maintenance Rule (a)(4) requirements. The shutdown model includes Mode 5, Mode 6 and de-fueled operations, resulting in a Safety Monitor model which analyzes all possible modes and plant operational states. Future plans include the substitution of the Defense-in-Depth program presently used with the Shutdown Safety Monitor. Lead PRA Engineer for development and use of the full power Safety Monitor Model. This model was improved to include Level II/III and LERF results, External Events including Fire and Seismic Events, and expansion of point estimate initiating events into fault tree initiating

events. Seismic modeling included all seismic sequences. Fire modeling included all possible fire sequences with core damage greater than 1E-09/year, or approximately 100 fire sequences.

- Lead PRA Engineer for the Risk-Informed In-service Testing (IST) project. SONGS was the second plant to receive IST relief from the NRC. Analysis was performed using Reg. Guide 1.174, 1.175 and ASME ONM-3 guidance. This analysis included first of a kind estimation of component importance for shutdown, multi-importance rankings including all internal and external events, and an analysis of the cumulative effect of IST changes using actual plant out of service data.

SCIENTECH – NUS – 10 YEARS
Executive Consulting Engineer and Senior Risk and Reliability Engineer

Responsibilities include project management and technical support of Qualitative and Quantitative Risk Assessments (QRA) for Industrial and Nuclear Plants. Risk Assessment techniques performed include Fault Tree and Event Tree Analysis, Fire-induced Vulnerability Evaluation (FIVE), FMEA, HAZOP analysis, GO analysis, Failure Data Analysis, Human Reliability Analysis (HRA), as well as other specialized risk assessment techniques.

- Lead Engineer for a total of six (6) Safety Monitor projects used for evaluation of plant safety during various plant operation and maintenance configurations. Lead Engineer for the development of the logic models, Safety Monitor software development and database development for the Wolf Creek, Callaway and Comanche Peak Safety Monitors. Model development performed for Full Power Level I and Level II, Shutdown Modeling, and External Events. Lead Engineer for the development of the Safety Monitor logic models for San Onofre Units 2 and 3 and the Timeline Nuclear Plant. Provided training on Safety Monitor and Top Logic development to over 10 organizations.
- Project Manager and lead analyst for the Wolf Creek Fire PRA. Analysis included a modified FIVE methodology, with additional COMPBRN runs and scenario analysis performed. Performed analysis for all project phases and assisted client in the preparation of the IPEEE submittal.
- Lead analyst for the Brunswick Fire PRA, including performance of the Fire Screening, walkdowns, detailed analysis, and Sandia Fire Scoping Study issues. Project analyst for the Fire Analysis of the Westinghouse AP600 Advanced Light Water Reactor design.

TENERA, L.P.
Senior Engineer Energy Services

- Performed Human Reliability Analysis for the Big Rock Point IPE, and Prairie Island IPE including the performance of Human Factors reviews and plant validation walkdowns.
- Performed a Root Cause Analysis review for Quad Cities Nuclear Plant, and a Nuclear Safety Review evaluation for Salem and Hope Creek Nuclear Plants.
- Project manager for a FIVE analysis for TVA's Sequoyah Plant. Responsibilities included performance of Seismic Fire interactions review and analysis of Sandia fire issues.

Gerardo Martinez-Guridi, BNL

Fields of Expertise

Probabilistic Risk Assessments (PRA) of nuclear power plants (NPPs): applications of PRA; risk-informed regulation and inspection of NPPs; digital systems; LOCA with consequential LOOP; reactor coolant pump (RCP) seal loss of coolant accident (LOCA). Software Engineering: development of software and software reliability.

Education

2003 - Graduate Certificate in Software Engineering, Polytechnic University, New York, USA.
1983 - M.S., Nuclear Reactor Science and Engineering, University of London, England.
1979 - B.S., Energy Engineering, Universidad Autonoma Metropolitana, Mexico.

Experience

1992 – Present	Brookhaven National Laboratory. Principal Investigator in projects related to Probabilistic Safety Assessments, Risk-Based Regulation, and Software Development.
1979 - 1992	Instituto de Investigaciones Electricas (Mexico). Head of a Research Project on Applications of PRA. Collaboration on projects of nuclear and non-nuclear PRA, Expert Systems, Software Development, and Simulation of Dynamic Systems.
1985 - 1986	RISO National Laboratory (Denmark). Visiting Researcher. Collaboration with the Danish team on a Benchmark Exercise on Common Cause Failures for the European Economic Community. Participation in a Scandinavian project t on Common Cause Failures. Development of Software for PRA calculations.
1990 - 1992	International Atomic Energy Agency (Austria). Consultant on the Development and Use of Software for PRA.

Selected Publications

1. T. L. Chu, G. Martinez-Guridi, M. Yue, et al., “Traditional Probabilistic Risk Assessment Methods for Digital Systems,” NUREG/CR-6962 Report, September 2008.

2. G. Martinez-Guridi, T. L. Chu, M. Yue, “Building a Reliability Model of a Digital System,” Transactions of the American Nuclear Society: 2008 Annual Meeting, Volume 98, Anaheim, California, June 2008.

3. T. L. Chu, G. Martinez-Guridi, M. Yue, et al., “A Review of Software-Induced Failure Experience,” 5th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology (NPIC&HMIT 2006), November 12 - 16, 2006, Albuquerque, NM, USA.

4. G. Martinez-Guridi, A. Kuritzky, R. Fitzpatrick, and J. Lehner, ”Conditional Probability of LOOP Given a LOCA: An Approach to Assessment Within the Framework of a Risk Informed Alternative to 10 CFR 50.46 and GDC 35,” presented at 2002 International Topical Meeting on Probabilistic Safety Assessment, October 8, 2002.

6. G. Martinez-Guridi, P. Samanta, T-L. Chu, and J.W. Yang, “LOCA with Consequential or Delayed LOOP: Modeling of Accident Sequences and Associated Core Damage Frequency,” Journal Nuclear Technology, Volume 131, Number 3, September 2000.

David Miskiewicz, Engineering Planning & Management, Inc.

Current Position

Risk Services Division Manager
Engineering Planning & Management, Inc

Summary

Nuclear engineer with over 30 years of experience working in the nuclear power industry. Currently Mr. Miskiewicz is managing the Risk Services Division for EPM. David has been a practicing PRA engineer for more than 20 years with extensive industry involvement including leading, presenting and instructional roles, and is a recognized expert in PRA. He has additional experience with software development and systems and design engineering activities including work related to reactor internals and reactor vessel integrity.

Education

1975–1979 B.S., Nuclear Engineering, Pennsylvania State University, State College, PA

Experience

2012–Present EPM, Inc., Raleigh, NC

- Manage operations and personnel within the Risk Services Division of EPM.
- Project manager and technical lead for development of Robinson Fire PRA to support NFPA-805.
- Project oversight and consulting support for completion of Point Beach Fire PRA and LAR preparation to support NFPA-805 transition.
- Member NEI 805 Task Force and Fire PRA Task Force
- Member of ASME CNRM Subcommittee on Model Maintenance, Special Committee on Inquiries, and the Part 4 (Fire PRA Standards) writing team
- Participant in various EPRI/NRC MOU projects

2005–2012 Progress Energy, Raleigh, NC

- Support the Progress Energy Fleet of Nuclear Plants. Responsibilities include maintaining PSA models, performing PSA applications, and responding to emergent plant issues.
- Project management and technical lead for development of fire PRAs to support transition of the Progress Energy fleet to NFPA-805.
- Software owner for PSA software used at Progress Energy. Upgraded and completed in-house SQA for the latest versions of EPRI R&R software in 2006.
- Participated in Limerick Peer Review against the ASME Standard
- Member NEI 805 Task Force and Fire PRA Task Force
- Member of ASME CNRM Subcommittee on Technology, Special Committee on Inquiries, and the Fire PRA Standards writing team
- Participant in various EPRI/NRC MOU projects

2001–2005 Progress Energy, Crystal River, FL

- Support the Progress Energy Fleet of Nuclear Plants
- Primary responsible individual for CR3 PRA models and applications. Extensive interface experience with plant engineering, operations, work controls, and licensing groups.
- Applications performed include 14day Emergency Diesel AOT extension, One time AOT extensions for Service water, Chilled water, Emergency Diesels, Emergency Feedwater, and ILRT extensions for several plants.
- Experienced with product development and regulatory interface related to the Significance Determination Process.
- Chairman of B&W Owners Group Risk Applications Committee
- Member NEI Risk Applications Task Force
- Member ASME PSA Standard Addendum B writing team
- Participated in 3 external NEI PSA Peer Certification Teams.
- Developed Tool and database for reviewing PRAs against the ASME Standard which was a prototype for the ePSA module offered by EPRI.

1987–2001 Florida Power Corporation, Crystal River, FL

- Responsible for the CR3 PRA model and applications
- Completed extensive models updates resulting from CR3 1.5 year design outage.
- Temporarily served as the Maintenance Rule Supervisor responsible for setting up CR3 expert panel and preparing for baseline 10CFR50.65 inspection. Also, served as Chairman of Maintenance Rule Expert Panel for several years.
- Member of B&W Owners Group Risk Applications Committee
- Involved in the preparation and submittal of IPE and IPEEE for Crystal River unit 3.
- Developed various in-house software applications which significantly increased the efficiency of certain aspect of PSA analysis. These included and online risk monitoring at CR3 (pre-EOOS), a plant specific data management tool, a fire scenario evaluation tool, HRA and maintenance unavailability calculators, a level 2 bridge tree tool, and a component risk ranking tool.

1983–1998 Florida Power Corporation, Crystal River, FL & St. Petersburg, FL

- Chairman and/or member of B&W Owners Group Materials Committee and Reactor Vessel Working Group respectively from 1986-1998.
- Technical lead for development of LTOP technical specifications for CR3. Also responsible for implementation of PLTR and management of the reactor vessel surveillance program at CR3.
- Engineer in Mechanical Design group responsible for plant modifications including replacement of reactor vessel internals bolting and HPI nozzle safe ends.

1979–1983 Gilbert/Commonwealth, Inc., Reading, PA

- Field engineer working as consultant/contractor for nuclear utilities. Primary field was radioactive waste system upgrades.
- Design engineer in the radwaste management section. Participated in radwaste reduction, spent fuel storage and decommissioning projects.

Steven Nowlen, SNL

Employer: Sandia National Laboratories
Title/Position: Distinguished Member of the Technical Staff
Employed Since: October 17, 1983

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 was 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).

Nathan Siu, NRC

Senior Technical Adviser for PRA Analysis
Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission

Education

B.S. (Engineering), University of California, Los Angeles, 1977
M.S. (Nuclear Science and Engineering), University of California, Los Angeles, 1980
Ph.D. (Nuclear Science and Engineering), University of California, Los Angeles, 1984

Employment

1977-84:	Postgraduate Research Assistant, UCLA
1980-84:	Associate Consultant, Pickard, Lowe and Garrick, Inc.
1984-85:	Postdoctoral Scholar, UCLA
1984-86:	Consultant, Pickard, Lowe and Garrick, Inc.
1986-91:	Assistant Professor of Nuclear Engineering, MIT
1991-92:	Associate Professor of Nuclear Engineering, MIT
1992-96:	Technical Staff Consultant, Idaho National Engineering Laboratory
1996-97:	Engineering Fellow, Idaho National Engineering Laboratory
1997-present:	Senior Technical Adviser, U.S. Nuclear Regulatory Commission

Areas of Expertise

Probabilistic risk assessment, external events risk analysis, uncertainty analysis, dynamic systems analysis

Research Interests

Probabilistic risk assessment methods development. Specific areas include: treatment of risk of dynamic accident sequences (including process variables and operator actions), human reliability analysis, simulation-based risk assessment, and fire risk assessment.

Honors and Awards

NRC Meritorious Service Award (2004)
NRC Senior Level System Performance Awards (multiple)
Fellow, American Nuclear Society (2003)
Lockheed-Martin Award for Excellence (1996)
Phi Beta Kappa (1977-present)
Graduated Summa Cum Laude (1977)

Committees and Memberships

Chair, OECD/NEA/CSNI Working Group on Risk Assessment (2007-present)
Associate Technical Program Chair, 1996 ANS international topical meeting on PRA (PSA ’96)

Member Technical Program and Organizing Committees, numerous PRA technical conferences and workshops
Member, American Nuclear Society (ANS) National Program Committee (1996)
Chair, ANS Nuclear Reactor Safety Division (NRSD) Technical Program Committee (1995)
Member, ANS NRSD/NISD Technical Program Committee (1989-1996)
Member, American Nuclear Society (1985-present)
Principal Member, NFPA Technical Committee on Fire Risk Assessment Methods (2000-present)
Member, National Fire Protection Association (2002-present)
Member, American Society of Mechanical Engineers (1994-1996)
Research Affiliate, Massachusetts Institute of Technology (1992-1997)
Member, IAPSAM Board of Directors (1994-2004)
Member, Reliability Engineering and System Safety Editorial Board (1997-1999)

Experience and Accomplishments

- Currently serving as a Senior Technical Adviser in Probabilistic Risk Assessment (PRA) for the Division of Risk Analysis of the Office of Nuclear Regulatory Research for the U.S. Nuclear Regulatory Commission (NRC). Responsible for advising management on PRA issues, for developing PRA research programs to address key issues, for providing PRA-related advice and support to technical staff, for supporting PRA-related cooperative research activities with U.S. and international organizations, and for supporting technology transfer to other technical communities (e.g., the fire safety community). Established technical direction for current NRC research activities in fire risk assessment and human reliability analysis, initiated, and provided oversight on research programs in these areas. Developed technical approach for treatment of uncertainties across multiple disciplines in NRC's research program on pressurized thermal shock. Played a leading role in post-9/11 security-related assessments. Current Chair of the Organization for Economic Cooperation and Development/Nuclear Energy Agency/Committee for the Safety of Nuclear Installations/Working Group on Risk Assessment (OECD/NEA/CSNI/WGRISK).

- While at the Idaho National Engineering Laboratory (INEL), directed the Center for Reliability and Risk Assessment, Risk Assessment and Applied Mathematics Group. (The Center performs advanced PRA research and development.) Co-organized a NATO Advanced Research Workshop on PRA for dynamic process systems and an international, multi-sponsored workshop series on advanced topics in reliability and risk analysis. Served as principal investigator for a number of risk-related projects, including an investigation of pitfalls with risk importance measures and a study of the use of risk assessment in oil spill prevention. Served as the Associate Technical Program Chair for the 1996 ANS international topical meeting on PRA (PSA '96), held in Park City, UT.

- While on the Massachusetts Institute of Technology (MIT) faculty, directed or co-directed a number of research projects in PRA methods development and applications, including investigations of: emergency planning strategies, process variable associated dependencies in accident sequences, and simulation techniques in reliability assessment. Key research outputs included: a dynamic event tree methodology that explicitly incorporate operating procedures and a simulation-based operator crew model that treats the cognitive behavior of and communications between individual operators. Was also responsible as primary lecturer for regularly offered courses on reliability analysis and risk assessment (with emphasis on process facilities). Co-organized and taught short course on Individual Plant Examinations.

- While at Pickard, Lowe and Garrick, Inc., participated in numerous nuclear power plant probabilistic risk analysis studies. Managed spatial interactions analyses, performed fire risk analyses, performed systems analyses, developed software for linking event tree modules. Also participated in the assessment of hazard of chemical plants and gas pipelines to nearby nuclear plants, in the analysis of the frequency of transportation accidents involving radioactive waste, and in a comparative risk study of PCBs and mineral oil in transformers.

- During postgraduate studies at the University of California at Los Angeles (UCLA), developed fire growth model COMPBRN which was used in several nuclear plant fire risk assessments, and supported the development of a methodology to directly integrate code results into a PRA. Developed stochastic model for fire suppression process. Assisted USNRC Research Review Group on Fire Risk in preparing program guidelines and prioritizing research needs; served as peer reviewer for USNRC RMIEP study in the area of fires, floods, and other dependent events.

- Has served on the technical program committees of numerous technical workshops and conferences. Has served on the Editorial Board of Reliability Engineering and System Safety.

- Has consulted on various risk assessment topics (including fire risk analysis, uncertainty analysis, systems analysis, hazardous materials transportation risk analysis; and common cause failure analysis) for: Pickard, Lowe and Garrick, Inc.; Electric Power Research Institute; Factory Mutual Research Corp.; American NuKEM Corporation; Arthur D. Little, Inc.; Brookhaven National Laboratory; and the U.S. Department of Energy.

Publications

Has authored or co-authored over 100 technical papers and summaries as well as numerous technical reports, and has served as co-editor for collections of invited papers on specific subjects. See attached list for a sample of publications. Full publication list available upon request.

Sample Publications

1. D. Helton, N. Siu, J. LaChance, T. Aldemir, R. Denning, and A. Mosleh, “U.S. NRC activities in the area of dynamic level 2 probabilistic safety assessments,” Proceedings of ESREL 2010 – Reliability, Risk and Safety: Back to the Future, Rhodes, Greece, September 5-9, 2010.
2. R. Youngblood, N. Siu, and H. Dezfuli, “PRA in design: increasing confidence in pre-operational assessments of risks (results of a joint NASA/NRC workshop),” Proceedings of PSAM 10, Tenth International Conference of Probabilistic Safety Assessment and Management, Seattle, WA, June 14-19, 2010.

3. N. Siu, A. Mosleh, and B. Meacham, “September 11, Columbia, Davis-Besse, and PRA: Business as Usual?” Probabilistic Safety Assessment and Managemen: PSAM 7 – ESREL ’04, C. Spitzer, U. Schmocker, and V. Dang, Eds., Springer-Verlag, London, 2004.
4. J. Forester, D. Bley, S. Cooper, E. Lois, N. Siu, A. Kolaczkowski, J. Wreathall, "Expert Elicitation Approach for Performing ATHEANA Quantification," Reliability Engineering and System Safety, 83, No. 2, 207-220, 2003.
5. N. Siu, “Nuclear Power Plant Risk Assessment,” in The SFPE Handbook of Fire Protection Engineering, 3rd Edition, National Fire Protection Association, 2002.
6. Organization for Economic Cooperation and Development, “CSNI Technical Opinion Paper No. 1: “Fire Probabilistic Safety Assessment for Nuclear Power Plants,” Nuclear Energy Agency, Committee for the Safety of Nuclear Installations, 2002. (Lead Author)
7. R. Woods, N. Siu, A. Kolaczkowski, and W. Galyean, “Selection of Pressurized Thermal Shock (PTS) Transients to Include in PTS Risk Analyses,” International Journal of Pressure Vessels and Piping, 78, 179-183, 2001.
8. N. Siu and M. Cunningham, “Using Risk Information: Lessons Learned from One Agency’s Approach,” Proceedings of United Engineering Foundation Conference on the Technical Basis for Performance-Based Fire Regulations, San Diego, CA, January 7-11, 2001, pp. 130-140.
9. H. Blackman, N. Siu, and A. Mosleh, Human Reliability Models: Theoretical and Practical Challenges, Center for Reliability Engineering, University of Maryland, College Park, MD, 1998.
10. N. Siu and D.L. Kelly, "Bayesian Parameter Estimation In Probabilistic Risk Assessment," Reliability Engineering and System Safety, 62, 89-116, 1998.
11. A. Mosleh, N. Siu, C. Smidts, and C. Lui, Model Uncertainty: Its Characterization and Quantification, Center for Reliability Engineering, University of Maryland, College Park, MD, 1995.
12. T. Aldemir, N. Siu, A. Mosleh, P.C. Cacciabue, G. Goktepe, Reliability and Safety Assessment of Dynamic Process Systems, Springer-Verlag, 1994.
13. N. Siu, "Risk Assessment for Dynamic Systems: An Overview," Reliability Engineering and System Safety, 43, No. 1, 43-73, 1994.
14. N. Siu, D. Karydas, and J. Temple, "Bayesian Assessment of Modeling Uncertainty: Application to Fire Risk Assessment," in Analysis and Management of Uncertainty: Theory and Application, B.M. Ayyub, M.M. Gupta, and L.N. Kanal, eds., North-Holland, 1992, pp. 351-361.
15. N. Siu, "A Monte Carlo Method for Multiple Parameter Estimation in the Presence of Uncertain Data," Reliability Engineering and System Safety, 28, No. 1, 59-98, 1990.
16. N. Siu and A. Mosleh, "Treating Data Uncertainties in Common Cause Failure Analysis," Nuclear Technology, 84, No. 3, 265-281, March 1989.
17. N. Siu and G. Apostolakis, "A Methodology for Analyzing the Detection and Suppression of Fires in Nuclear Power Plants," Nuclear Science and Engineering, 94, 213-226, November 1986.
18. M. Kazarians, N. Siu, and G. Apostolakis, "Fire Risk Analysis for Nuclear Power Plants: Methodological Developments and Applications," Risk Analysis, 5, 33-51, March 1985.
19. N. Siu and G. Apostolakis, "Probabilistic Models for Cable Tray Fires," Reliability Engineering, 3, 213-227, 1982.

Mano Subudhi, BNL

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.

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.

“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.

“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,” NUREG/CR-7150, Vol. 1, BNL-NUREG-98204-2012, EPRI 1026424, October 2012.

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

The Pennsylvania State University – University Park, PA
Bachelor of Science in Electrical Engineering
Graduated: December 2004

Registered Professional Engineer
Maryland, Reg. No. 38236, Fire Protection

Experience

U.S. Nuclear Regulatory Commission – Rockville, MD 11/2007–Present
Fire Protection Engineer *Office of Nuclear Regulatory Research (RES)*

- Panel Member of NRC/EPRI Electrical Expert PIRT (NUREG/CR-7150, Vol. 1)
- 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)

Publications

- ANS PSA 2013, *Fire PRA Advancements in Estimating the Likelihood of Fire-Induced Spurious Operations*, September 2013.
- NUREG-2128, *Electrical Cable Test Results and Analysis During Fire Exposure (ELECTRA-FIRE), February 2013*
- NUREG/CR-7150, *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*, October 2012.
- ANS 2011 Annual Meeting, *Electrical Failure Behavior of Kerite® FR Insulated Electrical Cable, June 2011*
- INTERFLAM 2010, *Electrical Circuit and Cable* Testing, July 2010
- PSAM 2010, *Fire-Induced Failure Mode Testing for dc-Powered Control Circuits*, June 2010.
- NUREG-1924, Electric Raceway Fire Barrier Systems in U.S. Nuclear Power Plants, May 2010.

Achievements

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, PES, ICC, SFPE, HKN

Jing Xing, NRC

Core Skills

Managing and Conducting Human Factors engineering in multiple domains including human performance analysis and experiments, human error identification, human-system interface design and evaluation, and human reliability analysis.

Collaborating and maintaining effective work relationships with technical and non-technical personnel.

Education

Ph.D in Neuroscience, University of Pennsylvania, 1993
M.S in Computer Vision and Biophysics, China Academy of Science, 1986
B.S in Electrical Engineering, Shandong University, China, 1983

Professional Experience

09/2008 - Present, Sr Human Factors Engineer and tech lead, Human Factors and Reliability Branch, Division of Risk Analysis, RES, NRC. Rockville, MD

Responsibilities: Served as a project manager and technical expert for conducting and directing human factors and reliability research for nuclear safety. Responsibilities included:

- Initiated, planned, and managed human factors (HF) and human reliability analysis (HRA) research projects for the NRC's regulatory activities.
- Integrated and coordinated the Branch's human factors (HF) and human reliability analysis (HRA) programs.
- Identified technical issues, applied HF and HRA methods/tools to develop resolutions, and made recommendations to management for decision-making.
- Maintained and facilitated communications among users, contractors, research colleagues, and management.
- Established and coordinated collaborations with research institutes, other government agencies, and international research communities.
- Provided technical support and supervision for the Halden Reactor Project as the NRC's HF and HRA representative.

09/2002 – 08/2008, Engineering Research Psychologist (FV-0180-J), Human Factors Research Division, Federal Aviation Administration (FAA), Oklahoma City, OK.

Responsibilities: Served as a principal investigator, project manager, and internal consultant in multiple domains of human factors and cognitive engineering. Areas of practice areas included human performance analysis, performance measurements, human-system interface design and evaluation, personnel selection and training, and safety intervention. Responsibilities included

- Developed, managed, and executed human factors research and engineering in air traffic control systems.
- Conducted all phases of human factors practices: identifying operational requirements, performing needs analysis, assessing solutions, developing research plans and

executing them, constructing theories/models, and delivering off-the-shelf products and strategic solutions to the agency.

- Analyzing operational issues and making recommendations to senior management on policy-making.
- Solicited, initiated, evaluated, and managed grants and contracts.
- Wrote reports/plans/proposals; made presentations to technical and non-technical audiences; organized meetings and work groups; coordinated collaborations within the FAA and between government agencies and industrial partners.

2000 – 2002 Senior Research Scientist, San Jose State University Foundation at Human Factors Division, NASA Ames Research Center, Moffett Field, CA

Responsibilities: Conducted research for space shuttle cockpit design, focusing on perceptual learning, attention, and image quality assessment. Conducted human factors engineering and practices in aerospace systems. Developed research programs and conducted full-cycle research; operated the visual psychophysics lab; written and verbal communications with grant monitors and stakeholders.

1998 - 1999 NIH Research Fellow, Department of Psychology, Stanford University, Stanford, CA

Responsibilities: Conducted research in Cognitive psychology, visual attention, object representation, and human performance measurement. Independently completed several research projects involving psychometric experimental design, statistic data analysis, and human performance modeling.

1993 - 1997 Research Associate, Brain and Cognitive Science, MIT, Cambridge, MA, and Computational Neural Systems, Caltech, Pasadena, CA.

Responsibilities: Conducted research in brain learning, attention and memory, neural network, and planning and cognitive control. Developed computational models to predict human learning performance and action intention; reviewed grant proposals and papers for journals and conferences; supervised graduate students; delivered presentations to academic audience and industrial founders.

1988 - 1993 Biomedical Fellowship Research Assistant, Departments of Physiology and Neuroscience, University of Pennsylvania, Philadelphia, PA

Responsibilities: Graduate study focused in cognitive neuroscience, behavioral psychology, and modeling/ simulation of complex systems. Thesis addressed brain learning, memory, and visual information processing. Independently constructed a set of heuristic learning rules, performed a series of neural network simulation of brain learning mechanisms, and developed models to predict learning performance under different ways of training. This research was a milestone in modeling of complex neural systems.

1986 - 1988 Engineering Researcher, National Laboratory of Pattern Recognition and Institute of Automation, China Academy of Science, Beijing, China

Responsibilities: Developed algorithms of image processing and prototyped pattern recognition systems for industrial applications.

Kiang Zee, ERIN Engineering and Research

Areas of Expertise: PRA/Fire PRA; 10 CFR 50.48(c) – NFPA 805; Electrical System Design; Single Failure Analysis; Electrical Separation; Reliability Analysis; Systems Engineering; Instrumentation and Controls; AC and DC Power Systems

Education

B.S., Electrical Engineering, San Jose State University

Work Experience Summary

Mr. Zee has over 30 years of experience in the nuclear and fossil power industries. His experience encompasses the broad spectrum of activities associated with power plant systems, electrical distribution systems, I&C systems, battery systems, protective relaying and coordination, PRAs and Fire PRAs, licensing and regulatory compliance, and circuit and raceway tracking systems. He has extensive experience in the development and application of Fire PRAs, design, review, and analysis of electrical systems, compliance with regulatory requirements and industry standards, 10CFR50 Appendix R, station blackout, and application PRAs. Mr. Zee is also fluent in applicable NRC requirements and industry standards and practices associated with electrical system operation, maintenance design, protection, and installation.

Work Experience

Mr. Zee is Vice President of the Engineering Services Group and has overall responsibility for all technical activities performed by that group. He has served in both project management and technical expert roles. He was the Project Manager and Lead Analyst for the updating of the Fire PRAs for the Exelon fleet as well as many plants transitioning to 10 CFR 50.48(c) – NFPA 805. These updates have reflected a graded approach to the application of state-of-the-art analysis methods which includes selected elements of NUREG-6850 as well as analysis refinements beyond that discussed in NUREG-6850. He participated in the development of the ANS Fire PRA Standard as a section writer and has participated on Peer Reviews. He assisted in the preparation of risk assessments in support of a R.G. 1.174 Exemption Request for Farley Plant that applied elements of the risk-informed/performance-based methods of NFPA-805. This Exemption Request was approved by the NRC.

Mr. Zee has provided technical support services related to at-power and shutdown fire risk studies for a number of nuclear facilities. These services have ranged from technical oversight and peer reviews to performing complete Fire PRAs. He has also performed detailed fire risk studies for the plant shutdown operating mode. He has provided fire risk related services for a significant fraction of the US Commercial Nuclear Industry. Mr. Zee is fluent with the applicable industry guidance associated with Fire PRA development. He has also developed detailed fire risk assessments in support of the Significance Determination Process (SDP). Mr. Zee is an active participant in industry activities related to fire risk technology. These activities include the development of the NEI Implementation Guide for NFPA 805 (NEI 04-02) as well as ongoing industry activities associated with enhancing and improving Fire PRA methods.

He has personally performed numerous other projects involving the application of probabilistic and deterministic technologies. These projects include fire risk assessments, plant system design as part of original facility design and construction as well as operating plant support, preparation of electrical design analyses, electrical separation and single failure analyses, Station Blackout, and R.G. 1.97 studies, maintenance program optimization, plant PRAs and Fire PRAs, USAR updates, and Design Basis Reconstitution.

He has developed innovative and cost effective solutions. His project-specific activities have included both the performance of detailed technical tasks as well as overall project management. Mr. Zee has performed detailed electrical system design adequacy reviews for many nuclear power plants. These reviews have included the comprehensive examination of the AC and DC system voltage and short circuit analyses, diesel generator analyses, coordination studies, and supporting analyses. The scope of reviews has also included those in preparation and/or support of an NRC SSFI and a subsequent EDSFI.

Mr. Zee has performed numerous plant modification reviews and prepared supporting safety evaluations as required by 10CFR50.59. He provided key technical oversight to ensure that required technical, installation, licensing, and design basis issues were properly addressed. This included issues such as interface with plant programs (IST, Appendix R, EQ, plant procedure, etc.), Single Failure, Electrical Separation, and Seismic.

He conducted regulatory compliance reviews for issues such as Electrical Separation, Single Failure, Station Blackout, R.G. 1.97, Appendix R, Generic Letters 89-10 and 96-01. Mr. Zee assisted in a comprehensive Electrical Separation assessment for SONGS-1 in support of SEP Topic closure. SONGS-1 was designed and constructed prior to the issuance of industry and regulatory guidance and presented numerous unique challenges. The scope of work required the development of an appropriate review criteria, evaluation methodology, and resolution plan for discrepant conditions. He also performed detailed Single Failure analyses for service water and electrical systems, as well as the ECCS for BWRs.

Mr. Zee performed reviews and evaluations relating to compliance with 10CFR50, Appendix R. His expertise includes safe shutdown equipment selection, safe shutdown logic development, support system reviews, identification of cabling vulnerabilities, hot short assessments, multiple high impedance short circuit studies, and regulatory compliance. His support of other industry issues includes Generic Letter 89-10 and 96-01. He has developed and implemented an analysis methodology for evaluating DC valve motor speed under reduced voltage and elevated temperature conditions. He has also performed comprehensive reviews of plant surveillance procedures to verify compliance with plant Technical Specification requirements.

He has participated in the development of the UFSAR for SONGS-1. This project was unique in that it was the Revision 0 document following completion of the SEP effort. Mr. Zee developed Design Basis and Criteria Documents for Electrical Separation and Single Failure and performed a detailed electrical separation review for SONGS-1. This plant was constructed prior to the development of industry standards and required the development of unique review criteria. He also performed detailed Single Failure reviews for both NSSS and BOP systems and participated in projects to support both original plant construction and operating plants, and has addressed configuration control issues.

PE License in Electrical: Alabama, California, Illinois, Maryland, Nebraska, and South Carolina.

APPENDIX B
PROJECT PLAN AND INSIGHTS

This appendix presents the project plan that was used in the PRA panel's expert elicitation process. This project plan details the roles and responsibilities of each expert in Table 2-1, the goals of each workshop, and other SSHAC Level 2 elicitation-process-related activities. Attachment 1 discusses moderator's insights gained from the PIRT and the PRA panel expert elicitation exercises undertaken in the JACQUE-FIRE program.

B.1 Background

The U.S. Nuclear Regulatory Commission (NRC) introduced numerous initiatives to transition from prescriptive rules and practices towards using risk information in decision-making. For fire protection, the NRC amended its requirements in Title 10 of the *Code of Federal Regulations*, Part 50 (10 CFR 50), Section 50.48 to permit existing reactor licensees voluntarily to adopt the risk-informed fire-protection requirements 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. This standard serves as an alternative to the existing deterministic fire-protection requirements in 10 CFR 50, Appendix R. The development of risk-informed/ performance-based approaches and insights are needed, in general, to support fire-protection decision-making.

Over the past decade, nuclear power industry and the NRC have conducted several testing programs, including the Electric Power Research Institute's (EPRI)/Nuclear Energy Institute (NEI) tests in 2002, the NRC's CAROLFIRE alternate current (AC) circuit tests in 2008, and the direct-current (DC) circuit testing of the NRC/EPRI's DESIREE-Fire program in 2012. The objectives of these programs varied, but all provided valuable data and identified the hot short-induced spurious operation phenomena associated with failures of electrical circuits in the event of a fire. The testing also offered insights on the risks of spurious operations for electrical circuits used in a Nuclear Power Plant (NPP). We can use the results of these tests to improve the application for licensees in both deterministic fire-safety protection and fire probabilistic risk assessments (Fire PRAs).

One key input to the latter is quantifying the probabilities related to the likelihood of spurious operation, after cable damage due to fire. The results from the tests mentioned above can be used to derive such probabilistic information, so to characterize the risk of fire-induced cable failure previous work undertaken by the EPRI in 2002 is documented in EPRI technical report 1006961, "*Expert Elicitation on Fire-induced Circuit Actuation*." However, this study was limited to data from only 18 tests. The recent test results of the CAROLFIRE and DESIREE-Fire program offer an additional 175 tests supporting the refinement of the best estimates of circuit failure probabilities given in the EPRI report, in addition to providing new data on ungrounded DC-circuit configurations.

B.2 Summary of Prior Efforts

Previously under Job Code Number (JCN) N6866, “Electric Circuit PIRT,” Brookhaven National Laboratory (BNL) completed a Phenomena Identification and Ranking Table (PIRT) study on the fire-induced effects of cable failure. A PIRT study constitutes a systematic approach to expert elicitation so to improve understanding of a technical issue and/or prioritize research. The results from the PIRT (NUREG/CR-7150, Volume 1) afforded qualitative insights on the importance of various circuit failures that will provide guidance for future research and for identifying any circuit configurations that may have been overlooked in the past testing programs and circuit analyses. The electrical PIRT study outlined the physics and physical parameters that influence fire-induced circuit-failure modes. These results offered qualitative information for the Fire PRA’s expert elicitation panel and recommendations for the NRC’s Office of Nuclear Reactor Regulation to consider in their regulatory applications of deterministic fire protection.

Based on the electrical PIRT panel’s recommendations, the NRC consolidated and analyzed the experimental data on fire-induced circuit and cable failure obtained from the EPRI/NEI- and NRC/SNL-tests for both AC and DC control circuits. The outcome was presented to the PIRT panel members in NUREG-2128 to aid them in assessing the effects of several influencing parameters on the spurious operations of electrical circuits.

The results of the electrical PIRT conducted under JCN N6866 will be used in the process of expert elicitation to focus research on developing best estimate conditional probabilities of various control circuit configurations for using in fire PRAs. The derived probabilities will reduce uncertainty with current estimates and also provide interim guidance on the conditional probabilities of spurious operations in control circuits.

B.3 Planning Meeting

This project selected a panel of fire PRA experts for a planning meeting held from January 31-February 2, 2012 during which the results of the electrical PIRT were presented to the PRA expert panel. They included examples of the control circuits most vulnerable to hot short-induced spurious operations of certain electrical end devices given a fire event in an NPP. They also encompassed the test data and their analyses from the EPRI/NEI and NRC/SNL cable-fire tests when affected by certain physical parameters on various control circuit configurations.

Based on the discussions of the PRA experts, it was decided that the sorting of the test data needed revision to obtain some meaningful estimation of certain circuit configurations associated with various end devices (e.g., MOVs, SOVs, Circuit Breakers). Additionally, certain control circuits with latching or a seal-in provision and other physical- and regulatory-factors (e.g., hot short duration, stroke time, end state, alternate shutdown panel) need to be considered in estimating the probabilities.

In addition, it was decided that an expert elicitation process, such as Senior Seismic Hazard Analysis Committee (SSHAC), must to be followed by the PRA experts to estimate the conditional probabilities of fire-induced spurious operation. A follow up “Go-To-Meeting” conference on March 22, 2012 among the PRA experts was held, and BNL presented the four Levels of SSHAC methodologies for the expert elicitation process.

B.4 Objectives

The objective of this project is to provide best estimate conditional probabilities on the likelihood of hot short-induced spurious operation given fire-induced cable damage for use in fire PRAs. These conditional probabilities are intended to revise, directly replace, or create new probabilities for Table 10 of NUREG/CR-6850 (Tables 10-1 through 10-5) and Figure 16-1 and Table 16-1 of its Supplement 1.

Specifically, using the SSHAC process, the project will achieve the following:

a. Estimate the distributions of the conditional probabilities and conditional duration probabilities of fire-induced cable and circuit failure phenomena for configurations where applicable test data are available, and,

b. Assess the distributions of the conditional probabilities and conditional duration probabilities of fire-induced cable and circuit failure phenomena for configurations where there are no applicable test data but expert judgment reasonably can offer quantitative estimates.

The hot short-induced spurious operation, a fire-induced cable and circuit-failure phenomenon, is defined as 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 of the circuit, (including the cables); examples are the spurious starting of a pump , or the spurious repositioning of a valve.

A fire-induced failure of a control cable for an end device (e.g., MOV or Circuit Breaker) may engender multiple possible failure modes of the device. To make the probabilities more useful in a fire PRA, the final state or failure mode of the end device, resulting from the hot shot-induced spurious operation signal from the control circuit, also expectedly will be assessed.

For example, in case of an MOV, given a fire-induced failure of its control cable, the valve may

- Remains as-is,
- Stroke into the full open- or full closed-position, or,
- Stroke continuously and randomly stop in some intermediate position as the valve cycles.

Assessing the final state or failure mode of the end device is an extension of the original objectives of the study that only considered estimating the distributions of the probabilities and durations.

B.5 Selection of SSHAC Level

The Senior Seismic Hazard Analysis Committee (SSHAC) process, described in NUREG/CR-6372, has four Levels of Study referred to as SSHAC Level 1, 2, 3, and 4. The objective is to assess all four to determine the appropriate Level that will be applied to this study.

The four Levels of study are defined in order of increasing resources (i.e., number of participants and funds available), and sophistication. In Levels 1 to 3, the technical integrator (TI) adopts the role of the “evaluator.” The TI develops the composite distribution of probability of spurious operation [P (SO)], i.e., an explicit probability distribution that can be incorporated in the fire PRA calculations. For Level 4, it applies the technical facilitator/integrator (TFI) approach in which a group of expert "evaluators" is identified and their judgments elicited. It involves a two-stage elicitation procedure. Each panelist playing an evaluator role provides mean estimate and uncertainty in the mean of P (SO) and each panelist playing an integrator role provides composite mean and composite uncertainty of P (SO). In its role as Integrator, the TFI develops a final composite assessment of P (SO) and the explicit probability distribution that can be incorporated in the fire PRA calculations. The important differentiation in terms of complexity, cost, and schedule exist between the simpler processes of Levels 1 and 2, and the more involved processes of Levels 3 and 4 that include workshops, a participatory peer review panel (PPRP), and, generally, larger groups of experts.

Based on the attributes associated with each of the four levels, the project management decided to adapt the SSHAC Level 2 approach for this project. However, the project will have the expert interactions via in-person workshops rather than individually. It also is desirable to include the PPRP in every workshop, though not strictly necessary.

B.6 Project Organization

The following table lists the project's participants and their main roles in the Level 2 SSHAC process for estimating the probabilities of hot short-induced spurious operations. Each individual identified below is expected to fulfill their specific role.

Role	Personnel
Project sponsor	Mark Henry Salley Richard Wachowiak
Project manager	Mark Henry Salley Richard Wachowiak Nicholas Melly David Gennardo
Technical Integrator (TI) team (Evaluator experts)	Raymond Gallucci Dave Miskiewicz Mano Subudhi (Moderator) Gerardo Martinez-Guridi
Proponent experts	Dennis Henneke Steve Nowlen * Gabe Taylor* Kiang Zee
Resource experts	Steve Nowlen * Dan Funk Gabe Taylor*
Participatory Peer Review Panel (PPRP)	Nathan Siu Robert Cavedo Jing Xing

* During the meetings and conference calls, each of these individuals should identify when he is acting as a proponent expert and when as a resource expert. In layman terms, the "hat" that he is wearing when offering his input should be clear to the rest of the experts.

The SSHAC's goal is "…Regardless of the scale of the … study the goal remains the same: to represent the center, the body, and the range that the larger informed technical community would have if they were to conduct the study…" Once a group of experts have evaluated all the available data, the center of these interpretations can be thought of as the best estimate or central value of the distribution of possible outcomes, that group determined. The term "body" can be thought of as the shape of the distribution of interpretations that lie around this best estimate, and capture the major portion of the mass of the distribution. The term "range" refers to the tails of this distribution and the limiting credible values.

In the rest of this section, each of the different roles is described in terms of the role of the individual or group in the process, the responsibilities that the individual or group assumes in the project, and the attributes that an individual should possess to contribute effectively in that particular position. In this discussion, attributes often are referred to as being required or necessary. In some cases, they may be considered desirable rather than indispensable, but a project is more likely to function successfully the more each participant is able and willing to conduct himself in accordance with the attributes of their assigned role.

Project Sponsor

The Project Sponsor is the entity that supports the project financially, hires the study team, and "owns" the study's results in the sense of property ownership.

Project Manager

The Project Manager (PM) is the point-of-contact between the project and the project sponsor, and is responsible for ensuring adherence to scope, schedule, and budget. The PM develops contracts with all technical personnel and subcontractors, organizes the workshops (including issuing invitations to all participants and observers), and keeps the sponsors apprised of progress in terms of scope, schedule, and budget. The responsibilities of the PM include holding each participant to their contractual roles and responsibilities.

Technical Integrator Team

The Technical Integrator (TI) team is responsible ultimately for developing the composite representation of the informed technical community (called the integrated distribution) for each conditional probability of spurious actuation. The main attributes of a TI are the ability to objectively evaluate the views of others in developing models and expressions of uncertainty, and to fully appreciate the influences of different models and parameters on the probabilities of spurious actuations. The TI also must be able to generate large volumes of clear, complete documentation on schedule, as well as to critically review all contributed documentation. The TI must be willing and able to make a major commitment of time and effort to the project.

In a Level 2 SSHAC process, the TI team comprises evaluator experts who play the most important role in this process. Their role is to examine objectively the data and diverse models, challenge their technical bases and underlying assumptions, and, where possible, test the models against observations. The process of evaluation includes identifying the issues and the applicable data, interacting with the experts (i.e., challenging other evaluators and proponent experts, interrogating resource experts), and finally considering alternative models and proponents' viewpoints.

The responsibility of the evaluator is to identify existing data, models, and methods as well as alternative technical interpretations and to evaluate them in terms of their general quality/ reliability and their specific applicability to the assessments being made. Evaluators must present a clear defense and rationale for their choices of selected models. They are not obliged to include in the models all proponent viewpoints, but must document their justification for excluding any particular model.

The attributes required for an evaluator expert include possession of a strong technical background, the ability to objectively evaluate the strengths and weaknesses of alternative models, and have at least some familiarity with approaches to quantifying uncertainties for PRA. A strong technical background is essential in enabling the evaluator to make informed decisions on existing models. For this reason, evaluator experts also should understand the basic mechanics of assessing probability distributions, and how those elements that they are charged with evaluating influence and impact estimates of the probabilities of spurious actuations.

Evaluator experts also must be able to work in teams; a congenial and respectful approach to other team members undoubtedly is very desirable. At the same time, an evaluator expert should have good communication skills to challenge a proponent’s views and to defend their own assessments. In addition, an evaluator must act with objectivity and be willing to forsake the role of proponent, up to and including critical assessment of models that they may have developed. An evaluator expert also must commit significant time and effort to the project.

Because interaction among evaluators is an integral and valuable part of the process, it is important that they bring different perspectives to the project. For this reason, it is desirable that no single organization or group is heavily represented within the team of evaluators.

Proponent Expert

The role of a proponent expert is to advocate a specific model, method, or parameter to use in assessing the probabilities of spurious actuations. The expert will advocate the model within the forum of a workshop. The proponent may be invited to present a model, usually his own, either because the model has been published, is widely known, and therefore, is considered a credible option or because the model is controversial. In some cases, a proponent may be invited to present a relatively new model, which may not have even been published, if it is thought that the model is directly relevant to the assessment and is credible.

The responsibility of a proponent is to promote the adoption of his model as input to calculating the probabilities of spurious actuations. The proponent is required to justify this assertion, to demonstrate the technical basis for the model, and to defend the model against technical challenges. The proponent also is charged with making full disclosure about the model in this process, including all underlying assumptions. A proponent expert has full responsibility for the material that he presents but does not participate in any way in evaluating alternative hypotheses or in the ownership of the models used for estimating probabilities.

An individual who has another role in the project (such as resource expert or a member of the evaluation team) could adopt the role of a proponent expert at a specific moment during the project. This necessitates assuring that everyone present is clearly aware of the switch of roles and that (in the case of an evaluator) the individual is prepared to subsequently revert to the role of impartial evaluator. This flexibility is useful, not least because in practice individuals have been willing to reveal in this way specific weakness or limitations of models that they developed, and, in some cases, even to propose that their models should not be adopted.

The attributes required of a proponent expert are knowledge (the same criteria as described for a resource expert) and the ability to defend his model and its basis.

Resource Expert

The role of a resource expert is to impartially present data, models, and methods, making this presentation in a workshop setting. The expert is expected to discuss his understanding of a particular data set, including how the data were obtained, or to present a model or a method with their limitations and caveats. In all cases, resource experts are expected to make the presentations without any interpretation, in terms of input, to estimating the probabilities of spurious actuations. The reason for this is that they are not undertaking the role of proponents or advocates of particular models or methods.

The main responsibility of resource experts is to share their technical knowledge impartially in their presentations to the evaluator experts. Accordingly, their presentation should make a full disclosure, including all caveats, assumptions, and limitations. The resource expert also is expected to respond candidly and impartially to questions from the evaluator experts. A resource expert has full responsibility for the material that they present, but does not participate in any way in the ownership of the models for assessing the probabilities of spurious actuations.

In this project, the resource experts are expected to prepare the “project database” containing all the data available for supporting the evaluation of probabilities of spurious actuations. As the project progresses and assessments are made, additional analysis may be needed to provide the information and analyses that the evaluators need for their assessments. As part of the project database, a comprehensive bibliography should be complied of applicable literature for the evaluators’ use, as well as providing documentation that the evaluators had knowledge of the literature during their assessments.

The necessary attributes of a resource expert are knowledge and impartiality. They must have a deep and broad knowledge of the subject, and often will have worked on that topic for many years and have publications related to their presentation. They must be able to withhold their judgment about the implications of the material that they present to estimating the probabilities of spurious actuations.

Participatory Peer Review Panel (PPRP)

The purpose of the peer review is to assure that a proper process was followed, that the study incorporates the diversity of views prevailing within the technical community that uncertainties were properly considered and incorporated into the analysis, and the documentation of the study is clear and complete.

The Project Sponsor or Project Manager assembles a peer review panel, possibly headed by a Chairman who is responsible for writing the panel's report (with a provision for expressing minority views if appropriate). The panel report is addressed to the Project Sponsor or the Project Manager, depending on the sponsor’s desires, provided that the peer reviewers can act, and feel that they can act, to provide independent comments.

PROJECT PLAN AND INSIGHTS

A Level 2 SSHAC process requires a “late-stage peer review” that occurs after the project is almost completed. Usually, it occurs when a draft of the final report has been prepared, or when the project's bottom-line results are close to being in final form. However, this project will incorporate a Participatory Peer Review Panel (PPRP) that is a feature of SSHAC Level 3 or 4 studies. The characteristics of this panel are described next.

Following the issue of the final project report, the PPRP must concur that the project conformed to the requirements of the specified study-level and that all technical assessments are adequately defended and documented.

The PPRP fulfills the following two parallel roles that collectively imply oversight to assure that the assessment is performed appropriately:

- Technical peer review is the review of the probabilistic aspects of the study, such as the models used for deriving the probability distributions of the spurious operations, and the completeness and quality of the data set used to derive these distributions. It also includes reviewing the assumptions, calculation methods, and the final results. This aspect requires expertise in interpreting the results of fire experiments, and in relevant probabilistic- and statistical-methodologies.

- Process peer review is the review of how the study is structured and executed, thus ensuring that the project conforms to the requirements of the selected SSHAC process-level. Because this study must rely heavily on expert interpretations of data that are sometimes scarce (or non-existent), the process peer review must concentrate on assuring that the uncertainties and the elicitation and incorporation of expert judgments is well considered. Reviewing this aspect requires expertise in expert elicitation, statistical analysis, and related disciplines, as well as adequate familiarity with the technical issues and methods related to the disciplines mentioned above (interpreting the results of fire experiments, and probabilistic- and statistical-methodologies).

One important point to emphasize is that membership of the PPRP always rests on an individual basis and not as an affiliate of any organization. Each member of the PPRP in the employ of an organization must ensure that it is clearly understood that they are not representing their employer or organization on the panel, but are serving in their own right as a recognized leader in their respective fields.

The responsibility of the PPRP is to provide clear and timely feedback to the TI and project manager to ensure that any technical- or process-deficiencies are identified at the earliest stage so that they can be corrected. More commonly, the PPRP provides its perspectives and advice on the manner in which ongoing activities can be improved or carried out more effectively. In terms of technical review, a key responsibility of the PPRP is to highlight any data, models or proponents that have not been considered. The PPRP also judges the justification provided for the models included or excluded.

The PPRP has the clear responsibility to be present as observers at all the formal workshops, and subsequently to submit a consensus report containing comments, questions, and suggestions. The basic responsibilities of the PPRP are the following[1]:

- Review the project plan.
- Review the workshop's agenda and lists of invited resource- and proponent-experts.
- Attend all workshops and submit written reports in a timely manner.
- Participate in daily debriefings with project or leaders at workshops.
- Directly challenge the evaluators' assessment at Workshop #3.
- Review the preliminary models for capture the center, body, and range of technically defensible interpretations.
- Review the draft of the final project report.
- Issue a consensus letter report after the final project report is completed.

One more responsibility of a PPRP member is to preserve their independent status throughout the project. On the one hand, this means not being drawn into the technical assessments to maintain objectivity. On the other hand, it involves resisting any temptation to represent the corporate views of the organization to which they are affiliated because PPRP members must always serve in an individual capacity on the panel, rather representative one.

The attributes of the PPRP can be defined both for individuals, and, in collective terms, for all of the members of the panel as a group. A key requirement is that each member of the group has an understanding of, and commitment to, the principles of the SSHAC process. In addition, the members of the panel must collectively cover all technical aspects of building models and of conducting a fire PRA. Similarly, it is desirable that the members of the PPRP are highly regarded within their technical communities. The members of the PPRP also should be prepared to commit sufficient time to the project to become fully familiar with the issues, data, and models, and to be able to review thoroughly the documentation developed.

The panel report will incorporate the two aspects of the review (i.e., technical- and process-peer reviews), and include a final evaluation of whether the TI team has considered the technical community's viewpoints, and has made a concerted attempt to capture the center, body, and range of the technical defensible interpretation in their final probability distributions. The report also should address the panel's final assessment of the process followed by the project, and whether or not that process is acceptable as a SSHAC process. The panel's assessment will be included in the final report of the project.

B.7 Work Plan's Key Task Areas

Workshops play a vital role in the SSHAC process in offering opportunities for key interactions to occur; for models and interpretations to be presented, debated, and defended; and, for sponsors and reviewers to observe the progress being made on the study. On the other hand, they are not the place where models are developed and technical assessments are made; that will occur between the workshops.

---

[1] Another PPRP responsibility is to highlight interface issues if these are not being addressed adequately. Such issues may arise when a project is divided into subprojects, each of which must interface correctly with the rest of the subprojects. However, for this particular project, there were no plans for such partition into subprojects at the time when the project plan was prepared.

The hallmark of a SSHAC process is the interaction that takes place in a series of structured, facilitated workshops. Each workshop has a specific focus and goal, and each requires that particular work activities have been conducted before its occurrence and certain work activities will occur following it. The ground rules for the workshops need to be established and presented at the beginning of each one, so that the attendees understand and can fulfill their particular roles. The ground rules also must be enforced consistently.

Three SSHAC workshops were planned for this project.

Workshop #1 Significant Issues and Available Data

The goals of workshop #1 are to identify (1) the technical issues of highest significance to evaluating the probabilities of spurious operations, and, (2) data and information that is available to support this evaluation.

At Workshop #1, the Technical Integrator (TI) team will establish the ground rules for all of the workshops. The workshop will begin by clearly defining its goals, explaining the process that will be followed, and defining the roles of all attendees.

First and foremost, the workshops are intended to provide information to assist the TI Leads and the evaluator experts in their technical assessments. Therefore, it is essential that they are given ample opportunity to ask questions and to thoroughly understand what is being presented. All other workshop attendees are “observers”, except as their participation is required. For example, at the first workshop, resource experts are asked to present and discuss the project’s database. Questions after each presentation first should come from the evaluator experts, not from other resource experts or other attendees. The TI is responsible for ensuring that the agenda is kept and all presentations occur equitably. A short period will be set aside at the end of each day for any observer at the workshop, including the PPRP, to make statements or to pose questions.

Before Workshop #1, the TI Leads should undertake preliminary evaluations and sensitivity studies to assist in identifying issues relevant to assessing the probabilities of spurious actuations based on the available data. The sensitivity analyses should be presented and discussed at the workshop; they can be supplemented by considering issues that experience generally showed to be important. The purpose of identifying these issues first is to provide a basis for focusing and prioritizing the development of the database; this part of the workshop should conclude with a listing of the issues for evaluating the probabilities, and a listing of the data available for resolving the issues.

The second part of Workshop #1 should focus on the data available to address the issues identified in the first part. The discussions of these data should be through a series of presentations by resource experts who have developed specific datasets. The goal of therein is to assist the TI members in identifying the data and information that should be made part of the project database, and in understanding, as far as possible, the attributes of the available data sets (e.g., any limitations or drawbacks) The resource experts also can offer their knowledge of additional data—beyond that given in their presentations—that the project should consider.

One concern that often emerges in the first workshop is the tendency for the resource experts to move from merely a presentation of available data into discussions of their interpretations of the data and the models that they have developed from it. In many science- and engineering-problems, no clear-cut boundary exists between what we call "data" and what we call "interpretations." The point here, from the standpoint of the SSHAC process, is that evaluator experts do evaluations of the data for the purpose of evaluating the probabilities of spurious operations. Moreover, Workshop #2 is the forum for hearing and debating alternative interpretations of the data.

On the other hand, since a project meeting already took place where resource experts initially presented the data available to all the experts (January 31 to February 2, 2012), part of Workshop #1 also may be allocated to initiate the activities in Workshop #2, as discussed next.

Workshop #2 Alternative Interpretations

The goals of Workshop #2 "Alternative Interpretations" are (1) to present, discuss, and debate alternative viewpoints on key technical issues; (2) to identify the technical bases for the alternative hypotheses and to discuss their associated uncertainties; and, (3) to offer a basis for the subsequent development of preliminary probabilistic evaluation models that consider these alternative viewpoints. The second workshop also affords an opportunity to review the progress being made on developing the database and to elicit additional input, as needed, on this activity.

A key attribute of this workshop is the discussion and debate of the merits of alternative models and viewpoints about key technical issues. Proponents and resource experts should discuss their interpretations and the data supporting them. Presentations of alternative viewpoints on the same topic should be compared, if possible, and a facilitated discussion should focus on the implications of the inputs to the evaluation of probabilities (not just on scientific viability) and on uncertainties (e.g., what alternative conceptual models would capture the range of interpretations and their relative credibility).

In capturing the spectrum of thinking across the entire technical community, a goal of this workshop is to provide an effective forum for exchanging ideas. More importantly for the SSHAC process, the workshop offers a unique opportunity for the evaluator experts to begin their consideration of the range of models and methods held by the larger technical community. Therefore, they should strive to not only understand these alternative interpretations, but also the degree to which each is supported by data. The proponent experts should be asked to be prepared to discuss the uncertainties in their interpretations, the strengths and weaknesses in their arguments, and their view of the degree of support that their interpretations have within the larger technical community. It often is useful for presenters to be given a list of questions developed by the TI so they can focus their presentations on areas of interest to model development. A role of the TI should be to offer support, as needed, to proponents to ensure that interpretations are not judged on the basis of presentation skills. Proponent experts should be encouraged to interact among themselves within the structure facilitated by the TI Leads. Some experience showed that asking proponents to consider the views of others in the community encourages useful discussion.

Workshop #3 Feedback

Following Workshop #2, the evaluator experts develop their preliminary models, based on which, preliminary calculations, and sensitivity analyses are conducted. The goal of Workshop #3 Feedback is to present and discuss the preliminary models and calculations in a forum offering feedback to the evaluators. It is given in the form of probability results and sensitivity analyses that illuminate the most important technical issues. Ideally, feedback is also given at this workshop via the participation of the peer review members in allowing them to ask questions about the preliminary probabilistic models and results. Feedback also is given at this workshop by the participation of the PPRP and allowing them to question the preliminary evaluation models. These interactions at this workshop will ensure that no significant issues were overlooked and will allow the evaluators to understand the relative importance of their models, uncertainties, and assessments of probabilities that will provide a basis for finalizing the models thereafter.

The workshop consists of two parts: (1) The evaluators presenting their preliminary models, particularly emphasizing the manner in which alternative viewpoints and uncertainties have been incorporated; and, (2) sensitivity analyses and probability calculations that affords insight into the preliminary models. In discussing the preliminary models, the technical bases for the assessments should be described to support discussions of the implications and constraints provided by the data. The PPRP will be expected to question and probe aspects of the preliminary model to understand the way in which the views of the larger technical community have been considered, and the range of technically defensible interpretations included.

In the second part of the workshop, the presentation of the sensitivity analyses and preliminary probability calculations will offer a means of focusing the discussions on those issues of the greatest probabilistic significance, including the largest contributors to uncertainty. In turn, this will focus the assessments undertaken after the workshop on those technical issues of most importance to the probabilistic results. It is important to include not only probability calculations and associated sensitivity analyses, but also sensitivity analyses that offer insights into the models themselves. For example, the relative contribution that the epistemic uncertainty in a particular element of the model has to an intermediate output can be explored. It is noted that these feedback calculations are not intended to afford a basis for artificially truncating or otherwise limiting the models that the evaluators developed. Rather, they are intended to give a basis for prioritizing the activities involved in developing the final models.

B.8 Project Schedule

As discussed earlier, this project will use the results from the electrical PIRT in determining the most vulnerable electrical control circuits in a typical nuclear power plant. Also, to calculate the best estimates of conditional probabilities for the hot short-induced spurious operations and their durations for these control circuits, the PRA expert panel will use the applicable EPRI/NEI- and NRC/SNL- cable test data.

The project involving the expert elicitation of PRA panel started at the beginning of this calendar year and will be completed by December 2013. The planning meeting during January 31-February 2, 2012 identified the appropriate control circuits and the types of data that will be available to the expert panel for their probability estimations.

On March 22, 2012, via a “Go-To-Meeting” BNL presented the overall training material entitled “Selecting an Appropriate SSHAC Level for Assessing the Probabilities of Fire-Induced Spurious Actuations” to all PRA expert panel members describing the roles and responsible that should be followed during the SSHAC Level 2 expert elicitation process.

The first and second workshops were planned for June 2012 and December 2012. Two separate Workshop #2 meetings of the PRA panel took place to discuss and determine the appropriate methods and processes to be used by all proponents for various cable-power supply configurations. The third workshop was held sometime in May 2013.

The draft NUREG report documenting the results from the expert elicitation of the PRA panel is now scheduled to be completed by September 30st 2013.

B.9 Deliverables

The project deliverable is a joint EPRI/NRC publication documenting the expert elicitation process and the best estimate probabilities of those control circuits vulnerable to hot short-induced spurious operations in the event of a fire in NPPs.

ATTACHMENT 1

INSIGHTS FROM EXPERT ELICITATION EXERCISES USED FOR ELECTRICAL PHENOMENON IDENTIFICATION AND REVIEW TABLE (PIRT), AND PRA EXPERT ELICITATION ON HOT SHORT-INDUCED SPURIOUS OPERATION OF DEVICES IN ELECTRICAL CIRCUITS

Mano Subudhi
Brookhaven National Laboratory

Over the past decade, the nuclear power industry and the U.S. Nuclear Regulatory Commission (NRC) conducted several cable-fire testing programs to identify the phenomena associated with electrical circuit failures, so that a better understanding of the phenomena could be used to improve fire safety and fire Probabilistic Risk Assessments (fire PRAs). The testing also provided insights into the risks of spurious actuations of safety devices in electrical circuits used in nuclear power plants (NPPs).

Under the auspices of NRC's Office of Nuclear Regulatory Research (NRC-RES), Brookhaven National Laboratory (BNL) performed two separate expert elicitation exercises on the Electrical Phenomena Identification and Ranking Table (PIRT) project (JCN N6866), and the PRA Expert Elicitation project (JCN N6980) under the JACQUE-FIRE program. In the PIRT study, the expert panel consisted of electrical and fire protection engineers with a balanced composition of panel members from the NRC and the nuclear power industry. The primary goal of this elicitation was to identify the electrical circuits (limited to control circuits) that are vulnerable to hot short-induced spurious operation of certain end devices (e.g., solenoid-operated valves (SOVs), motor-operated valves (MOVs), or circuit breakers). This phenomenon is conditional upon fire damage to associated electrical cables in NPPs. In the PRA expert elicitation project, the expert panel consisted of electrical and fire PRA engineers, with some basic knowledge of statistical- and reliability-analyses. Here also, the PRA panel comprised a balanced composition of regulators and industry members. The goal of this elicitation was to estimate the conditional probabilities of the hot short-induced spurious operations and their durations for the control circuits identified by the earlier Electrical PIRT program. The final outcome of these two exercises will aid in advancing the state-of-the-art of fire PRAs. Both qualitative- and quantitative-results can be used in fire PRAs in applying the National Fire Protection Association (NFPA) 805. In addition, these results could be incorporated into analyses of deterministic post-fire safe-shutdown circuits.

Both the Electrical PIRT expert panel and PRA expert panel utilized the same sets of test data obtained from cable-fire tests performed by the NRC, the EPRI, and Duke Energy. Expert judgment based on actual plant experience was used for cases where there are no test data.

The PIRT process systematically gathers information from experts (through open discussions) about those concerns that are not well understood and often require the convergence of a combination of several influencing factors that likely cause the occurrence of the phenomenon of interest . A test or an analysis may not address this happening absolutely with the desired level of certainty. Therefore, the expert elicitation by the Electrical PIRT panel was required to be comparatively unrestricted by rules so to harness the knowledge on the phenomenon from engineers with electrical-, testing-, and fire-safety background and to identify those electrical circuits that are vulnerable to hot short-induced spurious operations after the electrical cables were damaged by fire.

Once the PIRT panel identified the circuit configurations that are vulnerable to such failure modes, the PRA panel focused their elicitation process on assessing the conditional failure probabilities of these electrical devices. The objectives of the PRA panel are well defined by the test data and by the circuit configurations identified by the PIRT panel; therefore, a more restricted expert elicitation process governed by certain rules was considered appropriate in characterizing the analytical methods and processes that would estimate these conditional probabilities accurately from the findings from cable-fire tests. Unlike the PIRT panel that looked for circuit configurations influenced by the individual- and synergistic-effect of many physical parameters, the PRA panel’s primary focus was in appropriate analytical procedures and sorting of the fire test data that could be used, along with its expert judgment, in developing the probability estimates.

The details of all meetings associated with the Electrical PIRT program are given below.

PIRT MEETINGS

- FIRST PIRT MEETING (November 16-18, 2010)
    - Developed PIRT Process – Figures of Merit, Cable-Fire-Related Definitions, Excel® Scoring Sheets
    - Indentified Influencing Parameters for all Circuit Types

- SECOND PIRT MEETING (January 20-22, 2011)
    - Evaluated Panel Scores for all Circuit Types
    - Determined that because of lack of sufficient Test Data only Control Circuits were considered for the PIRT process. Power circuits – considered for certain open or unresolved cable-fire-related issues. Instrument Circuits – Panel suggested for future testing

- THIRD PIRT MEETING (February 16-18, 2011)
    - Determined that for Control Circuits, Test Data Analysis was needed
    - Formulated the analysis procedures for addressing all Influencing Parameters
    - Developed preliminary Ranking Tables

- FOURTH PIRT MEETING (May 11-13, 2011)
    - Discussed Both ac/dc Test Data Analysis (Preliminary)
    - Discussed Power Circuit and Instrument Circuit Issues
    - Re-scored (as a consensus) Influence Parameters based on AC/DC Preliminary Data Evaluation
    - Discussed PIRT Ranking Tables and Corresponding ac/dc Circuit Types to be addressed by the Panel

- FIFTH PIRT MEETING (September 27-29, 2011)
    - Evaluated Both AC/DC Test Data Analysis - Control Circuit Influencing Parameters
    - Discussed Power Circuit and Instrument Circuit Issues – Developed Scope and Resolutions
    - Re-evaluated Consensus Scores for Control Circuits and PIRT Ranking Tables

- SIXTH PIRT MEETING (November 29 – December 1, 2011)
  - Finalized PIRT Process Results for Control, Power and Instrument Circuits when subject to Hot Short-Induced Spurious Operations
  - Discussed the Framework for the PIRT Report
  - Discussed the 15 Control Circuit Configurations that are vulnerable to Hot Short-Induced Spurious Operation of SOVs, Breakers, and MOVs
  - Obtained Suggestions for Preparing the Volume 1 of NUREG/CR-7150

NUREG/CR-7150, Volume 1 documents the Electrical PIRT program's activities and the results of the expert elicitation exercise. The PIRT panel used the results from all fire tests to identify and rank 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 identified several circuit configurations that could be vulnerable to hot short-induced circuit failure modes resulting in spurious operation of certain end-devices. In addition to completing the PIRT exercise on control circuits, the PIRT panel reached technical consensus on several legacy issues associated with fire-protection circuits, such as power-cabling consequential hot shorts, open circuits on the secondary of current transformers, and multiple high-impedance faults. The panel noted a dearth of test data on instrument circuits and recommended future testing.

Utilizing the PIRT program's results for various control circuit configurations, the PRA panel used the expert elicitation process recommended by the NRC's Senior Seismic Hazard Analysis Committee (SSHAC) to estimate the conditional failure probabilities of certain end devices. Based on the attributes associated with each of the four levels of the SSHAC process, the project's sponsors decided to adapt the SSHAC Level 2 approach for this program. They also added several attributes of the SSHAC Level 3 and 4, such as expert interactions during in-person workshops rather than individually, included the participatory peer review panel (PPRP) in every workshop, and a technical integrator (TI) team. The details of all meetings and workshops associated with the PRA expert elicitation program are listed below.

PRA EXPERT ELICITATION WORKSHOPS

- INITIAL PRA EXPERT PANEL MEETING (January 31-February 2, 2012)
  - Introduced Control Circuit Results from the PIRT Exercise and Analysis of Test Data from NRC, EPRI, and DUKE
  - Discussed Elicitation Process and Methodology to be adapted in Estimating the Likelihood and Duration parameters
  - Reviewed the Project Plan describing the Scope and Roles of Individual Panel Members in accordance with the SSHAC Level 2 Process

- SSHAC LEVEL 2 WORKSHOP # 1 – Significant Issues and Available Data (June 5-7, 2012)
  - Defined and Assigned Roles for Expert Panel Members
  - Formed a Participatory Peer Review Panel per SSHAC Process
  - Discussed the Scope for Five Specific Circuit Cases and Decided Sorting of Test Data for each Case
  - Trained the Panel Members to follow the SSHAC Process

- SSHAC LEVEL 2 WORKSHOP #2 (MEETING #1) – Alternate Interpretations (October 9-12, 2012)
    - Discussed Approaches for Generating Conditional Probabilities of Spurious Operations
    - Debated Preliminary Results performed by One Proponent
    - Re-sorted the Test Data to obtain the Conditional Probabilities for Various Circuit Configurations

- SSHAC LEVEL 2 WORKSHOP #2 (MEETING #2) – Alternate Interpretations (November 27-29, 2012)
    - Discussed Different Approaches Recommended by Proponents
    - Incorporated PPRP Suggestions
    - Considered Approaches for Aggregating Proponent Inputs
    - Debated Methods for Estimating Likelihood and Duration Parameters

- SSHAC LEVEL 2 TECHNICAL INTEGRATOR (TI) TEAM MEETING #1 (January 30-31, 2013)
    - Formulated Aggregating Methods of the Information provided by Proponents
    - Devised Methods and Analysis Procedures for Developing the Community Distributions for Each Case

- SSHAC LEVEL 2 TECHNICAL INTEGRATOR (TI) TEAM MEETING #2 (April 9-10, 2013)
    - Finalized Conditional Probability and Duration Distributions
    - Incorporated Suggestions for Fine Tuning the Final Results for Each Control Circuit Cases

- SSHAC LEVEL 2 WORKSHOP # 3 – Feedback (May 7-9, 2013)
    - Presented the Final Results to the Full PRA Expert Panel
    - Presented the Final Results to the PIRT Panel Members
    - Finalized Procedures to Recalculate Probabilities Based on Recommendations from Both Panels
    - Obtained Suggestions for Preparing the Volume 2 of the NUREG/CR-7150

NUREG/CR-7150, Volume 2 (i.e., this report) documents the findings of the PRA expert elicitation and includes the best estimate conditional probabilities of hot short-induced spurious operations of control circuits, given fire damage to electrical cables.

The Table B-1 below presents several insights gleaned from the two expert elicitation processes.

Table B-1. Insights from Electrical PIRT and PRA Expert Elicitation Processes

ELECTRICAL PIRT (NON-STRUCTURED)	PRA EXPERT ELICITATION (STRUCTURED)
A. Expert Panel	
1. Individual panel member(s) may freely discuss anything and therefore, some may dominate the elicitation process	Each panel member participates in the elicitation process in a well-defined independent role(s)
2. Role(s) of each panel member is not pre-defined and most members serve multiple roles (such as proponent, peer reviewer, integrator)	Role(s) of each panel member is pre-defined. Overlap may be assigned of certain roles by an individual panel member (if deemed necessary)
3. More likely that one individual's agenda is discussed extensively	Less likely that one individual's agenda is discussed, unless the entire panel decides to include it in the scope
4. Moderator may control the panel or may let the panel control itself	Moderator controls the panel and the agenda of the meeting at all times
5. Less expensive and number of participants may be smaller	Costs more and number of participants is typically larger
B. Elicitation Process	
6. Elicitation of the same topic can be repeated as panel members revisit the topic (i.e., elicitation process is non-structured)	Avoids or minimizes duplicate elicitation of the same topic (i.e., elicitation process is structured and restricted)
7. The elicitation process allows free discussions and, therefore, panel members openly discuss their views	The elicitation process is governed by rules and therefore, panel members are restricted in openly discussing their views
8. Each workshop is characterized only in general, and the panel often restructures the agenda	Each workshop is clearly defined and the moderator controls the agenda
9. Requires no outside peer review during the elicitation process	Participatory Peer Review Panel (PPRP) provides guidance throughout the elicitation
10. Analysis requirements of input information from various sources (e.g., experience data, test data) change more often	Manipulation of input information is dictated by the proponents' direct need
11. The entire elicitation process dynamically changes with the panel discussions and needs	The elicitation process is structured and openly discussed. The agenda of each workshop is defined and followed by the panel

Table B-1. Insights from Electrical PIRT and PRA Expert Elicitation Processes

ELECTRICAL PIRT (NON-STRUCTURED)	PRA EXPERT ELICITATION (STRUCTURED)
12. Feedback is part of the general discussions by the panel in each workshop or meeting	Feedback is done at the last workshop or meeting after proponents and integrators complete their roles
C. Results	
13. The elicitation process ends with a consensus approach. May introduce biases due to pressure from a member(s)	Individual proponents provide inputs that are considered by the technical integrator(s). Biases are minimized
14. Often, results from the elicitation process are qualitative and may reflect an individual member's idea or suggestion	Results are based on proponents' proposed methods and values. The technical integrators decide the final outcome and technically justify their approach and values
15. Final results are the opinions of the panel, which may not include members with diverse attributes (e.g., academicians) outside the primary stake holders	Final results are designed to be a composite representation of the knowledge of the group and of the technical community at large
D. Miscellaneous	
16. Controlling the panel to stay on course and on schedule can become difficult	Controlling the panel to stay on course and on schedule become less problematic
17. Documentation becomes more difficult in presenting the information in a structured manner, when discussions are so wide-ranging	Documentation is structured to the elicitation process

Lessons Learned

- A diverse panel is beneficial to both elicitation processes. For example, an academician may have added different views for the phenomena or the method of estimating probability
- Moderator or facilitator needs to have a general understanding of the subject area
- Goals and Figure-of Merits or methods of analysis should be characterized clearly
- Information must be sorted or analyzed to support the panel's needs (e.g., the same fire-test data was sorted by influencing parameters for the PIRT panel, and by the failure mode for the PRA panel)

PROJECT PLAN AND INSIGHTS

- Stakeholders' need must be clearly stated (e.g., NRC's needs: identification of hot short-induced spurious operation phenomena in control circuits of interest and estimation of conditional probabilities for these phenomena)

- Participating members must commit to, and perform their assignments for the entire period (Typically, each member spends very little preparation time before attending the meetings or workshops – this was a problem for both panels)

- Views of experts in a focused subject area may be invited to better understand the physical process or mathematical approach (e.g., a statistician may suggest appropriate method of aggregating proponent numbers)

- Experts must be willing to write their ideas, conduct research, collect and review data collection (i.e., each member should spend additional time in writing down his ideas, undertake research if necessary, and read recent published materials on the subject).

- Standby experts participated the elicitation process are available and may act as substitutes if an active panel member decides to drop out.

APPENDIX C
SUMMARY OF PROPONENT REPORTS AND PANEL DISCUSSIONS

The purpose of this appendix is to offer readers an overview of how the proponents performed their assessment for each failure mode-circuit configuration in light of the data on cable-fire tests available to them. Sections C.1 and C.2 herein provide additional details on the estimations discussed in Section 3 of this report. In particular, they elaborate on the estimations of the conditional probabilities of spurious operation for specific cases associated with single break and double break control circuits. The information herein is a consolidation of that obtained from the fire testing and from the experts as delineated in proponents' reports, and as discussed during both the PRA and PIRT panels' deliberations. ***Therefore, this information should be considered as a summary rather than the consensus opinion of either panel.***

Section C.3 contains a technical discussion on developing the "CS-Model" of the Weibull distribution for estimating the probability of spurious operation duration. Martin Stutzke and Gabriel Taylor of NRC developed this model; Section 6 gives the results of duration probabilities for AC and DC control circuits.

The individual reports from all four proponents are included in a compact disk accompanying this Volume 2. Since each proponent provided his input in different format, Section C.4 offers a road map to better understand these e-files.

Attachment 1 to this Appendix includes sample templates of proponent inputs that the PRA panel presented to each of them to address each cell of Tables 3-1 and 3-2 associated with single break and double break spurious operation probability, and the estimation of duration likelihood.

C.1 Single Break Control Circuits (Base Case – SOV)

This section addresses only the SOV Base Case. The MOV case employs the estimated probabilities for the SOV sub-cases using a 'MOV Multiplier' approach, as discussed in Section 4.2. All rows and columns referred in Section C.1 are associated with Table 3-1 of the main report, and "**SB 0X_0Y**" below represents Row X Column Y of the Single Break sub-case cell in this table.

C.1.1 Grounded AC Power Source (Columns 1-3)

For the grounded AC power source, most proponent's assessments for thermoset (TS)-insulated, thermoplastic (TP)-insulated, and armored target cables are largely based on direct analysis of test data, adjusted by the individual expert's judgment. The case with the least test data is the "metal foil shield wrap cable" that was analyzed by extrapolating available test data, expert judgment, and an assumption that the cables are to have a robust metallic shield wrap. An aluminized Mylar® type shield wrap, and the like, do not constitute a robust metallic shield.

These cases should use the base case spurious operation probability values for TS- or TP-insulated conductor cable in Row 1 or 2, respectively.

The Column 3 probability values are derived from Column 1 and 2 numbers using a Boolean "OR" method described in Section 2.3.6, assuming that either one of these two hot short modes could occur in a fire.

Thermoset-Insulated Conductor Target Cable (Row 1)

In general, Table 3-1 applies only to any source cable; therefore they are not noted therein. However, Row 1, the "Thermoset-insulated Conductor Cable" case applies only to a cable configuration of TS source cable. For the inter-cable failure mode, the PIRT panel concluded that the case with TP source cable and TS target cable (i.e., TP→TS) is an incredible scenario (Table 3-3 in Volume 1)[1], and therefore, is excluded from this evaluation. In actual plant configurations, the PRA panel believed that there would be a few cases where a TS-insulated (target) cable is surrounded solely by TP-insulated cables with no other TS-insulated cable within the same raceways. Thus, the PIRT and PRA panel agree that a TP-insulated source cable causing a spurious actuation in a TS-insulated target cable via an inter-cable failure mode is incredible. The PRA panel also thought that this case is an uncommon configuration.

Note that this case of a specific, grounded AC, single break circuit with a single target has not been tested explicitly, but is analyzed by extrapolation from the test data on a grounded AC-simulated MOV circuit (with two targets) done under the EPRI/NEI, Duke Energy, and NRC/SNL (CAROLFIRE and DESIREE-Fire) programs.

SB 01_01: TS Intra-cable Hot Shorting (Column 1)

The PIRT panel initially assumed that the spurious operation probability numbers are weakly dependent on the types of conductor insulation (TS versus TP). However, a direct evaluation of the test data does not convey this. The differences are not large, but are enough to warrant separating the two cases at the beginning of the analysis, and allowing for the possibility of convergence after the likelihood estimates. As a practical matter, the two aggregates of probabilities for TS- and TP-insulated target cables are very similar. Having one aggregate number applicable to both would allow analysts to complete the analysis without needing to determine the cable type, which clearly is a desirable simplification.

For this expert elicitation, each proponent treated these cases separately; their findings later were combined by the technical integrators (TIs) into one number for intra-cable hot shorts regardless of insulation type, since the final probability numbers were very comparable. During deliberations, the PIRT and PRA panels concluded that the type of insulation material has no effect on the conditional probabilities of intra-cable hot short-induced spurious operation given cable damage[2] due to a fire. The insulation material already is consumed by the fire; the copper conductors are exposed for interaction with adjacent conductors within the same cable, or the

---

[1] Fire tends to char thermoset (TS) insulation material (at a relatively higher temperature) rather than melting it like thermoplastic (TP) material. TP insulation material tends to melt away from the conductors early at a lower temperature under a fire than does TS material, thereby allowing more direct access to the conductors from external cables or ground.

[2] Cable damage here assumes that fire has consumed the insulation materials leaving the copper conductors bare in TP-insulated conductor cables, and charred in place for TS-insulated ones.

ground in the case of TP-insulated cable; any mechanical force (e.g., water spray, movement of the cable during fire) would expose the copper conductors for a similar interaction in TS-insulated cables. However, for inter-cable hot shorts in Column 2 and aggregates in Column 3 both panels believed that type of insulation influences the likelihood of hot shorts (HSs) because of their timing of cable damage (and threshold-damage temperatures) that could influence the interaction with conductors from adjacent cables or the ground; therefore, they are kept separate.

SB 01_02: TS Inter-Cable Hot Shorting (Column 2)

Despite many opportunities for interaction between multi-conductor cables in tests, there was no occurrence wherein a direct 'TS→TS' inter-cable spurious operation occurred. There was one relevant case in CAROLFIRE, where the insulation-resistance monitoring system (IRMS) recorded a TS→TS inter-cable short formed as a primary failure mode. The mitigating consideration here is that the IRMS is non-specific to source/target configuration; that is, it says only that conductors in two separate multi-conductor TS cables shorted together before any other failures were observed. Had those two conductors in that test case been associated with a source and target conductor, it would have been highly likely that a spurious operation would have occurred. While not an actual spurious operation event, the IRMS does suggest that such interactions between two cables could occur.

The spurious operation event would depend on the random chance that one conductor was a compatible source and the other the target of concern. The lack of any other cases outside of the one IRMS event argues for a probability estimate less than that for the intra-cable case.

Thermoplastic-Insulated Conductor Target Cable (Row 2)

The "TP-insulated Conductor Cable" target cable case includes configurations of both TS and TP source cables (TS→TP and TP→TP). The analysis of test data and expert judgment here parallels that for the TS target cable case and many of the comments given above also apply to the TP target cable.

SB 02_01: TP Intra-Cable Hot Shorting (Column 1)

The test numbers for spurious operation occurrences are slightly lower (~10%) than those seen for the TS target cable case. Testing showed that TP cables tended to have more wide-spread conductor involvement in hot shorting groups; that is, once shorting begins, many conductors tended to become involved compared to TS cables where the shorting was somewhat more restricted.

SB 02_02: TP Inter-Cable Hot Shorting (Column 2)

Inter-cable interactions from both TS and TP source conductors to TP target conductors (TS→TP and TP→TP) were observed in CAROLFIRE and EPRI testing. The former noted a few instances where inter-cable hot shorts were caused by a TS-source partially energizing a TP-target cable. The latter observed inter-cable TP→TP interactions but the test configuration is not typical (i.e., single conductors surrounding a multi-conductor cable)[3].

Metal Foil Shield Wrap Target Cable (Row 3)

This analysis assumes a grounded robust metallic shield wrap (not simply aluminized Mylar®). In addition to the shield wrap, a drain wire may or may not be present and the results still apply. If the shield wrap is not grounded or is similar to a Mylar® construction, the base cases for “Thermoset- or Thermoplastic-insulated Conductor Cable” are applicable.

For this case, there are only three tests, all based on a Japanese-manufactured cable; no spurious operation events were observed in any. This supports the idea that a robust grounded shield wrap will reduce the probability of spurious operation. However, the evidence is considered rather weak, due to the small sample of cables tested.

SB 03_01: Shield Wrap Intra-cable Hot Shorting (Column 1)

The presence of a robust shield wrap much enhances the ground plane that is a mitigating effect for grounded circuits. The likelihood of interactions between the source conductors and ground rises, likely by a significant amount compared to the base case (TS without drain wire or shield wrap). No tests have been undertaken to show whether the shield wrap has an effect as strong as armor.

SB 03_02 - Incredible: Shield Wrap Inter-cable Hot Shorting (Column 2)

Both panels deemed inter-cable hot shorting through a robust grounded shield wrap independent of ground as “incredible”.

Armored Target Cable (Row 4)

The primary test data for armored cable was from Duke Energy’s testing. It had the two unique attributes.

- First, the motor starter relays were mechanically and electrically interlocked. Hence, both motor starters could not pick up at the same time. However, the voltage data for these devices was acquired upstream of the interlock, as shown in the electrical diagrams in the Duke Energy report. Hence, had both targets seen hot shorts, this would be reflected in the data, at least “nominally.”

- Second, the Duke Energy tests used a relatively slow data-scan rate (in every 15 seconds) so that the data often missed the voltage and current pickup associated with hot shorts and spurious operations. The test report includes alternative observations (i.e., visual observations) of the spurious operation events based on the actual lock-in on the motor starters, so it is unlikely that any actual spurious operation events were missed. Indeed, it also appears that the spurious operation duration times were

---

[3] However, none of the follow-up testing programs was designed to look for TP→TP inter-cable interactions. The test results might lead to the conclusion that the TP→TP inter-cable hot shorts could occur with greater likelihood than TS→TS.

determined independently (from visual observation) since most reported durations were less than a full data-scan cycle.

The main shortcoming of using a slow rate of data acquisition is that it is not possible to determine reliably if or when both motor starter relay conductors may have exhibited hot shorts. Any hits to the first coil activated were identified. Therefore, a slow scan rate is not a problem for counting the first spurious operation's lock-in since we do not have to rely on only the electrical data; we have an alternate basis (i.e., visual) for identifying spurious operation of first target hit. It appears that, similar to other tests undertaken by the EPRI and the NRC, where, in many cases, there were hot shorts to both conductors as evidenced by increased voltage and current reading on both the relay targets. However, the slow scan rate makes it impossible to determine the peak values. Hence, an analysis of the data similar to that of other tests, where the active targets are counted individually, is not applicable to Duke Energy's test data.

The test circuit design and slow data rate together mean that one cannot split the two targets and derive individual target counts for the SOV cases in the way that was done for the EPRI/NEI and NRC/SNL test data. One can see the first motor starter locking-in via data and visual observations, but once one relay locks-in, the second is locked-out. Therefore, "nominally" is added to the first bullet above because one should have seen a voltage spike to the conductor leading to the second starter coil because the voltage monitoring appears to be up-stream of the electrical interlock. Theoretically, if there was a hot short to that conductor, it should show in the data. However, the slow scan rate means those data are not reliable indicators because they easily could have missed a hit to the second coil if the hot short persisted less than 15s (one scan interval), and most of them were less than 15s. For the second coil, there is no visual observation to act as backup because the second relay is locked-out and never moves. Thus, one cannot use the "count two independent SOVs" approach.

In view of the comparatively short duration of the spurious operation signals reported by Duke Energy tests for the armored cables compared to the non-armored ones, it does not appear appropriate simply to apply a reduction factor based on the non-armored tests. Clearly, duration and timing play a key role in the behavior leading to both targets seeing spurious operation signals; the armored and non-armored tests do not agree well in this regard.

Accordingly, the test data were considered to be a single target circuits. This decision may represent a very modest conservatism, but seemingly is the only reasonable way to look at the data.

SB 04_01: Armored Intra-Cable Hot Shorting (Column 1)

The test data for grounded AC and armored cable are sparse, but some information is available from the EPRI/NEI tests and those tests from Duke Energy based on their proprietary test report.

The EPRI/NEI tests showed 1 out of 7 spurious operations, but that case is suspect because it violated the requirement for the cable bend radius. Duke Energy's testing included a fairly large number of additional test cases (i.e., 6 tests each with 8 possible SOs) where no spurious operations were observed for grounded AC circuits. Overall, the testing shows that the presence of the grounded armor has a strong mitigating effect on spurious operation likelihoods for grounded AC circuits. Note that actual proprietary test data details from Duke Energy's testing are not stated here, although they are included in the estimation of probabilities for this sub-case in Section 4.

SB 04_02 - Incredible: Armored Inter-Cable Hot Shorting (Column 2)

Both panels considered that inter-cable hot shorting through grounded armor to a target cable associated with a grounded circuit is “incredible.”

C.1.2 Ungrounded AC with Individual CPTs Power Source (Columns 4-6)

There are no test data to directly support most cases under this power-supply configuration. There are limited data from the CAROLFIRE program for an ungrounded CPT-driven MOV circuit with TS- and TP-insulated cables, but, at most, for a single circuit per test (there is no possibility of circuit-to-circuit interactions). Hence, most cases were developed largely from extrapolations from other, via expert judgment. For armored cables, all proponents except one considered the Duke Energy test data; he reported his evaluation before receiving the proprietary Duke Energy Test Report late in the expert elicitation process.

Column 6 probability values are derived from Columns 4 and 5 numbers using Boolean “OR” method described in Section 2.3.6, assuming either one of these two hot short modes may happen during a fire.

<u>Thermoset-Insulated Target Conductor Cable (Row 1)</u>

SB 01_04: TS Intra-Cable Target Hot Shorting (Column 4)

CAROLFIRE testing included this cable-circuit configuration indicating higher spurious operations due to intra-cable shorting. The ungrounded AC w/CPTs case resulted in slightly higher SOs than the corresponding grounded AC based mainly on the fact that for ungrounded circuits; grounded conductors and external grounds do not act as mitigating factors until multiple shorts occur. That is, a single short to ground does not clear circuit protection here (whereas it does for grounded AC) leaving more opportunity for hot shorts and spurious operation given intra-cable shorting. The only single short that will cause a fuse-clear failure is when an energized conductor shorts with a common return conductor from the same power supply.

SB 01_05: TS Inter-Cable Target Hot Shorting (Column 5)

The ungrounded AC power source cases assume power is supplied to each circuit from an individual ungrounded CPT with each circuit contained in its own multi-conductor cable. Hence, inter-cable spurious operations would occur only when the CPT for one circuit (one source cable) energizes a second circuit (target cable). However, separate ungrounded CPTs are not considered as compatible power sources. Hence, a single hot short between separate CPT circuit cables cannot cause a spurious operation. For one circuit to power another, both sides of a common CPT must act as sources against the specific target conductors in the target circuit. This requirement sharply reduces the likelihood of direct inter-cable hot shorts leading to spurious operation compared to the grounded AC case where only a single inter-cable hot short is needed.

It is assumed that one of the two hot shorts may result from a ground fault equivalent hot short (GFEHS) event. That is, if one side of the source circuit power supply and one side of the target circuit end device become grounded, then a single additional inter-cable hot short could cause spurious operation provided that the source circuit fuses are intact. Overall, the inter-cable shorting configurations leading to spurious operation are specific and must occur concurrently.

There are no test data for this sub-case. The PIRT panel did not explicitly consider this power-source configuration in its deliberations; rather, it was added later as the final tables were re-organized for this expert panel's use. The GFEHS configuration is the only shorting configuration that has any chance for causing failure from spurious operation. Concurrent direct conductor-to-conductor shorts between specific conductors pair on two separate multi-conductor cables under a compatible power source was judged implausible.

Table 3-1 does not include the GFEHS mode for this power supply case, since there are no test data, unlike the ungrounded DC (or ungrounded distributed AC) power supply cases. Therefore, the TI team considered in their probability estimates the GFEHS mode as part of the inter-cable hot short mode, even though proponents proposed their estimates separately, as discussed in Section 3.1.2.

Thermoplastic-Insulated Target Conductor Cable (Row 2)

SB 02_04: TP Intra-Cable Hot Shorting (Column 4)

This is another case with minimal test data set in the CAROLFIRE. The raw number of spurious operation events there is 60-80% given the small number of trials (i.e., ~5 trials). As discussed for the "Thermoset-insulated Conductor Cable" target cable the lack of a grounded power source appears to increase likelihood of spurious operation, although the wiring configuration is important too.

Overall, the TP target intra-cable numbers are consistent with those seen for TS target cables under SB 01_04.

SB 02_05: TP Inter-Cable Hot Shorting (Column 5)

This case parallels that described for the "TS-insulated Conductor Cable" for SB 01_05.

Metal Foil Shield Wrap Target Cable (Row 3)

SB 03_04: Intra-Cable hot Shorting (Column 4)

No test data is available for this case. The assessment is compared the Thermoset- or Thermoplastic-Insulated Conductor Cable" case and that of the "Armored Cable." The armor's effect was to marginally lower spurious operation probability. The armor likely has a much stronger ground-plane effect than does a metal-shield wrap.

SB 03_05 - Incredible: Inter-Cable Hot Shorting (Column 5)

Both panels considered this case "incredible."

Armored Target Cable (Row 4)

Discussions under grounded AC power supply cases (Row 4, Columns 1 and 2) in Section C.1.1 apply here.

SB 04_04: Intra-Cable Hot Shorting (Column 4)

The data for ungrounded AC with armored cable is based exclusively on the results from the Duke Energy tests since there are none from tests undertaken NRC or EPRI. The Duke Energy tests included a fair number of tests and had eight circuits per test. Overall, they indicated spurious operation in approximately 58% of their tests. Similar to NRC programs Duke Energy used the source-centered wiring configuration known to produce more conservative results (i.e., more spurious operations).

SB 04_05 - Incredible: Inter-Cable Hot Shorting (Column 5)

Both panels considered this case “incredible.”

C.1.3 Ungrounded DC (or Ungrounded Distributed AC) Power Source (Columns 7-10)

Both the PIRT and PRA panels concluded that ungrounded DC powered circuit failure modes also are applicable to circuits powered from an ungrounded distributed AC power supply, since the hot short modes of failure for these two configurations are presumed to behave similarly under fire.

There are considerable data for the ungrounded DC power source from DESIREE-Fire, KATEFIRE, and the Duke Energy tests. Hence, most of these cases are based on data rather than extrapolation. The major exception is the case of the metal-foil-shield wrap target cable (Row 3) for which there is no tests data or a limited amount (from Japanese cables tested by NRC/SNL). Therefore, extrapolation between the Thermoset-insulated or Thermoplastic-insulated base cases and the armored target cable was used for Row 3, in addition to expert judgment.

One of the more significant challenges related to DC circuits is the GFEHS failure mode observed in the DESIREE-Fire testing. As described in the findings of data analysis in the roll-up table, a substantive number of these events were seen during the DESIREE-Fire test program. The data analysis, presented in the data spreadsheets by the NRC staff, cites the number of GFEHS-induced spurious operation events that occurred for various cable groups and, as a companion datum, the number of “tests” associated with these events. However, the companion datum actually is the number of individual circuit trials for each group (i.e., each individual test had more than one circuit present, so there are far more circuit trials than separate tests). In total, there were 30 GFEHS spurious operation events (16 from Intermediate Scale and 14 from the small-scale Penlight tests) in 169 individual circuit trials where the opportunity existed. This is a larger number of events indicating roughly a 1-in-6 overall rate of GFEHS spurious operations.

One question concerns the applicability of the small-scale Penlight test data. In some cases, a higher percentage of events are associated with Penlight tests, while in others, more are associated with the Intermediate Scale tests. Overall (blending all cases), the fractions are similar (Table C-1).

The final spurious operation ratio values are similar, well within the general uncertainty bounds. From this testing, it essentially is inevitable that, as a result of the battery bank, will be grounded due to cable failures. Hence, the question is whether or not an appropriate target conductor experiences a short to ground concurrent with the appropriate side of the battery bank (e.g., the positive side) being grounded.

Table C-1. Comparison of Intermediate Scale and Penlight Test Data For GFEHS Spurious Operation Failure Mode

Test Scale	Total Circuit Trials	GFEHS Spurious Operation Events	Nominal Ratio (Spurious Operation Events/Circuit Trial)
Intermediate Scale	97	16	0.16
Small Scale Penlight	72	14	0.19
Both combined	169	30	0.18

Another aspect of analyzing a GFEHS-induced spurious operation event is that in other cases (e.g., intra-cable shorting modes) adjustment factors typically are applied to account for experimental biases related to wiring configuration, and the fact that spare conductors were not generally grounded, as discussed in Section 3.1.3. For GFEHS-induced spurious operations neither factor applies. In an ungrounded circuit, spare conductors would not be grounded. It is unclear how the wiring configuration would impact the likelihood of GFEHS-induced spurious operation events. There likely is some effect, but no basis for assessing it.

Column 10 aggregate probability values are derived from Columns 7, 8 and 9 numbers using the Boolean "OR" method described in Section 2.3.6, assuming that any one of these three hot short modes may happen in a fire.

Thermoset-Insulated Conductor Target Cable (Row 1)

SB 01_07: TS Intra-Cable Hot Shorting (Column 7)

There is sufficient data for different types of circuits (MOV1, MOV2, SOV1, SOV2, Large Coil and 1" valve SOV) to form a set for evaluation. Penlight data also is available for this intra-cable case.

SB 01_08: TS Inter-Cable Hot Shorting (Column 8)

Many tests were performed, and no inter-cable hot shorts were found in them. There are no new data or insights on this case beyond that considered in that of the grounded AC. It was recommended that due to the locations of cables within the test chamber that the data from the Penlight tests should not be combined with that from the Intermediate Scale test.

SB 01_09: Ground Fault Equivalent Hot Shorting (Column 9)

For the TS cables, there were 14 GFEHS-induced spurious operations in 87 circuit-test trials. Including the Penlight test data was recommended since there is not much difference in the two test conditions of the DESIREE-Fire program.

Thermoplastic-Insulated Conductor Target Cable (Row 2)

SB 02_07: TP Intra-Cable Hot Shorting (Column 7)

The discussions under TS-insulated Conductor Cable SB 01_07 above apply.

SB 02_08: TP Inter-Cable Hot Shorting (Column 8)

This case has no data or insights to offer beyond that considered in the grounded AC case in Section C.1.1.

SB 02_09: Ground Fault Equivalent Hot Shorting (Column 9)

This is an interesting case and one that is an outlier in some respects. This is the one case where the disparity between Penlight and Intermediate Scale results is large. In Penlight there were six GFEHS spurious-operation events in 28 trials, yielding a ratio of 0.21 spurious operation events per trial. In the Intermediate Scale there were just three GFEHS spurious operations 35 trials for a ratio of 0.09 spurious operation events per trial. Why the two test scales differ is not understood.

For consistency, it is appropriate to look at the aggregate of the two test scales yielding nine GFEHS spurious operation events in 63 total trials for a ratio of 0.14 events per trial. This value once again is surprisingly consistent with the nominal ratios of 0.16 events per trial illustrated in Table C-1. Consequently, the Penlight and Intermediate Scale test data are combined as the basis for this case.

Metal Foil Shield Wrap Target Cable (Row 3)

SB 03_07: Intra-Cable Hot Shorting (Column 7)

This case has three spurious operation events in seven trials for a nominal likelihood of 0.43, again a very limited data set. As with other shield-wrap cases, the probability numbers to fall somewhere between the TS- and TP-base cases (Rows 1 and 2), and that of the armored cable (Row 4). The basis for this assessment matches the discussions for grounded and ungrounded AC with individual CPTs cases.

SB 03_08 - Incredible: Inter-Cable Hot Shorting (Column 8)

Both panels considered this case “incredible.”

SB 03_09: Ground Fault Equivalent Hot Shorting (Column 9)

This is a case with only seven trials. There were two GFEHS spurious operation events in them for a nominal ratio of 0.29 spurious operation events per trial, is consistent with other effects for the shield-wrap case. That is, in other cases the behaviors of the shield-wrap cable fell in-between the base TS- and TP-cables and the armored cable. This applies here to the TS-insulated or TP-insulated at point estimates of 0.16 and that for the armored cable of 0.50.

Armored Target Cable (Row 4)

SB 04_07: Intra-Cable Hot Shorting (Column 7)

This case is difficult given the small set of experimental trials from the DESIREE-Fire tests. There are some fairly serious issues and spurious operation events with the Duke Energy testing that forms part of the basis for this case. In some of those tests their measurement shunts, and some test-relay target coils ignited. One of the two relevant tests was ended early due to safety concerns; only five of the eight circuits present failed in testing.

This assessment is based, in part, on the MOV and SOV cases from DESIREE-Fire that encompasses six circuit trials with armored cables. Since three of them involved the dual-target MOV circuits, they were analyzed using the target approach as in other cases, yielding nine total circuit/target trials (identified in the roll-up table: MOV tests D-IT-9-MOV2, D-P-22-MOV1, D-P-22-MOV2, and SOV tests D-IT-9-SOV2, D-P-20-SOV1, D-P-20-SOV2). The overall results for these cases are consistent. Considering all the individual targets, there were a total of six spurious operation events in nine circuit/target trials giving a nominal 0.66 probability of spurious operation.

The Duke Energy tests included two with ungrounded DC MOV circuits (Tests 13 and 14). In Test 13, there were eight spurious coil operations out of a possible 16, but, in some cases, the shunts in the circuit burned early in testing and this may have prevented additional spurious operations from being observed. More telling is Test 14 that was ended due to safety concerns when five of the eight circuits had failed. However, all 10 of the target coils in the five damaged circuits experienced spurious operation for a nominal 100% ratio. If the two tests are taken as cited, this represents 18 out of 26 spurious operations, or a point estimate of 0.7. However, this figure may be low due to the problematic burning of the shunts and, in some cases, the coils themselves, plus the early termination of the second test.

SB 04_08 - Incredible: Inter-Cable Hot Shorting (Column 8)

Both panels considered this case “incredible.”

SB 04_09: Ground Fault Equivalent Hot Shorting (Column 9)

This case had very few trials, but a relatively high number of GFEHS-induced spurious operation events, viz., 6 in just 12 circuit trials giving a nominal ratio of 0.5 events per trial. i.e., higher than any other case, but likely reflects the prevalent role of the grounded armor in the shorting behavior. That is, with grounded armor present, the cable conductors have ready access to that ground plane, so that when the battery becomes grounded, a GFEHS-induced spurious operation event seems likely. This conclusion is consistent with the fact that for grounded AC circuits, the grounded armor virtually eliminated spurious operations.

C.2 Double Break Control Circuits

All rows and columns referred to Section C.2 are associated with Table 3-2 in Section 3 of this report and "**DB 0X_0Y**" below represents Row X Column Y of Double Break sub-case cell in this table.

C.2.1 Ungrounded AC (w/ Individual CPTs)

As discussed in Section 3.1.2, one of the two hot shorts in an ungrounded AC circuit, with power from individual CPT is the result of a GFEHS. Examples of such circuits are illustrated in Appendix C of Volume 1. The GFEHS is the only shorting configuration that has any real chance for causing this configuration to fail from a spurious operation. Concurrent direct inter-cable hot shorts seem more unlikely. Therefore, there is no particular difference either between Column 2 and Column 4 or between Column 3 and Column 5 in Table 3-2, since to have an intra-cable or an inter-cable hot short-induced spurious operation in such an ungrounded circuit, one of the two needed hot shorts must be a GFEHS, as discussed in Section C.1.2, under SB 01_05.

Therefore, the Columns 4 and 5 for this power source configuration are eliminated from the Table 3-2 in the result in Section 5. Also, there is no corresponding single break test data available in Table 3-1 for the GFEHS mode of failure for this power-source configuration.
All cells marked "incredible" in Table 3-2 are considered so by both panels; therefore, the PRA panel did not consider the probability values for their spurious operation. However, when Column 2 and Column 4 are merged for the Rows 3 and 4, those in the resulting Column 2 represent the Column 4 values instead of the originally marked "incredible" events.

However, for this power supply, the new Column 4 (Column 6 in Table 3-2) represents the aggregate and its probability values are derived from the numbers in Columns 1, 2, and 3 using the Boolean "OR" method described in Section 2.3.6, and assuming that any one of the combinations of these three hot short modes may happen in a fire.

For this power-supply proponents differed in providing their inputs for all columns of Table 3-2. The TI team, in consultation with the proponents, concluded that the proponents' inputs in Column 4 and Column 5 should be combined to Columns 2 and 3 using Boolean "OR" method, respectively. Because of this, revised cells in DB 03_02 and DB 04_02 will include the proponent inputs for DB 03_04 and DB 04_04, respectively. Thus, unlike the cases for ungrounded DC (or ungrounded distributed AC) power supply sub-cases (where single break hot short failure mode values were used), both Columns 2 and 4 for AC with CPTs power supply will use the proponent inputs for their double break sub-cases. Note that no values for single break hot short failure mode for the GFEHS mode are calculated, as shown in Table 3-1.

C.2.1.1 SOV Control Circuits (Base Case)

Intra-Cable Plus Intra-Cable Double Contacts (Column 1)

DB 01_01 to DB 04_01: Intra-Cable Plus Intra-Cable Hot Shorts (Rows 1-4)

The results directly from the single break table assuming independence of the faults as discussed in Section 3.3, are used to determine the probability numbers.

Intra-Cable Plus Inter-Cable Double Contacts (Column 2)

DB 01_02 and DB 04_02: Intra-Cable Plus Inter-Cable (including Ground Fault Equivalent) Hot Shorts (Rows 1-4)

For the ungrounded AC with separate CPT power sources, there was no specific consideration of the likelihood of the GFEHS case. The only distinction between the cases in Column 2 and Column 4 is that the one of the two shorts required for their spurious operation occurs via two conductors in the cable shorting to ground for Column 4 versus the same two conductors shorting directly to each other for Column 2. In a practical application, no analyst will make such subtle distinctions when the circuit/cable wiring requirements and the net effect on the circuit both are identical. That is, all of the interactions are occurring based on the faulting of a single cable, and whether an external ground becomes involved is not relevant to a practical analysis. The fact is that the cable has the required conductors present and a single composite number is needed to reflect the likelihood that shorting among those conductors entails spurious operation, and the involvement of the ground plane is irrelevant.

Overall, the results that were provided for Column 2 (intra-cable plus inter-cable) bound the contribution from the very specific faulting configuration assumed in Column 4. That is, Column 2 is redefined as “intra plus inter“, and includes GFEHS cases involving only the conductors of the target cable and any available ground plane.

Inter-Cable Plus Inter-Cable Double Contacts (Column 3)

DB 02_03: Inter-Cable Plus Inter-Cable (including Ground Fault Equivalent) Hot Shorts (Row 2)

The configuration required for an ungrounded AC circuit with individual CPTs to power a target circuit involves two concurrent hot shorts; one on each side of the power source, and that the most likely mode of such interaction would involve one inter-cable short and a GFEHS, i.e., identical to the requirement for the double break case. Hence, assessing the likelihood for double break cases in Column 3 and Column 5 is considered to be identical.

C.2.1.2 MOV Control Circuits

Intra-Cable Plus Intra-Cable Double Contacts (Column 1)

DB 01_01 to DB 04_01: Intra-Cable plus Intra-Cable Hot Shorts (Rows 1-4)

As proposed by the proponents during the last SSHAC Workshop #3, the results for the double break control circuit cases (Base Case - SOV) in Section C.2.1.1 are multiplied by a factor (0.7 for median, 0.6 for lower bound, and 1.0 for upper bound) to take into account all conditions associated with the MOV’s functional requirements discussed in Section 3.2.1.

Intra-Cable Plus Inter-Cable Double Contacts (Column 2)

DB 01_02 and DB 04_02: Intra-Cable Plus Inter-Cable (and Ground Fault Equivalent) Hot Shorts (Rows 1-4)

The results for the cases of double break control circuits in Section C.2.1.1 apply.

Inter-Cable Plus Inter-Cable Double Contacts (Column 3)

DB 02_03: Inter-Cable Plus Inter-Cable (and Ground Fault Equivalent) Hot Shorts (Row 2)

The results for the cases of double break control circuits in Section C.2.1.1 apply.

C.2.2 Ungrounded DC (or Ungrounded Distributed AC)

Column 6's aggregate-probability values are derived from the numbers in Columns 1 through 5 using the Boolean "OR" method detailed in Section 2.3.6, assuming that any one of these five hot short mode combinations may happen in a fire.

C.2.2.1 SOV Control Circuits (Base Case)

The ungrounded DC double breaks are easier to resolve because the GFEHS case was analyzed independently under the single break analysis. Hence, essentially all of these cases are covered by the sum of two single break cases as discussed in Section 3.3.

C.2.2.2 MOV Control Circuits

The results for the double break control circuit (Base Case - SOV) cases in Section C.2.2.1 apply to Columns 2, 3 and 5. For Columns 1 and 4, the same multiplier to the double break control circuits for Column 1 in Section C.2.1.2 applies.

C.3 Development of the CS-Model for Estimating the Probability of the Duration of Spurious Operation

The development of the CS-Model of the Weibull Distribution for the duration of spurious operation is described here. We used the c-value and s-value recommended by the proponents (discussed in Section 6 of this report) to plot the spurious operation durations for AC and DC control circuits. The test data used to fit this modified Weibull distribution model is discussed in Section 6, while the corresponding calculation files are in Appendix E.

Let T be a random variable that denotes the duration of a hot short-induced spurious operation. Assume that T has a Weibull distribution in the form:

$$R(t) = \Pr\{T > t\} = \exp(-\lambda t^{\beta}) \tag{1}$$

Where,

β is a shape parameter
λ is a scale parameter

R(t) is commonly called the reliability function or survival function; it is the complementary cumulative distribution function (CCDF) of T.

We have the experimental pooled data set $\{t_1, t_2, \ldots, t_n\}$, and want to estimate the parameters λ and β, and the bounds on R(t).

Weibull Probability Plot

First, we must confirm that a Weibull distribution is an appropriate characterization of the experimental data. One way to do so is to construct a probability plot. Equation (1) can be linearized such as;

$$y = mx + b \tag{2}$$

Where,

$x = \ln(t)$
$y = \ln\left\{\ln\left[\frac{1}{R(t)}\right]\right\}$
$m = \beta$
$b = \ln(\lambda)$

If the pooled data set $\{t_1, t_2, \ldots, t_n\}$ are sorted (low to high), then $R(t_i)$ can be approximated by its median rank:

$$R(t_i) \approx \frac{n-i+0.7}{n+0.4} \tag{3}$$

To recap the approach,

1. Sort the data $\{t_1, t_2, \ldots, t_n\}$ from low to high
2. For each t_i, use Equation (3) to find $R(t_i)$
3. Use Equation (2) to transform each pair $[t_i, R(t_i)]$ into (x_i, y_i)
4. Plot y_i vs. x_i
5. Provided that the (xi, yi) pairs fall on or near a straight line, then it is reasonable to describe T with a Weibull distribution.

Figure C-1 shows a Weibull plot for the pooled set of duration data; it graphically confirms that T can be described with this distribution.

Median Rank Regression

One approach to estimating the parameters λ and β is to apply the method of least squares to the plot of Weibull probability. This approach is called median rank regression (MRR). It is a straightforward “engineering” approach to estimating parameters; however, the estimates that it produces are not necessarily the “best” statistically.

Figure C-1 shows the results of applying MRR to the pooled data on duration.

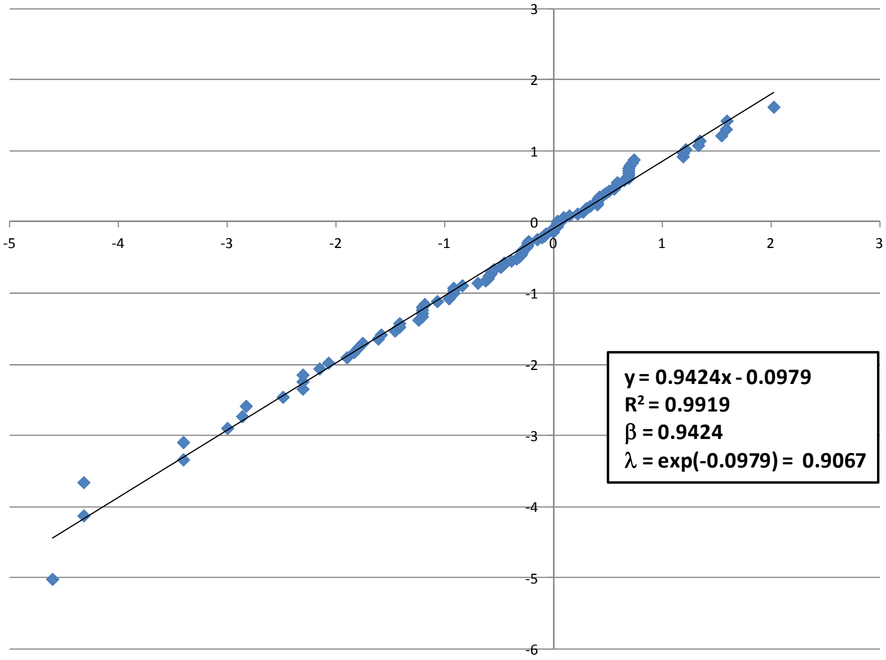


Figure C-1. Weibull Probability Plot and Median Rank Regression

Estimation of Maximum Likelihood

From Equation (1), the probability density function (pdf) of T is:

$$f(t) = \lambda\beta t^{(\beta-1)}\exp(-\lambda t^{\beta}) \tag{4}$$

The likelihood function, $\mathcal{L}(\lambda,\beta)$, is the product of the pdfs evaluated at each data point:

$$\mathcal{L} = \prod_{i=1}^{n}\left\{\lambda\beta t_i^{(\beta-1)}\exp(-\lambda t_i^{\beta})\right\} \tag{5}$$

It is convenient to work with the log-likelihood function, $L(\lambda,\beta) = \ln[\mathcal{L}(\lambda,\beta)]$;

$$L = n\ln\beta + n\ln\lambda + (\beta-1)\sum_{i=1}^{n}\{lnt_i\} - \lambda\sum_{i=1}^{n}\left\{t_i^{\beta}\right\} \tag{6}$$

The maximum likelihood estimate, MLE, is the pair (λ, β) that maximized Equation (6). That is, the MLE is the pair (λ, β) that satisfies the following:

$$\begin{cases} \frac{\partial L}{\partial\beta} = 0 = \frac{n}{\beta} + \sum_{i=1}^{n}\{\ln t_i\} - \lambda\sum_{i=1}^{n}\left\{t_i^{\beta}\ln t_i\right\} \\ \dfrac{\partial L}{\partial\lambda} = 0 = \dfrac{n}{\lambda} - \displaystyle\sum_{i=1}^{n} t_i^{\beta} \end{cases} \tag{7}$$

After some algebra, we see that

$$\frac{\sum_{i=1}^{n}\left\{\mathrm{t}_{\mathrm{i}}^{\beta}\ln t_i\right\}}{\sum_{i=1}^{n}\left\{t_i^{\beta}\right\}}-\frac{1}{n}\sum_{i=1}^{n}\{\ln t_i\}-\frac{1}{\beta}=0 \tag{8}$$

$$\lambda=\frac{n}{\sum_{i=1}^{n}\left\{t_i^{\beta}\right\}} \tag{9}$$

Equation (8) must be solved numerically; we note that the MRR estimates make a good starting point. The theory of maximum likelihood estimate provides a method for determining the uncertainty in the maximum likelihood (ML) estimates. The covariance matrix of the ML estimates is

$$\hat{\mathrm{E}}=\begin{bmatrix}\mathrm{Var}(\hat{\beta}) & \mathrm{Cov}(\hat{\beta},\hat{\lambda})\\ \mathrm{Cov}(\hat{\beta},\hat{\lambda}) & \mathrm{Var}(\hat{\lambda})\end{bmatrix}=\mathrm{I}^{-1} \tag{10}$$

where;

Var(β)= variance of β
Var(λ)= variance of λ
Cov(β,λ) = covariance of β and λ
I = Fisher information matrix

The Fisher information matrix, I, is

$$I=\begin{bmatrix}-\frac{\partial^2 L}{\partial\beta^2} & -\frac{\partial^2 L}{\partial\beta\partial\lambda}\\ -\frac{\partial^2 L}{\partial\beta\partial\lambda} & -\frac{\partial^2 L}{\partial\lambda^2}\end{bmatrix} \tag{11}$$

where, the partial derivatives are evaluated at the ML estimates. Differentiating Equation (7) yields

$$\frac{\partial^2 L}{\partial\beta^2}=-\frac{n}{\beta^2}-\lambda\sum_{i=1}^{n}\left\{t_i^{\beta}(\ln t_i)^2\right\} \tag{12}$$

$$\frac{\partial^2 L}{\partial\beta\partial\lambda}=-\sum_{i=1}^{n}\left\{t_i^{\beta}\ln t_i\right\} \tag{13}$$

$$\frac{\partial^2 L}{\partial\lambda^2}=-\frac{n}{\lambda^2} \tag{14}$$

Applying the pooled data set

$$\hat{\beta}=0.9544,\ \hat{\lambda}=0.9106$$

$$\hat{E}=\begin{bmatrix}0.005103 & -0.002550\\ -0.002550 & 0.009097\end{bmatrix}$$

Note that the ML and MRR estimates are similar.

Bounds on R(t)

For large samples, it is acceptable to estimate the mean and variance of R(t) using the method of statistical error propagation:

$$\hat{R}(t) = mean\ of\ R(t) \approx \exp(-\hat{\lambda}t^{\hat{\beta}}) \tag{15}$$

Var[R(t)]= variance of R(t)≈ $\left(\frac{\partial R}{\partial \beta}\right)^2 Var(\hat{\beta}) + 2\left(\frac{\partial R}{\partial \beta}\right)\left(\frac{\partial R}{\partial \lambda}\right) Cov(\hat{\beta},\hat{\lambda}) + \left(\frac{\partial R}{\partial \lambda}\right)^2 Var(\hat{\lambda})$

Again, the partial derivatives are evaluated using the ML estimates.

$$\frac{\partial R}{\partial \beta} = -\lambda \exp\left(-\lambda t^{\beta}\right) t^{\beta} \ln t = -\lambda t^{\beta} \ln t - R(t)$$

$$\frac{\partial R}{\partial \lambda} = -t^{\beta} \exp\left(-\lambda t^{\beta}\right) = -t^{\beta} - R(t) \tag{16}$$

We seek bounds on R(t) such that:

$$Pr\{R(t) \le R_L(t)\} = 0.05$$

$$Pr\{R(t) \le R_U(t)\} = 0.95 \tag{17}$$

Note that 0 ≤ R(t) ≤ 1 for any t. Define a new random variable G(t) as the transformation of R(t):

$$G(t) = \ln\left[\frac{R(t)}{1-R(t)}\right] \tag{18}$$

As R(t)→0, G(t) → $-\infty$
As R(t)→1, G(t)→ ∞

With the shape of the uncertainty distribution unknown, assume that G(t) has a normal distribution with mean μ_G and standard deviation σ_G, then:

$$Pr\left\{G(t) \le g_{\wp}\right\} = \wp = \Phi\left(\frac{g_{\wp}-\mu_{\wp}}{\sigma_{\wp}}\right) \tag{19}$$

As a result:

$$g_{\wp} = \mu_{\wp} + z_{\wp}\sigma_{\wp} \tag{20}$$

Where $z_{\wp}$ is the $\wp^{th}$ percentile of the standard normal distribution. Specifically, $z_{0.05} \approx -1.645$ and $z_{0.95} \approx +1.645$. Also:

$$\mu_G = \ln\left[\frac{\hat{R}(t)}{1-\hat{R}(t)}\right]$$

$$\sigma_G = \sqrt{\left(\frac{\partial G}{\partial R}\right)^2 Var[R(t)]} = \frac{\sigma_R(t)}{\hat{R}(t)\left[1-\hat{R}(t)\right]} \tag{21}$$

Where,

$$\sigma_R(t) = \sqrt{Var[R(t)]}$$

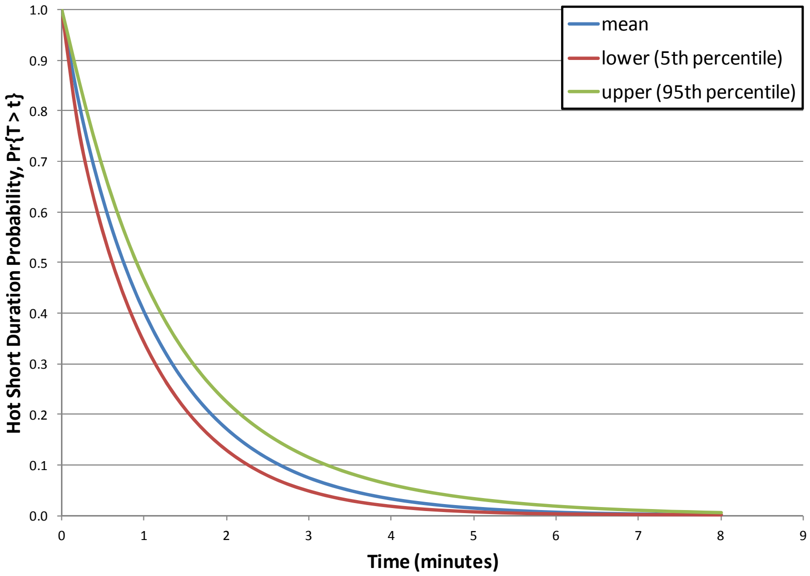


Figure C-2. Probability of Hot Short Duration (Maximum Likelihood Estimate with Approximate Normal Confidence Bounds)

Making further algebraic reductions:

$$R_{\wp}(t) = \frac{\hat{R}(t)}{\hat{R}(t)+[1-\hat{R}(t)]\ exp\left\{-\frac{z_{\wp}\sigma_R(t)}{\hat{R}(t)[1-\hat{R}(t)]}\right\}} \tag{22}$$

Figure C-2 shows R(t) and the approximate normal confidence bounds.

Adjusting for In-plant Conditions

The data $\{t_1, t_2, \ldots, t_n\}$ was collected from a series of experiments, and may not be representative of the actual in-plant conditions that exist during a fire. For example, the rate of heat release and the geometry associated with an in-plant fire will differ from the experimental conditions used to measure the duration of hot shorts. In general, adjusting experimental data to reflect in-plant conditions is complex.

One possible approach to doing so is to scale the duration of hot shorts:

T_{EX} : random variable denoting duration of hot short during experiment
T_{IP} : random variable denoting duration of hot short during actual in-plant fire

Assume: $T_{IP} = cT_{EX}$ (23)

where c is the time scaling factor.

Reliability engineers often use accelerated testing to “make time go more quickly” so that reliability information can be obtained rapidly. Using a time scaling factor is called a scale-accelerated failure time (SAFT) model. In applying a SAFT model to hot short durations, we expect that “c” is greater than 1(that is, the duration of hot shorts in actual fires is longer than in experiments). The time-scaling factor, c, is established by engineering judgment. The parameters λ and β are determined by ML estimation to the experimental data, as before. Figure C-3 illustrates the effect of the scaling factor c=1.4.

$$\hat{S}(t) = Pr\{T_{IP} > t\} = Pr\{cT_{EX} > t\} = R\left(\frac{t}{c}\right) = \exp\left[-\hat{\lambda}\left(\frac{t}{c}\right)^{\hat{\beta}}\right] \tag{24}$$

Using statistical error propagation:

$$Var[S(t)] = \sigma_S^2 \approx \left(\frac{\partial S}{\partial \beta}\right)^2 \sigma_\beta^2 + 2\left(\frac{\partial S}{\partial \beta}\right)\left(\frac{\partial S}{\partial \lambda}\right) Cov(\beta, \lambda) + \left(\frac{\partial S}{\partial \lambda}\right)^2 \sigma_\lambda^2 \tag{25}$$

$$\frac{\partial S}{\partial \beta} = -\hat{\lambda}\left(\frac{t}{c}\right)^{\hat{\beta}} \ln\left(\frac{t}{c}\right) \cdot \hat{S}(t) \tag{26}$$

$$\frac{\partial S}{\partial \lambda} = -\left(\frac{t}{c}\right)^{\hat{\beta}} \cdot \hat{S}(t) \tag{27}$$

$$S_\wp = \frac{\hat{S}(t)}{\hat{S}(t) + [1-\hat{S}(t)]\, exp\left\{-\frac{z_\wp \sigma_S(t)}{\hat{S}(t)[1-\hat{S}(t)]}\right\}} \tag{28}$$

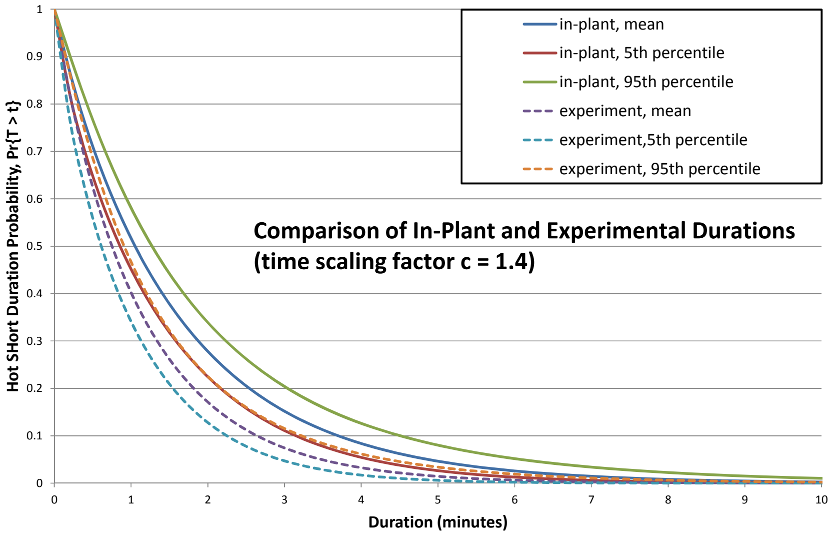


Figure C-3. Comparison of In-Plant and Experimental Durations (Time-scaling Factor c=1.4)

The uncertainty or bounds of $\hat{R}(t)$ at $\wp^{th}$ percentile

$$R_{\wp}(t) = \frac{\hat{R}(t)}{\hat{R}(t)+[1-\hat{R}(t)]\,exp\left\{-\frac{z_{\wp}\sigma_R(t)}{\hat{R}(t)[1-\hat{R}(t)]}\right\}} \tag{29}$$

where $z_{\wp}$ is the $\wp^{th}$ percentile of the standard normal distribution. Specifically, $z_{0.05} \approx -1.645$, $z_{0.5} = 0$, and $z_{0.95} \approx +1.645$. $\sigma_R(t)$ is a function of c, λ, and β. Adding the "s" scalar term to the equation allows adjustment to the uncertainty distribution without affecting the median. Since $z_{0.5} = 0$, "s" has no effect on the median.

$$R_{\wp}(t) = \frac{\hat{R}(t)}{\hat{R}(t)+[1-\hat{R}(t)]\,exp\left\{-\frac{sz_{\wp}\sigma_R(t)}{\hat{R}(t)[1-\hat{R}(t)]}\right\}} \tag{30}$$

Figure C-4 presents the duration curve with c = 1.4 and s=1.9 without the floors.

Figure C-5 adds the floors to the plots of AC and DC durations. Section 6 describes the development of these plots using the methodology presented here and Figure C-5 illustrates the same plots as shown in Figures 6-4 and 6-5.

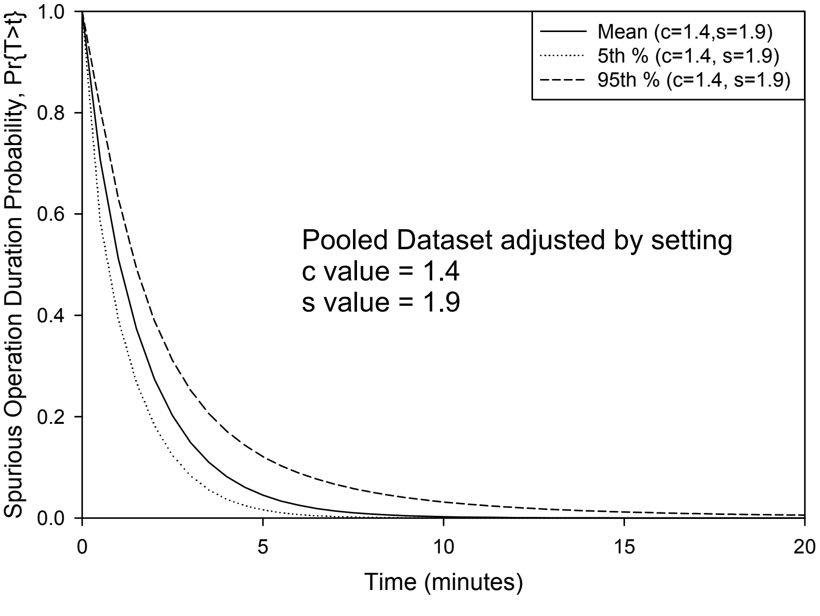


Figure C-4. Duration Curve with c=1.4 and s=1.9

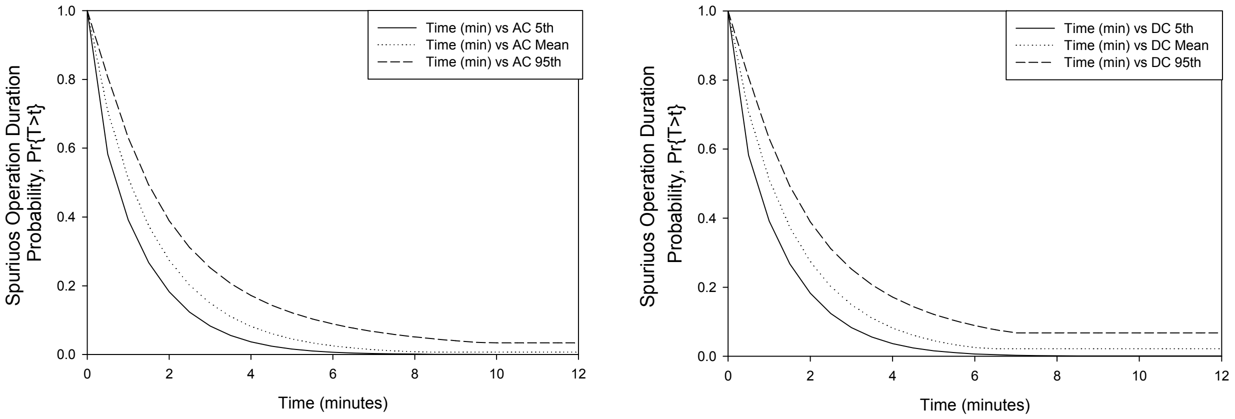


Figure C-5. AC and DC Duration Curves with Floors

C.4 Reports Submitted by Proponents

None of the four proponents addressed or offered recommendations for all the case studies associated with two major control circuit designs identified in the introductory part of Section 3. Proponents #1 and #3 provided a complete set[4]. Proponent #2 did not include the circuit breaker and spurious operation duration. Proponent #4 did not include the cases of circuit breaker, double break, and spurious operation duration. Proponents #2 and #3 gave their opinions in a report form, each of which is included as one Word file. Proponents #1 and #4 used the PRA panel's guidance templates discussed in Section 2 for estimating spurious operation probability for single break "Base Case – SOV". They also added several other files and emails that either revised their original input values for certain sub-cases, or included other case studies, such as spurious operation duration probability and double break spurious operation probability estimations.

We note that the proponent names are not included. The proponent's reports were updated with the final material submitted by each proponent.

C.4.1 Proponent # 1

Files contained in file folder of Proponent #1 include:

- Proponent #1's Word File
- Analysis of Breaker
- Double Break Analysis
- Analysis of Duration Data
- MOV Spurious Operation and Final Position

---

[4] The proponent's reports do not include the double break MOV control circuit since this was added during the last workshop by members of both the PIRT and PRA panels.

C.4.2 Proponent # 2

Files contained in file folder of Proponent #2 include:
Proponent #2's Report Word File

C.4.3 Proponent # 3

Files contained in file folder of Proponent #3 include:
Proponent #3's Report Word File

C.4.4 Proponent # 4

Files contained in file folder of Proponent #4 include:
Proponent #4's Word File
MOV Spurious Treatment, Rev C
Single Break – Duration Estimates Excel® File
MOV Treatment R1 – Grounded AC
MOV Event Trees

ATTACHMENT 1
REQUESTED INFORMATION FORMAT FOR PROPONENTS

I. INSTRUCTIONS

A. INSTRUCTIONS FOR DOCUMENTING THE PROBABILITY OF SPURIOUS OPERATION (SINGLE BREAK)

This document gives instructions for each Proponent to document his evaluation of the probability of spurious operation given certain conditions [P (SO/C)] for the Single Break configuration.

There are two top-level files giving an overview of the information about this configuration.

File “Probability Single Break Table Values 09-14-12.docx”
It contains the latest counts of hits (SOs) out of the number of tests for each case being evaluated, as prepared by NRC staff.

File “Probability Single Break Table Reference 09-14-12.docx”
Note the following points about this file:

1. Each cell in the table gives an identifier for the case that comprises the row and column of the cell. For example, case P_SB_01_01 stands for Probability, Single Break, Row 1 and Column 1. The row and column numbers are in the table to facilitate identifying each cell.
2. There is a separate file for each identifier, named a “case file.” Each Proponent is expected to fill out each file. If you consider that the evaluation of one case can be used as-is for another case, then it is not necessary to fill out the file again; write a note in the file indicating the file containing the complete evaluation.
3. According to this table, there are 44 cases (and corresponding files) to be evaluated for the Single Break configuration.

Case File
The event being evaluated is spurious operation, which is defined as “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).”

The file is divided into four main sections: 1. General Information, 2. Statistical Analyses, 3. Expert Judgment, and 4. Expert’s Additional Comments. In principle, statistical analyses are preferred because experimental data can be used to support the evaluation. Expert judgment is typically used as a last resort when data are scarce or lacking. Accordingly, a Proponent may use statistical analyses only (Section 2), expert judgment only (Section 3), or a combination of both (Sections 2 and 3) for assessing each case.

The ultimate goal is to obtain both a point estimate of each P(SO/C), and a distribution for this probability. The distribution reflects the uncertainty about the probability’s value, and then can be entered into a PRA code[5].

The following *text in italics* gives instructions for filling out a case file:

1. General Information

Expert	*Enter your name*
Date	*Enter the date of your evaluation*
Quantity	*Already filled. You do not need to change.*
Case	*Already filled. You do not need to change.*
Applicable diagrams	*Generic diagrams are already in this row. Feel free to add, modify, or delete diagrams as you consider appropriate for each case.*

2. Statistical Analyses

If you carry out statistical analyses, document your evaluation in the following table.

Description of Analyses	*Describe the assumptions, considerations, and evaluations that you carried out within the framework of statistical analyses. Make sure to clearly identify the data used, such as the cell(s) from file "Probability Single Break Table Values.docx", and any other data or relevant information.*
Distribution obtained	*If you estimate the probability distribution, specify it here preferably in terms of the type of distribution (e.g., beta, gamma) and the parameters of the distribution. Otherwise, assess the median and two quartiles, include them in the corresponding rows in Section 3, and also fill out the row "Justification of median and quartiles."*

3. Expert Judgment

If you use expert judgment, please document your evaluation in the following table.

Median	*Enter the median*
Lower Quartile	*Enter the lower quartile*
Upper Quartile	*Enter the upper quartile*
Justification of median and quartiles	*Justify the median and two quartiles.*
Fitted distribution	*This is a place holder for the distribution that best fits the median and two quartiles. You may leave this row empty; BNL will carry out the fitting.*

4. Expert's Additional Comments

State here any additional information that you consider relevant for evaluating this case, including the references to publications that you quote. Leave it empty if there is no additional information.

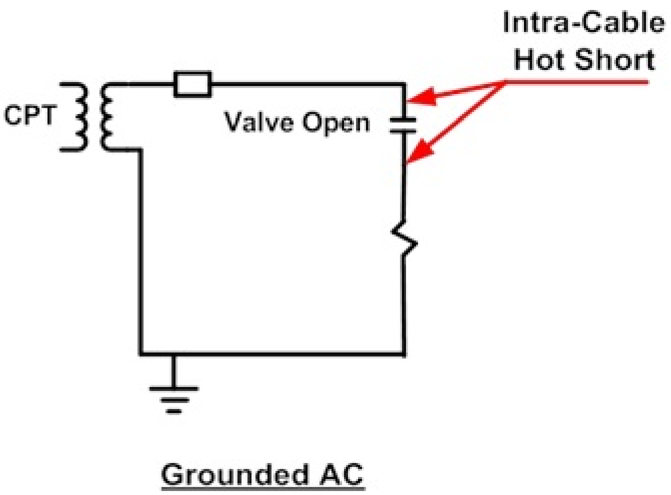
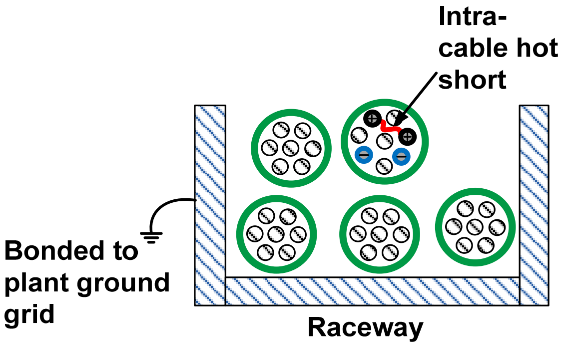
---

[5] Once the distributions of basic events are entered into the code, the parameter uncertainty of a risk metric can be assessed.

II. SAMPLE TEMPLATES

A. ASSESSING THE DISTRIBUTION OF THE SINGLE BREAK PROBABILITY OF SPURIOUS OPERATION (SAMPLE CASE)

1. General Information

Expert	
Date	
Quantity	Probability of Spurious Operation
Case	P_SB_01_01 Single Break Generic Grounded AC Intra-Cable TS target cable
Applicable diagrams	 

2. Statistical Analyses

If you carry out statistical analyses, please document your evaluation in the following table.

Description of Analyses	

Distribution obtained	

3. Expert Judgment

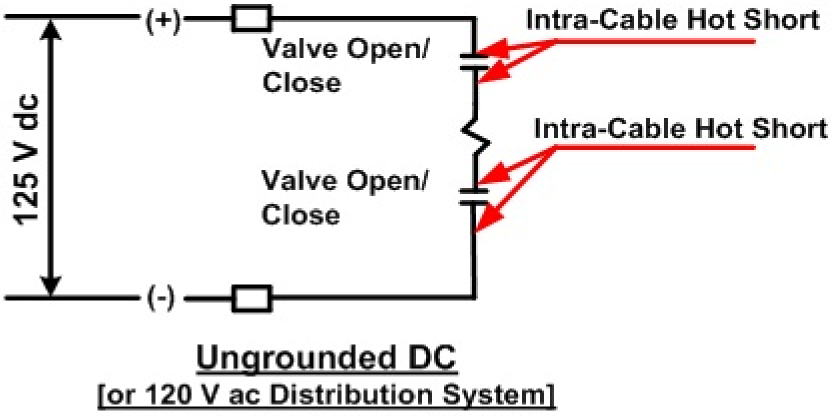
If you use expert judgment, please document your evaluation in the following table.

Median	
Lower Quartile	
Upper Quartile	
Justification of median and quartiles	
Fitted distribution	

4. Expert's Additional Comments

B. ASSESSING THE DISTRIBUTION OF THE DOUBLE BREAK PROBABILITY OF SPURIOUS OPERATION (SAMPLE CASE)

1. General Information

Expert	
Date	
Quantity	Probability of Spurious Operation
Case	P_DB_DC_01_01 Double Break Ungrounded DC Intra + Intra cable short TS insulated source and target cables
Applicable diagrams	

2. Statistical Analyses

If you carry out statistical analyses, please document your evaluation in the following table.

Description of Analyses	
Distribution obtained	

3. Expert Judgment

If you use expert judgment, please document your evaluation in the following table.

Median	
Lower Quartile	
Upper Quartile	
Justification of median and quartiles	
Fitted distribution	

4. Expert's Additional Comments

C. ASSESSING THE DISTRIBUTION OF THE DURATION OF SPURIOUS OPERATION (SAMPLE CASE)

1. General Information

Expert	
Date	
Quantity	Duration of Spurious Operation
Case	
Applicable diagrams	

2. Statistical Analyses

If you carry out statistical analyses, please document your evaluation in the following table.

Description of Analyses	
Distribution obtained	

3. Expert Judgment

If you use expert judgment, please document your evaluation in the following table.

Plausible range	
Median	

Lower Quartile	
Upper Quartile	
Justification of range, median and quartiles	
Fitted distribution	

4. Expert's Additional Comments

APPENDIX D
CABLE-FIRE TEST DATA

The NRC's staff in collaboration with an NRC contractor reviewed and analyzed the test data to support the PIRT and fire PRA expert elicitation panels. Much of this work is documented in NUREG-2128, "Electrical Cable Test Results and Analysis during Fire Exposure (ELECTRA-FIRE), "A consolidation of three major fire-induced circuit and cable failure experiments performed between 2001 and 2011." After completing this work, the fire PRA expert elicitation panel requested access to the Microsoft Excel® database containing the consolidated test data to support their evaluation. The NRC staff developed a roll-up table appropriate for their use. The pdf file contains the instructions for using the Excel® test data file. The Excel® database that contains this roll-up table is included in the compact disk attached to the back cover of this report.

APPENDIX E
TECHNICAL INTEGRATION OF PROPONENT INPUTS

BNL's technical evaluators (members of the TI team) undertook all statistical calculations of the probabilities for single break and double break control circuits. The results, presented in Sections 4, 5, and 6 of this report had undergone many intermediate steps from the proponents' inputs to the final probability tables. This appendix contains all these intermediate files as discussed in the respective sections. The pdf file contains the instructions for all other Excel® files. They are contained on the compact disk located inside the back cover of this report.

APPENDIX F
PARTICIPATORY PEER REVIEW PANEL REPORT

The participatory peer review panel was an integral part of the SSHAC process that improved the quality of this work. This appendix includes panel's final report summarizing panel's overall assessment of the elicitation process and the technical evaluation methods. Many of the suggestions documented in this appendix were subsequently incorporated into the final report. The PPRP also provided individual comments on the final draft version of NUREG/CR-7150, Volume 2, which were incorporated where possible prior to the publication of the joint NRC/EPRI publication.

F.1 Background

The "Estimating Conditional Probabilities of Hot Short-Induced Spurious Operations" expert elicitation project, although following a SSHAC Level 2 process [1][1], involved a Participatory Peer Review Panel (PPRP), a feature of the more resource intensive SSHAC Level 3 and Level 4 processes. The purpose of the PPRP was, as stated in the project plan [2]:

> "…to provide assurance that a proper process has been followed, that the study incorporates the diversity of views prevailing within the technical community that uncertainties have been properly considered and incorporated into the analysis, and the documentation of the study is clear and complete."

To meet this purpose, the PPRP was charged with:

1) providing clear and timely feedback during the course of the study on both technical and SSHAC process matters, and

2) writing a final peer review report documenting the conclusions of the PPRP.

The PPRP was requested to address the project's conformance to the requirements of a SSHAC Level 2 process and the extent to which all technical assessments were adequately defended and documented.

F.2 Process

As a participatory panel, the PPRP provided input throughout the course of the project. The PPRP members participated in project workshops and other meetings, providing comments and suggestions during group discussions as well as during periods identified in meeting agendas set aside for PPRP input. These comments and suggestions covered the goals of the SSHAC process (the principal goal being the development of community distributions for fire PRA parameters of interest, rather than group consensus distributions), the project's implementations of that process, and various technical issues regarding modeling and computation. The PPRP also supported the development of the project's training materials

---

[1] [ ] identifies the reference number listed in Section F.4.

authored by Brookhaven National Laboratory (see Appendix G) and reviewed the project's draft final report.

F.3 PPRP Conclusions

The following conclusions are derived from the PPRP's observations over the course of the project and from the PPRP's review of the project's draft final report [3]. The discussion is based on the main report's description of project elements (which, for example, covers the activities of two expert panels: the electrical PIRT panel, whose work is more fully discussed in Vol. 1 [4]; and the PRA panel, whose work is the subject of this report).

F.3.1 Technical Approach and Results

The overall assessment of the PPRP is that the elicitation approach used by the project (an enhanced SSHAC Level 2 process) was reasonable for the problem and the approach was reasonably executed. The goals of the elicitation process and the participants' various roles in achieving these goals were clearly communicated, and the participants performed in accordance with their roles. The workshop interactions were constructive (viewpoints were supported with technical arguments, challenges to proponent positions were generally made to enhance group understanding) and the participants exhibited appropriate levels of flexibility in their positions following group discussion.

The following observations concern potential weaknesses in the project's execution of the SSHAC elicitation process. Because relevant test data were available for most of the cases considered, these weaknesses are not believed to be sufficiently great to significantly affect the central tendencies of the quantities addressed by the PRA panel. However, they are likely to affect the uncertainty in a few of the derived community distributions for those quantities.

- The PRA panel was charged with developing estimates (including uncertainties) for a very large number of parameters. In the absence of large amounts of directly relevant data, the careful expression of beliefs is a time-consuming process. Perhaps as a consequence, some of the PRA panel's proponents did not address all cases of interest. In at least one case (see Section 5.2.1), it appears the assessment relies entirely on the estimate provided by one proponent. The PPRP believes that the distributions derived for cases involving limited panel input are likely to under-represent the full range of uncertainty of the informed, technical community.

- Although the PRA panel was charged with estimating the likelihood of both spurious operation occurrences and durations, the panel spent most of its time on the former (the treatment of occurrences). Partly for this reason,[2] while agreeing with the PIRT panel that the duration of a spurious operation is dependent on a number of scenario-specific factors, the PRA panel chose to develop only two distributions for spurious operation duration: one for AC circuits and one for DC circuits. Moreover, the parameters characterizing these distributions were treated as single values (estimated by averaging inputs from proponents), rather than as distributed quantities. The PPRP expects that

---

[2] Practicalities in the performance of fire PRA (e.g., potential difficulties in obtaining the information needed to determine the fire exposure environment for a target cable) also influenced the panel's chosen approach.

the stated uncertainties in the early (pre-“floor”) portion of the spurious operation duration distribution likely under-represent the full range of uncertainty of the informed, technical community. We note that as a matter of general principles, further efforts to characterize uncertainty might shift the central tendency of the distribution as well as increase its breadth.

- In order to develop results that could be easily used by current PRA software, the project placed a heavy emphasis on using a standard probability function (the beta distribution) to approximate the spurious operation probability estimates of individual experts and of the panel as a whole. In some cases, the fitting process was straightforward. In others, because of the limited flexibility of the beta distribution, choices had to be made as to which portions of the experts’ distributions should be emphasized in the fitting process.[3] In a few cases, the use of the beta distribution may have masked situations where multi-modal distributions (representing the possibility of distinct, competing “models of the world”) accurately represent the current state of knowledge.[4] Overall, it is not clear whether the use of the beta distribution has a positive or negative effect when representing the range of uncertainty of the informed, technical community.[5]

The PPRP also observes that modeling guidance on the treatment of multiple spurious operations, provided in Section 7.3.4.2 of the main report, was developed following the completion of the last SSHAC workshop and therefore outside of the SSHAC process used in this project. Recognizing that the modeling guidance could be useful to some readers, the PPRP recommends that this guidance be moved to an appendix to the main report.

The following observations have a less clear connection with the project results but suggest lessons for future elicitation projects.

- Initially, a number of PRA panel members were reluctant to exercise their judgment for cases for which test data were lacking. Some appeared to question the premise of the elicitation process, dismissing their own expertise (e.g., via statements such as “I have no basis to quantify”) even when they had opinions regarding phenomenology and expected trends. Over the course of the project, most of the experts appeared to become more comfortable with the process. Nevertheless, as shown in the main report, the panel employed various strategies (e.g., grouping of cases, excluding cases) to avoid providing estimates for a number of data-poor situations. Recognizing that the experts’ reluctance to provide estimates based on holistic judgments (rather than discrete, easily identified sets of test data or mathematical model predictions) may be difficult to change, the training portion of future elicitation projects should nevertheless spend more time addressing panelist qualms and empowerment.

---

[3] The PPRP notes that the panel’s proponents did verify that the beta distributions fitted to their input were reasonable representations for ranges of values they were most concerned about (typically, the larger values). In some cases, however, this fitting resulted in relatively poor matches of the experts’ input for other ranges of values.

[4] The PPRP notes that this is only a possibility. Although workshop discussions addressed the rationale supporting each proponent’s input, they did not explore whether differences in rationale suggested the need for a multi-modal community distribution.

[5] The PPRP notes that more flexible, yet relatively simple parametric distributions (e.g., the Pearson family of probability distributions [5]) are available and may be worth considering in future projects.

- As likely side effect of the experts' reluctance to express their judgments concerning data-poor cases, the PRA panel spent a considerable amount of time discussing situations for which there were relatively ample data (by normal PRA standards). Although there were some differences between the experts' estimates (due to differences in interpretations and treatments of the data), these differences were relatively minor (again, by normal PRA standards). (See, for example, Figure 2-1, which shows that for one case, the experts' best estimates range from 0.57 to 0.72.) Future elicitation projects should try to ensure that the panel spends a greater fraction of time on issues of greatest uncertainty. The training for such projects should address the sensitivity of parameter estimates to changes in data sets. For example, for a given sample size, what kinds of changes are needed to make a large difference in the estimate? (Or, similarly, the extent to which changes in the parameter of interest can explain changes in the observed data). Such training can also help avoid expert overcompensation for the overconfidence biases identified in current training.

- The training should also remind the experts that even in situations where empirical data are available (e.g., as the result of a testing program), their expert judgment is needed in assessing the relevance of that data to the practical (field) situations of interest. Mechanical processing of such data using standard statistical techniques may not result in appropriate representations of parameter central tendencies, let alone uncertainties.

- Also regarding training, the expert elicitation training for this project included a calibration exercise intended to provide the experts with some practice in quantifying their beliefs regarding event probabilities. The particular exercise involved predicting the results for a number of events in the 2012 Summer Olympic Games. This exercise, although potentially of interest to some panelists, was not particularly analogous to the problem faced by this project since it involved the outcome of a one-time event (as opposed to the outcome of a repeated series of trials). The exercise was not performed by a number of panelists. Future elicitation projects should employ exercises more closely aligned to the problem at hand.

- As indicated earlier, this project required the elicitation of a very large number of parameters. The panelists employed a number of strategies to enable project completion within available time and resource constraints. Nevertheless, it appeared that there were considerable demands on panelists during meetings, and the quality of the elicitation may have been affected. Future elicitation projects should consider and counter, to the extent possible, the effect of "meeting fatigue" on the elicitation process.

- In addition to the previously mentioned grouping of cases and exclusion of others, the experts used a number of heuristics to simplify the judgment process. One of the most common heuristics used was "anchoring and adjustment:" the identification of a similar situation for which an estimate was already available, and then adjusting that estimate (the "anchor") to account for differences between the case at hand and the anchoring case. As pointed out by the training performed for this project, the anchoring and adjustment heuristic is a potentially important source of bias; the anchor may be incorrectly selected, the adjustment may be insufficient, or both. Nevertheless, the experts appear to have little else to rely upon when addressing a situation for which they have no directly applicable data. Future elicitation training materials should re-examine guidance in this area, including the implications of different adjustment strategies (e.g., using absolute values versus relative values or percentages or such approaches as "splitting the difference" between bounding estimates).

- Another simplification employed by the expert panel involved the pooling of hot short duration data. This simplification, which reduces the numbers of parameters to be estimated, was facilitated through the use of statistical tests determining whether it is appropriate to model a set of data as coming from the same underlying population. These same tests identified statistical outliers (i.e., data that don't appear to belong to the population), which were explicitly discussed and dispositioned by the panel. In general, the PPRP notes that empirical data can reveal realistic behaviors not included in models and that, therefore, data outliers should not be discarded based solely on statistical arguments. Similar to this project, future elicitation projects should ensure that any data screening be done with caution, that any screening have a sound phenomenological or practical applications basis, and that the basis be carefully documented.

- In one case (the treatment of motor operated valves), the panel did not, at the beginning of the project, have a common understanding of what constituted a "spurious operation." This common understanding was developed after considerable discussion. Recognizing that analogous situations might arise dynamically over the course of any project, nevertheless future elicitation projects should try to ensure that the subjects of the elicitation are clearly defined prior to engaging the expert panel.

- In a number of cases (involving the spurious operation of motor-operated valves, the treatment of "double break" circuits, and the duration of a spurious operation), the elicitation process required estimates for a parameter that was not directly elicited. Instead, the parameter was represented as the output of a mathematical model whose parameters were the ones actually elicited.
    - The SSHAC process allows (and calls) for the proponents to bring their models to the workshop discussions. The proponents can agree upon a consensus model, but care should be taken to ensure that the workshop discussions do not force a consensus model.
    - When using a mathematical model for the parameter of interest, the probability distribution for that parameter is a mathematical function of the distributions for the elicited parameters. When developing a project team, care should be taken that the team has sufficient expertise (or access to such expertise) to understand how the project's chosen software tools develops the output distribution, what are the potential cautions in using such tools, and how to develop the distribution if a software solution is not readily available.

- As indicated in the main report, although the Technical Integration (TI) team requested that the proponents provide their estimates in the form of a set of pre-designated quantiles,[6] some of the proponents had alternate, preferred ways of expressing their uncertainties and didn't always comply with the TI requests. Over the course of the project, this difference led to some angst on the part of some TI team members. The PPRP observes that quantitatively expressing one's uncertainties on a particular matter

---

[6] These quantiles were suggested by the TI team's review of the literature on expert elicitation.

involves a certain degree of introspection, and that many analysts do not think naturally in terms of the quantiles requested by the TI team. The PPRP recommends that future elicitation projects continue to provide guidance as to the desired format for reporting uncertainties, but remain flexible in accepting expert input in the form the expert feels most representative of his/her beliefs. Furthermore, as indicated earlier, the project should ensure that any mathematical representations of these beliefs do not unduly distort the beliefs for the sake of convenience.

Finally, the PPRP notes that the project demonstrated a number of good elicitation practices. These practices are worth emulating in future elicitation projects.

- At every elicitation session, remind the participants regarding:
    - the basic SSHAC philosophy of developing a community distribution (not the “right answer”); and
    - the participants’ assigned SSHAC roles (be it technical integrator, resource expert, proponent, or participatory peer reviewer).
- Encourage participants to openly share their point of view, even if it is not shared by others. Find ways to help an expert overcome his/her reluctance to quantify his/her beliefs even when test data or mathematical model predictions are not available.
- Ensure panel discussions include adequate consideration of application issues, including: a) the effect of potentially key differences between test and field conditions when interpreting test data (e.g., hundreds of conductors in a typical tray versus 10 in a typical test; a predominance of one particular polarity in the field versus an even polarity distribution in a typical test), and b) how the elicitation results are likely to be used in PRA studies.
- Ensure panel discussions include adequate consideration of previous, relevant efforts (e.g., the PIRT panel discussions in this case).
- Perform sanity checks to ensure the estimates are consistent with the experts’ beliefs.
    - Check elicited and derived estimates for implications regarding the random variable (e.g., the number of failures in a set of trials), not just the parameter (e.g., the failure probability).
    - Check estimates for trends across cases and determine if there is a justification for those trends.
    - Check uncertainty representations for consistency with the amount of information. (In general, the uncertainties should be larger when less information, including data from tests and information regarding actual plant conditions, is available.)

F.3.2 Technical Presentation and Writing

The PPRP believes that the draft final report provides a reasonable description of the project objectives, approach, and results. It also believes that the report is most accessible to experts already familiar with the technical issues associated with the treatment of fire-induced spurious operations in fire PRA. Most of the following suggestions are aimed at making the report more accessible to a broader audience. Some suggestions are aimed at clarifying the technical basis for the project results.

- Expand the background discussion to provide more details regarding:
  - the fundamental physical situation[7];
  - why the project needed separate PIRT and PRA panels;[8]
  - what is the relationship between this work and the earlier EPRI/NEI work (and, in particular, are the earlier results being "supplemented" or "replaced");
  - the motivation behind using an expert elicitation process; and
  - the key philosophy behind the SSHAC process, i.e., the goal of representing the informed technical community's beliefs (as opposed to developing a panel consensus).

- Reduce the use of acronyms, particularly of those (e.g., HS, SO, CD, SBD) not already in common usage.

- Reduce or provide an early explanation of technical jargon. In particular, define "Boolean OR" and "Boolean AND," taking care to distinguish between the logical (true/false) variables representing event occurrences, the event probabilities (or split fractions) quantifying the likelihood of these event occurrences, and the probability distributions quantifying the uncertainties in the event probabilities. The arithmetic operations for these three types of quantities are different; errors in the draft report should be corrected. Provide an appendix showing the different operations.

- Reduce or eliminate chronologically-oriented discussions of process. Focus only on those elements of the process that would affect the credibility of the results. If it's important from a historical perspective to document the evolution of the results, relegate that material to an appendix.

- Similarly, consider if it's important to indicate exactly which proponent suggested what. The important issue at the end is whether the product reasonably represents the informed technical community's range of views.

- Simplify the writing style.
  - Break long, complex sentences into pieces.
  - Eliminate repetitive phrases and unnecessary modifiers (e.g., "standard beta distribution" vs. "beta distribution").
  - Avoid using multiple terms for the same concept (e.g., "LOP curve" vs. "LOP distribution").

---

[7] For example, one such description is that: a fire has damaged a cable or cables; this damage can lead to one or more "hot shorts" which: a) can cause spurious operation of equipment, and b) can last some period of time before "clearing"; and both the occurrence of a spurious operation and the duration of that spurious operation are random.

[8] Note that the PIRT panel assessed certain cases as being "implausible" or "incredible," but these were consensus judgments; the PIRT panel was not charged with developing community distributions.

- Consider re-organizing the report material.
    - Consider whether detailed explanations are needed early in the report.
    - Reduce the amount of overlap from chapter to chapter.
    - Consider making a stronger separation of methods-related discussion from results-related discussion.

- Ensure the report provides appropriate emphasis to important points.
    - Highlight those sub-cases where expert opinion was truly needed (particularly when data are sparse or entirely lacking).
    - Highlight those sub-cases where there were significantly divergent points of view and the reasons for these divergences.
    - Provide a technical discussion of the results addressing, for example,
        - cross-comparisons of different sub-cases (including discussions of consistency and trends, considering both mechanistic and statistical issues);
        - situations where the results are sufficiently close that grouping-related simplifications might be warranted (see, for example, the MOV and breaker results); and
        - any caveats in the use of the results (e.g., where uncertainties in the community distribution may be understated due to the project approach).
    - Identify and discuss potentially important technical issues that the panel considered but then decided not to address (e.g., the effects of field wiring practices on the likelihood of ground fault equivalent hot shorts).
    - Discuss the ultimate role of any data processing (particularly the preparation of summary tables) in the final elicitation results.
    - Identify any key differences of opinion between the PIRT and PRA panels and, if such exist, discuss the PRA panel's rationale for divergence.
    - Consolidate important modeling guidance in one place (Chapter 7).
    - Reduce the emphasis on issues not addressed in the SSHAC workshops (particularly, the treatment of multiple spurious operations).

- Ensure that: key equations (particularly, for the “CS-model”) are provided in the main report, the terms are fully defined and explained, and the derivation of these equations is fully documented in Appendix C.

F.4 References

1) R. J. Budnitz, G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, and P. A. Morris, “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts,” NUREG/CR-6372, Vols. 1 and 2, 1997.

2) M. Subudhi and G. Martinez-Guridi, “Estimating Conditional Probabilities of Hot Short-Induced Spurious Operations – Project Plan,” May 25, 2012.

3) NUREG/CR-7150 and EPRI 3002001989, “Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE) - *Expert Elicitation Exercise for*

Nuclear Power Plant Fire-Induced Electrical Circuit Failure," Draft Report, BNL-NUREG-98204-2012, Volume 2, November 15, 2013.

4) NUREG/CR-7150 and EPRI 1026424, "Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE) - *Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure*," BNL-NUREG-98204-2012, Volume 1, October 2012.

5) N.L. Johnson and S. Kotz, *Distributions in Statistics*, Wiley, New York, 1976.

APPENDIX G
SELECTED PRESENTATION VIEWGRAPHS

During the meetings of the fire PRA expert elicitation BNL presented the panel with numerous data in a power point format. This appendix includes a selected number of these presentations to document the information given to panel members. The information found in this appendix is for reference only, and is superseded by any and all information detailed in the main body of this report. The viewgraphs are contained on the compact disk included in the back cover of this report.

APPENDIX H
TECHNICAL INTEGRATOR AND PROPONENT OPINION ON APPLICATION OF LIKELIHOOD ESTIMATES FOR MULTIPLE SPURIOUS OPERATION CASES

Section 7 provides guidance on the application of the likelihood estimates developed by the expert elicitation panel for multiple spurious operation (MSO) scenarios. Although an evaluation of MSOs was not in the original scope of this project, the team believed that guidance would benefit the fire PRA applications. Since this MSO guidance was added late in the project it didn't follow the strict application of the SSHAC process.

Development of the MSO guidance consisted of a proponent developing the base guidance, and then several interactions between the TI team and both the PRA panel and the PIRT panel members. During these calls the technical experts voiced their opinion on the MSO guidance to the TI team. In November, the TI team had a conference to finalize the guidance as documented in Section 7.3.4.2. During this conference the TI team could not reach a consensus and one TI team member's opinion which differed is documented in Section 7.3.4.2. The PPRP did not take any part in this effort.

This appendix serves to document the PRA expert panel TI team members' technical position and the proponent members' opinion on the method for application of the likelihood estimates for various MSO scenarios.

H.1 One TI-Team Member's Views

This section describes the opinion of one member of the TI team who did not agree with the team's consensus. The majority opinion is described in Section 7.3.4.2 and individual proponent opinions are provided in Section H.2.

"The proponent who addressed dependence among the duration exceedance probabilities recommended using the 95th percentile probability for the second spurious operation and 1.0 for all subsequent (see Section H.2). Relaxing this somewhat, if one allows the 95th percentile for the second and third, and 1.0 thereafter, the minimum joint probability on duration exceedance, based on the AC "individual "floor" (lower than DC) is 0.0071 x 0.034 x 0.034 = 8.2E-6, which is just around the recommended "floor" limit for joint human error probabilities (HEPs) of 1E-5 (discussed below), which is the same value as recommended in Section 7.3.4.2 for duration exceedance. However, since these duration exceedance probabilities are conditional upon the occurrence of the SOs, there are also three occurrence probabilities that would multiply these. I'm not sure what the electrically allowed minimal triplet would be, but if I just pick the lowest mean value from the various occurrence probability tables, I get $(8.5E\text{-}4)^3$ = 6.1E-10, which compounds to a ridiculously low value of 5.0E-15. Using a more typical value, I get 0.42^3 = 0.074. This is compounded with the floor value of AC yielding 6.1E-7.

TECHNICAL INTEGRATOR AND PROPONENT OPINION ON APPLICATION OF LIKELIHOOD ESTIMATES FOR MULTIPLE SPURIOUS OPERATION CASES

While I recognize that there is no strict justification for any specific numerical value for a joint floor, if I halved the occurrence probabilities used in the estimate of 6.1E-7, I would lower this minimum by a factor of 8 to ~ 8E-8; if I "thirded" them, by a factor of 27 to ~ 2E-8. "Fourthing" brings it to ~ 1E-8. While I recognize that this is not strict justification, it may lend some credence to what I would propose as a floor on BOTH the joint occurrence AND duration exceedance probabilities of ~ 1E-8. Note this aligns on an order of magnitude basis to the product of an occurrence floor of 0.001 (0.1 occurrence probability triplet) and duration floor of 1E-5 (recommended above). I was willing to consider even a lower joint floor for both occurrence and exceedance duration, but disagree with recommending no floor, either individually or as part of a joint restriction, on the occurrence probability.

I partially support this with an analogy to human reliability analysis, where common-cause failures (CCFs) are not modeled, but dependencies are. For HEPs, a floor on their joint product of ~1E-5 (or, in special cases, 1E-6) is recommended. Since SOs are not modeled via CCFs, similar to HEPs (no CCFs) but different from non-fire (random) equipment failures (CCFs), I favor this analogous joint "floor" approach as a guard against non-conservatism for a phenomenon not thoroughly examined at this point in time."

H.2 Proponents' Technical Views

Proponent #1

"I disagree with the floor value used, and would like to document an opinion in the report with this disagreement. I have mentioned before my belief that there is dependency between the first and second spurious operation, particularly in the area of duration. I did a quick review of the data, and re-confirmed that I did not see a pattern on spurious operation probability, other than spurious operation of the other contact in the same cable (previously discussed as 78%). In essence, I would expect to see a random distribution of spurious operations in other cables in the same test, around 30-40% of cables; and this is what I see. If there were high dependence, I would see a lot of spurious operations in a limited number of tests, and a lot of tests with zero spurious operation.

On duration; I partially completed a dependency analysis that is presently showing dependency on duration. My initially simplistic analysis was to look for the probability of long duration spurious operations, given a long duration spurious operation occurred. So the simplified analysis was simply to look for tests where the following occurred: 1) a long duration spurious operation occurred, as defined by being above the mean duration of approximately 1 minute, and 2) a second spurious operation occurred.

So the test is that, given the long duration occurred, there should be a 50/50 probability that the second spurious operation is above 1 minute. In fact, the way the analysis is being performed, given I am looking at both durations, the probability should be less than 50/50; but I am using 50/50 as the starting point for the test.

My initial look was on Grounded AC – one I was proposing no dependency in my previous proposal. So in starting with HGL (where I think the dependency is greatest); I found 6 tests where two spurious operations occurred, and a greater than 1 minute duration in at least one of the two spurious operations. Of the 6 tests; 4 of the other spurious operation circuits also had a spurious operation of greater than 1 minute. These included the following:

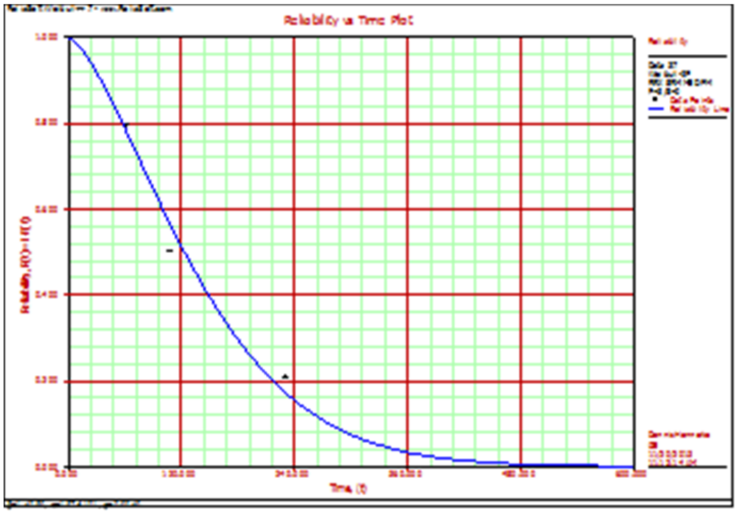
- C-IT-1-CK4
- D-IT-12-CK1 (counted as both 1 above and 1 below due to three spurious)
- E-I-7-CK1 (counted as 2 above)

So using the above, I am getting a 66% change of a long duration spurious operation on the second, given the first is long duration (as defined as being above the mean). This clearly shows dependency.

When I look at HGL for DC – The number above is 100% for HGL. In other words; all of the DC HGL Hot Shorts (all tests) and SOs (D-IT-2) were greater than 1 minute for both hot shorts/SOs, when more than 1 occurred. This is a clear trend; in other words, there is dependency between long duration spurious operations.

The problem, of course, is showing this translates into the probability of both being above a certain time. The probability is not 66% for AC and 100% for DC, but it can easily be derived (given a few days of analysis). I tried this with the HGL Grounded AC, and got the following: 1) The conditional probability of the second hot short exceeding the first is 0.625, and 2) The time for the second hot short, given it exceeds the first is shown below. This curve demonstrates that not only is the second hot short duration longer; but also higher than the 95th percentile curve in the NUREG. Of course, this is only for HGL AC; but it demonstrates again that the duration of the second is dependent on the first.

HGL – Grounded AC – Hot Short Duration of the Second Hot Short



So just looking at HGL; there is clear evidence of dependence. For me there are two ways to address this: 1) Develop a separate duration curve for HGL, which will overly complicate the FPRA, or 2) Develop a dependent number for the second Spurious Operation.

I would like my strong disagreement on the use of a floor value in place of a dependency evaluation noted in the report."

TECHNICAL INTEGRATOR AND PROPONENT OPINION ON APPLICATION OF LIKELIHOOD ESTIMATES FOR MULTIPLE SPURIOUS OPERATION CASES

Proponent #2

No feedback provided

Proponent #3

"Regarding the "likelihood of spurious operations for MSO scenarios"; based on my through review of the data and analytical techniques used to evaluate the data, I cannot identify any generic phenomena that would contribute to a dependency on hot short occurrence for MSO scenarios, provided that the hot shorts are in the different cables. The only potential dependency for hot short likelihood of occurrence for MSOs would be cases were armored or shielded cables are used. In these cases, the ground plan interaction may play a role in influencing the occurrence of spurious operation, however, I believe that thermal conditions in the vicinity of the cables associated with the MSO play a substantially more dominate role.

Regarding the "duration of spurious operation for MSO scenarios," I believe that dependencies can exist, but are highly dependent on the thermal conditions and physical arrangement of the cables associated with the MSO scenario. Again, this view does not include multiple hot shorts within the same cable, as those have a direct dependency. As documented in Volume 1, the PIRT panel concluded that thermal conditions have a "HIGH IMPACT" on spurious operation duration. From the data presented in NUREG-2128, there is a general trend for longer duration when cables are exposed to a slower heat up rate (or hot gas layer [HGL]) exposure than fast heat up rates observed in flame and plume exposure data. Although there is some aleatory nature to the duration of the spurious operation for the individual bins (HGL, plume, flame), HGL exposure typically were longer in duration. Due to the longer duration likelihood for single events, there is more opportunity for other hot shorts to occur during this time that could result in a MSO scenario. Thus, because for these phenomena, I believe that there can be dependencies for the application of duration likelihoods for MSO scenarios. Therefore, I agree with the guidance provided in Section 7.3.4.2 of this report because it provides a conservative approach where there is limited data and large dependence on the thermal conditions and physical arrangement."

Proponent #4

No feedback provided

NRC FORM 335 U.S. NUCLEAR REGULATORY COMMISSION
(12-2010)
NRCMD 3.7

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)
NUREG/CR-7150 Vol 2
BNL-NUREG-98204-2012
EPRI 3002001989

2. TITLE AND SUBTITLE
Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE)

Volume 2: Expert Elicitation Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure

3. DATE REPORT PUBLISHED

MONTH	YEAR
May	2014

4. FIN OR GRANT NUMBER
JCN N-6980

5. AUTHOR(S)
M. Subudhi and G. Martinez-Guridi

6. TYPE OF REPORT
Technical

7. PERIOD COVERED (Inclusive Dates)
1/1/2012 - 4/30/2014

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)
Department of Energy Sciences and Technology
Brookhaven National Laboratory
P.O. Box 5000
Upton, New York 11973

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
Gabriel Taylor, NRC Technical Project Manager

11. ABSTRACT (200 words or less)

The objective of the PRA panel's expert elicitation is to estimate the conditional probabilities of the hot short-induced spurious operation failure mode of control circuits and its duration, given fire-induced cable damage. These results are intended for use in fire PRA applications. Using an enhanced Senior Seismic Hazard Analysis Committee's (SSHAC's) Level 2 process for the expert elicitation (NUREG/CR-6372), the panel suggested parametric distributions of the probability of occurrence, and duration of fire-induced circuit-failure phenomena. Distributions are developed for control circuit configurations where applicable test data are available, as well as when there are none, but expert judgment reasonably can offer quantitative estimates. The electrical PIRT study in Volume 1 identified the configurations of the electrical control circuits that could be vulnerable to hot short-induced spurious operations, applying the physics and physical parameters that influence the modes of fire-induced circuit failure. For these control circuits, the PRA panel derived the distributions of conditional probability on the hot short-induced spurious operation of certain end devices and also the conditional probability distributions of their spurious operation duration. Both conditional probability distributions were derived using the results from recent cable-fire tests undertaken by the EPRI, Duke Energy, and the NRC and expert judgment. These conditional probabilities advance the state-of-the-art and are intended for revising, directly replacing, or creating new probabilities in NUREG/CR-6850 (Tables 10-1 through 10-5) and in its Supplement 1 (Figure 16-1 and Table 16-1) that the nuclear power industry currently use in their fire PRAs.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

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

13. AVAILABILITY STATEMENT
unlimited

14. SECURITY CLASSIFICATION
(This Page)
unclassified
(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

STAY CONNECTED

BLOG CHAT You Tube

NUREG/CR-7150, Vol. 2
Final

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

May 2014