EXPERT JUDGMENT: AN APPLICATION IN FIRE-INDUCED CIRCUIT ANALYSIS

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Abstract

Expert judgment has been used to develop both qualitative guidance and quantitative estimate of hot short-induced spurious operation of equipment as a result of fire damage to electrical cables located in a nuclear power plant (NPP). This paper summarizes the research efforts and explores the quantitative risk differences. The U.S. Nuclear Regulatory Commission (NRC) sponsored Brookhaven National Laboratory to facilitate this project with the Electric Power Research Institute (EPRI) under the NRC-RES/EPRI Memorandum of Understanding. The first phase of using expert judgment followed a Phenomena Identification and Ranking Table (PIRT) process using a group of electrical engineering experts to identify and rank the parameters that influence fire-induced cable damage. In addition to the PIRT results, this electrical engineering expert panel also provided technical consensus on several long time contentious fire safety issues related to electrical circuit analyses. Specifically, the electrical engineering expert panel results categorized circuit configurations as being possible, implausible or incredible; which provided strong technical recommendations to support regulatory activities. The results of the PIRT panel also identified areas where knowledge is low and suggested future research prioritized on risk insights. A second expert panel of fire PRA experts was convened with the goal of using expert judgment for quantifying probabilities and durations of hot short-induced spurious operations caused by fire damage to electrical cables, utilizing the Senior Seismic Hazard Analysis Committee (SSHAC) process. Following this process, this second panel results are expected to represent the opinion of the relevant informed technical community. These results are mainly derived for performance-based applications. The updated results of this expert judgment exercise are used in a few select case studies to evaluate the change in conditional risk from the original 2005 fire PRA methodology.

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ABSTRACT[1]

Expert judgment has been used to develop both qualitative guidance and quantitative estimate of hot short-induced spurious operation of equipment as a result of fire damage to electrical cables located in a nuclear power plant (NPP). This paper summarizes the research efforts and explores the quantitative risk differences. The U.S. Nuclear Regulatory Commission (NRC) sponsored Brookhaven National Laboratory to facilitate this project with the Electric Power Research Institute (EPRI) under the NRC-RES/EPRI Memorandum of Understanding. The first phase of using expert judgment followed a Phenomena Identification and Ranking Table (PIRT) process using a group of electrical engineering experts to identify and rank the parameters that influence fire-induced cable damage. In addition to the PIRT results, this electrical engineering expert panel also provided technical consensus on several long time contentious fire safety issues related to electrical circuit analyses. Specifically, the electrical engineering expert panel results categorized circuit configurations as being possible, implausible or incredible; which provided strong technical recommendations to support regulatory activities. The results of the PIRT panel also identified areas where knowledge is low and suggested future research prioritized on risk insights. A second expert panel of fire PRA experts was convened with the goal of using expert judgment for quantifying probabilities and durations of hot short-induced spurious operations caused by fire damage to electrical cables, utilizing the Senior Seismic Hazard Analysis Committee (SSHAC) process. Following this process, this second panel results are expected to represent the opinion of the relevant informed technical community. These results are mainly derived for performance-based applications. The updated results of this expert judgment exercise are used in a few select case studies to evaluate the change in conditional risk from the original 2005 fire PRA methodology.

Key Words: Fire, PRA, Circuit Analysis, Electrical Cable, Expert Judgment

1. INTRODUCTION

1 This paper was prepared (in part) by employees of the United States Nuclear Regulatory Commission. It presents information related to NRC upcoming testing programs. NRC has neither approved nor disapproved its technical content. This paper does not establish an NRC technical position.

A vital component for safe nuclear power plant (NPP) operation is the electrical cables. Operating experience and testing has shown that fire-induced cable failures can adversely affect operators' ability to safely shutdown the reactor. Recently, two expert panels were formed to advance the state-of-the-art for modeling fire-induced cable failures in a fire PRA. The project was conducted jointly between the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) (NRC-RES) and the Electric Power Research Institute (EPRI) under their Memorandum of Understanding (MOU) for collaborative research. The experts on both panels were made up of equal numbers regulator (NRC staff and NRC contractors) and EPRI representatives (nuclear utility staff and contractors). The first panel focused on identifying how various electrical circuit and cable characteristics influence fire-induced cable failure, while the second panel used the results to develop best-estimate conditional probabilities and durations for various fire-induced cable failure modes and configurations. Brookhaven National Laboratory (BNL) was responsible for facilitating the meetings and documenting the conclusions of the first panel, defining the technical approach used for evaluating the probabilities, assessing the probability & duration distributions and documenting the conclusions for the second panel. NUREG/CR-7150, "Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE)" [1] documents this work and the results. The results of both panels' work is now being used to update the current state-of-the-art method for conducting fire PRAs, documented in EPRI TR 1011989 and NUREG/CR-6850 [2], as well as updating applicable regulatory guidance.

1.1 Description of the Fundamental Safety Issue

Electrical cables provide the path for transmitting electrical energy (e.g., power, control, instrumentation signals) between two points in an electrical circuit, while simultaneously maintaining the electrical integrity of the signals from each other and from other media that can cause interference. As learned from the 1975 fire at the Browns Ferry NPP and from numerous fire testing programs, the effects of fire on electrical cable can have varying impacts on electrical cable functionality ranging from the loss of system control to spurious operations of systems and components. From a safety perspective, a fire affecting the ability of an electrical cable to perform its function can compromise the operators' ability to safely control and shutdown the plant. The quantity of electrical cable within a NPP varies from a few hundred miles to nearly 1,000 miles [3]. Given the large quantity and types of electrical cable in NPPs and the fact that cables represent a large fraction of the total combustible loading, the importance of protecting them, especially those associated with safety systems, from the adverse effects of fire is necessary. Deterministic and performance-based approaches to fire protection programs are currently available for use in the regulatory environment. In the deterministic approach, strict levels of performance and circuit protection provide a minimum level of safety while the fire PRA methods relies on a rigorous process to locate the cables, model and calculate the risk associated with the effects to electrical cables from fire-induced damage.

1.2 Deterministic Fire Protection Requirements Related to Circuit Analysis

The Browns Ferry Nuclear Power Plant fire of 1975, illustrated the safety significance that fire can pose to NPP operations. In response to the near miss accident, the NRC developed deterministic fire protection requirements and guidance[2]. The objective of the fire protection requirements and guidance is to provide reasonable assurance that one train of systems necessary to achieve and maintain hot shutdown is free of fire damage. This includes protecting circuits whose fire-induced failure could prevent the operation, or cause maloperation, of equipment necessary to achieve and maintain post-fire safe shutdown. This protection is the third echelon of a fire protection defense-in-depth philosophy where the first two

[2] Fire protection regulations and guidance refers to Title 10 of the Code of Federal Regulations, Section 50.48 (10 CFR 50.48), 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 3, Appendix R, Section 9.5-1 of the Standard Review Plan (SRP), NUREG -0800, and the licensees individual fire protection licensing bases.

echelons include preventing fire from starting, and rapidly detection and suppressing any fire that do occur.

In an effort to make nuclear power plants safe in light of the Browns Ferry Fire, the NRC used the best data available at the time (late 1970's) coupled with engineering judgment to develop explicit prescriptive requirements which plants in various phases of operation, construction, and development were required to follow per a regulatory backfit. Because of the time constraints, perceived risk significance, and lack of understanding the fire induced failure mechanisms for electrical cable, the guidance has been perceived to be either over conservative, unclear, or impractical for plants to implement. These complications resulted in numerous generic communications to help clarify the requirements and issuance of exemptions from specific requirements which could not be met on a plant by plant basis. In the late 1990's the NRC temporarily suspended inspecting fire-induced circuit failure until additional research could be conducted to better understand fire-induced failure modes, and better implementation guidance for fire protection circuit analysis and safe shutdown analysis be issued.

1.3 Fire PRA Method

In 2004, the NRC amended is regulations to allow for a risk informed performance-based approach to fire protection to incorporate by reference the 2001 edition of the National Fire Protection Association (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants" 2001 edition. To support applicant's use of the NFPA 805 standard, the NRC and EPRI developed a state of the art method for developing a fire PRA as documented in EPRI 1011989 (NUREG/CR-6850), "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities." This report presents a multi-task, iterative process for quantifying fire risk. Cable and circuit analyses are described in Task 3, "Fire PRA Cable Selection;" Task 9, "Detailed Circuit Failure Analysis;" and Task 10, "Circuit Failure Mode and Likelihood Analysis." Task 3 focuses on identifying and locating the electrical cables associated with the fire-PRA components identified in Task 2, "Fire PRA Component Selection." Task 9 provides a method to perform a deterministic circuit analysis aimed at identifying the possible circuit failure modes and excluding any cables that cannot have an adverse effect on the PRA success criteria. Task 10 assigns a probability of spurious operation (conditional on the occurrence of fire) based on the deterministic circuit analysis (Task 9) and test results performed by the Nuclear Energy Institute (NEI)/EPRI in the early 2000s.

1.4 Fire-Induced Circuit Failure Test Data

Fire tests focusing on nuclear safety have been conducted since the early 1970s. The majority of the early fire testing focused on quantifying the fire phenomena (e.g., heat-release rate, heat flux, flame spread, etc.) of potential NPP fire scenarios. In 2001, NEI in collaboration with EPRI conducted 18 fire tests which evaluated the electrical performance of cables under severe thermal fire conditions. At the time, there was varying opinion on the likelihood of fire-induced hot shorts[3] that can cause equipment to spuriously operate. The results of this testing is documented in EPRI TR 1003326 [4] and demonstrated that hot short-induced spurious operations [4]of components associated with cables damaged by fire occur more frequently than had previously been assumed. Following these tests, the NRC conducted a facilitated workshop and EPRI conducted an expert elicitation to quantify the likelihood of fire-induced

[3] Individual insulated conductors of the same or different cables that come in contact with each other and that may result in an impressed voltage or current on the circuit being analyzed (per PIRT panel's definition in NUREG/CR-7150, Volume 1 [1]).

[4] 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 cables) of the circuit. For example, a pump (starting or stopping) or a valve spuriously repositioned (per PIRT panel's definition in NUREG/CR-7150, Volume 1 [1]).

hot shorts based on these test results. The results of this effort are documented in EPRI TR 1006961 [5] and concluded that the likelihood of fire-induced hot shorts to be in the range of 0.005 – 0.75 depending on the cable configuration. The likelihood estimates developed by EPRI were subsequently incorporated into EPRI 1011989 (NUREG/CR-6850) under Task 10. In Task 10, Tables 10-1 through 10-5 provide best estimates based on various cable characteristics, such as insulation type, raceway type, hot-short failure mode (intra-cable or inter-cable), armoring, and whether a control power transformer was used as the circuits' power source.

Given the limited number of tests performed by NEI/EPRI in the early 2000s and to address several regulatory issues documented in Regulatory Issue Summary (RIS) 2004-03, "Risk-Informed Approach for Post-Fire Safe-Shutdown Associated Circuits Inspections, [6]" NRC-RES sponsored two subsequent fire test projects focused on collecting data on a variety of circuit characteristics for alternating current (AC) and direct current (DC) systems [7, 8]. The NRC data obtained was also used to further develop a fire model to predict cable damage.

2. EXPERT PANELS

2.1 Objectives of the Panels

One of the objectives of the panels was to advance the state-of-the-art methods in quantifying the risk of fire-induced circuit failures beyond that presented in EPRI 1011989 (NUREG/CR-6850). Due to scarce (or in some instances non-existing) test data and/or analyses, it was decided to use a structured expert judgment process to derive positions to represent the knowledge of the broad scientific community. Because of the technical complexity of the problem, and the different skills needed, the expert judgment process was divided into two panels. The first panel involved a group of electrical engineering experts who performed a Phenomena Identification and Ranking Table (PIRT) exercise. The PIRT panel's specific objectives included: 1) identifying the phenomena that lead to fire-induced hot shorts causing the spurious operation of equipment important to safety; 2) ranking the influencing parameters affecting fire-induced hot shorts, and assessing the current level of knowledge for each of the identified phenomena; and 3) providing consensus technical positions on long-standing fire-protection circuit issues. Thus, the experts on the PIRT panel provided the technical basis for why and how electrical cables and circuits fail from fire effects. This PIRT study is based on established expert elicitation methods employed by other PIRT panels that the NRC used in other technical areas where tests or analyses alone could not address the technical issues with the desired level of certainty [9, 10].

The second panel consisted of experts knowledgeable in fire PRA. The specific objective of the PRA expert elicitation panel was to develop best-estimates for the probability and duration of spurious operation due to fire-induced cable damage using the information derived from the PIRT panel, the complete set of results from the tests listed above, and their own expertise. The Senior Seismic Hazard Analysis Committee (SSHAC) process was used by this panel, so the results obtained are expected to represent the opinion of the relevant informed technical community.

2.2 PIRT Process and Results

A complete history of the PIRT results are presented in 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"[1]. This section provides a summary of the results obtained.

To complete the PIRT process, two Figures of Merit were defined, namely:

Spurious Operation[5]: After fire-induced cable damage has occurred to an appropriate conductor in an electrical circuit resulting in a hot short(s), a spurious operation(s) of the component occurs driven by the same electrical circuit.

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

Based on detailed discussions of the various aspects of hot short-induced spurious operation, the PIRT panel identified 16 influencing parameters:

Conductor Count
Fire Exposure Conditions
Cable Routing / Raceway Type
Cable Raceway Fill
Conductor Insulation Type
Cable Aging
Cable Jacket Insulation Material
Time-Current Circuit Characteristics
Cable Grounding Configuration (AC only)
Power Supply Voltage (AC only)
Armoring: Grounded vs. Ungrounded (AC);
 Armored vs. Unarmored Cable (DC)
Cable Wiring Configuration
Conductor Size
Fire Suppression
Circuit Latching
Grounded vs Ungrounded Circuit (AC only)

The PIRT panel recommended additional analyses of test data which resulted in the development of 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" [11]. Using the results of this document allowed for the experts on the PIRT panel to make further refinements and rank the influencing parameters based on importance for both spurious operation and duration.

For the first Figure of Merit, spurious operation, the PIRT panel indicated the following parameters as having a HIGH IMPACT on likelihood:

Wiring Configuration
Conductor Insulation Material (for inter-cable shorts)
Grounding Configuration
Cable Raceway Routing Configuration (panel wiring)
Raceway Fill (bundle configurations)

For the second Figure of Merit, duration, the PIRT panel identified the following parameters as having a HIGH IMPACT:

Fire Exposure Conditions
Time-Current Characteristics
Wiring Configuration
Cable Raceway Routing (Panel Wiring)
Cable Raceway Fill (bundles)

[5] Spurious operation 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). For example, such modes include a pump (starting or stopping) or a valve spuriously repositioning.

In addition to the ranking of parameter importance, NUREG-2128-(ELECTRA-FIRE) also allowed for the PIRT panel members to elaborate on a newly identified (but previously postulated in NUREG/CR 6834[13]) failure mode wherein multiple shorts to ground cause a DC circuit to spuriously operate. This failure mode is referred to as “ground fault equivalent hot shorts,” abbreviated GFEHS and is the only inter-cable failure mode observed in DC circuit testing. Illustrative examples of GFEHS are shown in Figure 1. This failure mode can impact circuits routed in dedicated conduits since this particular phenomenon occurred between cables co-located on the same raceway, as well as between cables located on different raceways provided they both belonged to the same ungrounded common-power supply. The results from the data analysis of NUREG/CR-7100, “Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-Fire): Test Results”, shows that these events occurred in nearly every test during the intermediate-scale testing.

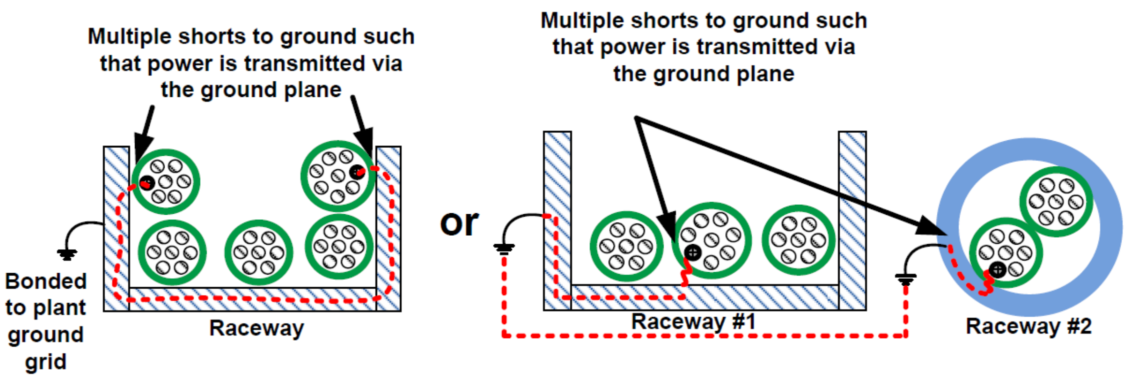

Figure 1. **Illustrative Examples of Ground Fault Equivalent Hot Shorts**

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

Once the formal PIRT process was complete, the electrical expert panel continued to develop an advanced understanding of fire-induced cable failure by developing tables for the follow-on PRA expert elicitation panel, and by defining and classifying various circuit configurations as either implausible or incredible. Definitions of these two terms are essential to understanding the process:

> Implausible: The term “implausible,” when used in conjunction with a fire-induced circuit failure phenomenon, supports the PIRT panel’s conclusion that the phenomena happening, while theoretically possible, would require the convergence of a combination of factors that are so unlikely that the phenomenon’s occurrence can be considered statistically insignificant. In these cases, the PIRT panel could find no evidence of the phenomenon ever occurring, neither in operating experience nor during a fire test.

> Incredible: The term “incredible,” when 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 principle or technical argument to support its happening during a fire.

Circuit configuration not classified as either implausible or incredible are considered possible. The PIRT panel also developed consensus technical positions on several longstanding fire protection circuit issues. These positions were supported by data, engineering principles, physical configurations, manufacturers' input, operating experience, and expert judgment. Using the same definitions developed previously (implausible, incredible), the PIRT panel reached consensus technical positions[6] on the following items:

Implausible
- A single inter-cable hot short between
    - Two thermoset insulated cables
    - Thermoset insulated source[7] cable and a thermoplastic insulated target cable
- Two inter-cable hot shorts between two thermoplastic insulated cables

Incredible
- Inter-cable hot short between
    - Thermoplastic-insulated source cable and thermoset-insulated target cable regardless of the number of shorts needed to cause equipment spurious operation[8]
    - Two inter-cable hot shorts between a thermoset-insulated source cable and a thermoplastic-insulated target cable
- Consequential three-phase AC short
- Consequential hot shorts in a DC compound-wound motor
- Multiple high impedance faults (MHIFs)
- Secondary fire concern for current transformers with turn ratios below 1200:5

2.3 PRA Expert Elicitation Process and Preliminary Results

The PRA expert elicitation panel was responsible for completing the final objective of this expert judgment effort, which is to develop best-estimates for the probability and duration of spurious operation given that cable damage happened due to fire. Specifically, the PRA panel was tasked with evaluating the probability distributions of the following main areas:

Probability[9] of spurious operation for:
- single-break solenoid operated valve (SOV) circuits
- double-break SOV circuits
- single break motor operated valve (MOV) circuits and
- medium-voltage circuit breakers

Probability of duration of spurious operation

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[6] Several of these positions are based on underlying assumptions/conditions that need to be met for the particular issue to be dispositioned as either implausible or incredible (see Volume 1 of NUREG/CR-7150 [1] for details).

[7] The term "source cable" as used represents a cable that supplies energy to a "target cable" which receives energy and is associated with a device that can spuriously operate. These terms are only applicable to inter-cable failure modes.

[8] The PIRT panel believed that the difference in insulation robustness between a thermoset-insulated and a thermoplastic-insulated cable affects failure timing of cables. The panel determined that thermoplastic-insulated source to thermoset-insulated target configurations are incredible, while the failure characteristics of thermoset to thermoset-insulated cables should be considered implausible.

[9] All probabilities are <u>conditional</u> on cable damage due to fire.

- All circuit configurations

To implement this effort, the project selected the expert elicitation process known as the Senior Seismic Hazard Analysis Committee (SSHAC) process. Using the SHAC process to represent the relevant informed technical community, the expert elicitation estimated the probability and duration distributions for all cable configurations, including those configurations where there was limited applicable test data. The SSHAC process is described in NUREG/CR-6372, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts" [12], and defines four levels of effort, with Level 1 being the most elementary (and least resource-intensive), and Level 4 being the most comprehensive (and most resource-intensive). The project management chose to conduct a Level 2 SSHAC process with inclusion of several Level 3 aspects, such as in-person panel workshops and the review by a participatory peer review panel (PPRP). Three in-person workshops were included to support communication among the panel members on complex issues, and the PPRP reviewed the technical aspects of the project as progress was made (as opposed to reviewing after the technical evaluations have been completed, when making changes is more difficult and resource-intensive), providing assurance that the proper process was followed. Specifically, the PPRP consisted of three experts from the NRC and the nuclear industry who were responsible for ensuring that the SSHAC process was followed. The primary focus of the PPRP was to ensure that the study incorporated the diversity of views prevailing within the technical community, that uncertainties were properly considered and incorporated into the analysis, and that the documentation of the study would be clear and complete.

Following the SSHAC process, the experts were classified into three categories, namely, evaluator experts, proponent experts, and resource experts. The evaluator experts constitute the technical integration (TI) team and are responsible for ultimately developing the composite representation of the informed technical community (called the community distribution) for each probability distribution for likelihood and duration of spurious operation. The role of a proponent expert is to advocate a specific model, method, or parameter for use in assessing the probabilities and durations of spurious actuations. The TI team evaluates the proposals developed by the proponent experts. Resource experts were responsible for presenting data in an impartial manner to inform the other panel members of the facts or technical understanding of the data. In an effort to provide continuity across the two panels, several of the experts on the electrical expert PIRT panel also served on the PRA panel.

Following two workshops and after having been provided input from the proponent and resource experts, the TI team developed the draft community distributions. A different approach was used for probabilities and for durations. For probabilities, this was accomplished in three steps. First, a beta distribution was fitted to the quantiles provided by each expert to obtain a probability distribution representing the expert's knowledge about a probability. In the second step, the TI team decided to use mathematical aggregation to combine the distribution from each expert into a single distribution. The linear opinion pooling (LOP) method was used, which is a weighted average of the individual distributions with weights wi summing to 1, as shown below.

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

where θ is an unknown quantity, such as the probability of spurious operation, fi(θ) is the individual distribution of expert i, n is the number of experts providing input, and f(θ) is the aggregated distribution.

In general, the TI team assigned equal weights to the individual proponent distributions. Since the distribution resulting from combing several distributions is typically not a parametric distribution, for convenience a beta distribution was fitted to the quantiles of the aggregated distribution, and the fitted distribution was considered the draft community distribution. Hence, the third step consisted of carrying

out such fitting. Beta distributions were used in steps one and three because of two features of this type of distribution:

1) its range is the interval [0, 1], which corresponds to the values of probabilities; and
2) it is a flexible distribution that can take different shapes.

Figure 2 illustrates the last two steps, where PDF is defined as probability density function, and p(SO/fire) is the probability of spurious operation given fire damage. The dotted distributions are the distributions of four experts (Exp1 to Exp4), the thin continuous curve is the aggregated distribution resulting by applying the LOP method (previous equation), and the thick continuous distribution is the fitted distribution, that is, the draft community distribution (CD).

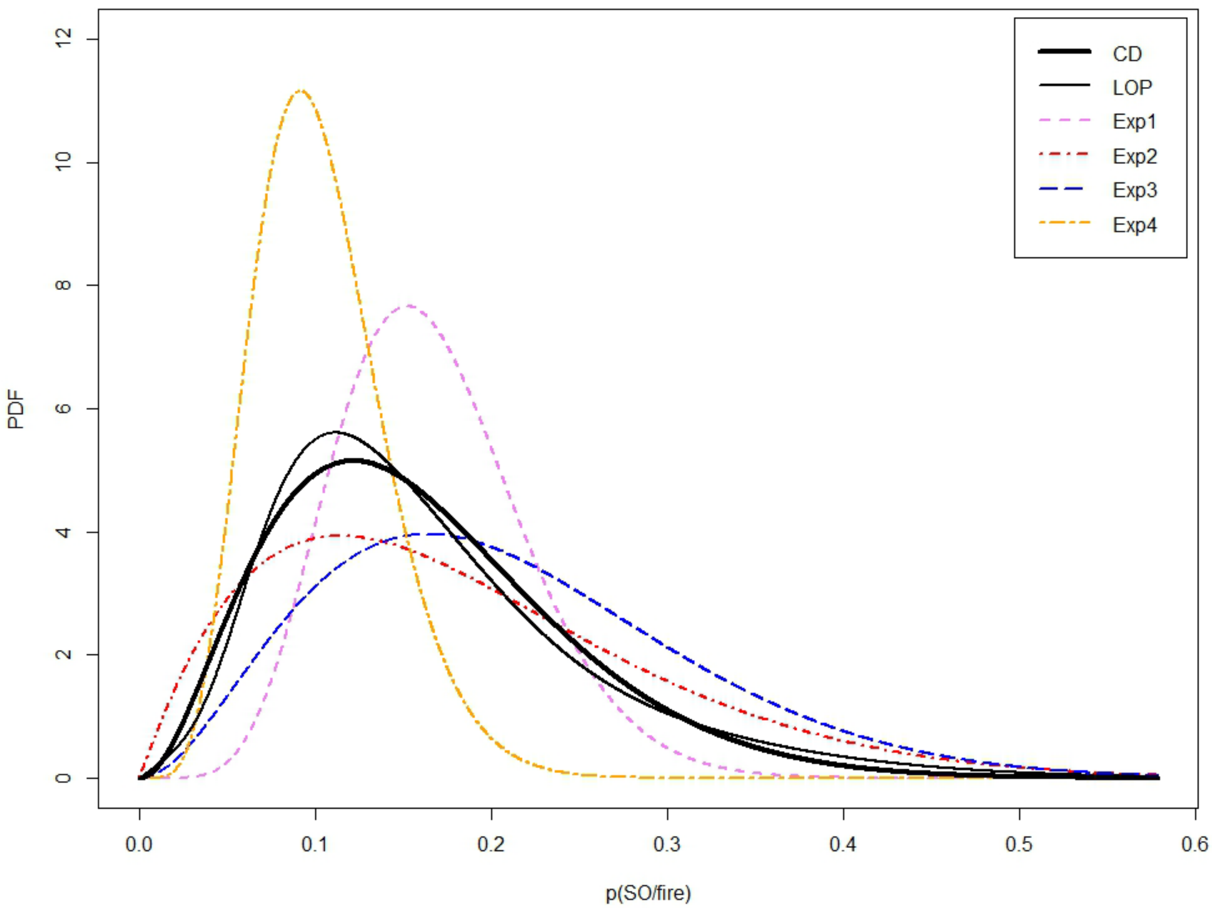

Figure 2. **An example of aggregating several individual distributions into a community distribution**

After considering the input from the proponent experts, the TI team selected the approach of carrying out a top-level evaluation for developing the draft community distributions for durations. In other words, a draft distribution for AC circuits and another for DC circuits were established, instead of a draft distribution for each combination of cable configuration (e.g., thermoset-insulated or thermoplastic-insulated cables) and failure mode of cables (e.g., intra-cable or inter-cable).

After the TI team develops the draft community distributions for probabilities and durations of spurious operations, a third and final SSHAC workshop was held. Workshop 3 focused on presenting and discussing the TI team's preliminary models and calculations in a forum that provides the opportunity for feedback by experts and the PPRP prior to finalization and documentation of the results. Following

Workshop 3, the BNL moderator and the TI team finalized the calculations and documented the result in NUREG/CR-7150, 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." The quantitative results are presented in Tables 1,2, and Figure 3.

Table 1. **Summary of Mean Conditional Probabilities of Spurious Operation for 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		Device Type	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	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

Table 2. **Summary of Mean Conditional Probabilities 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

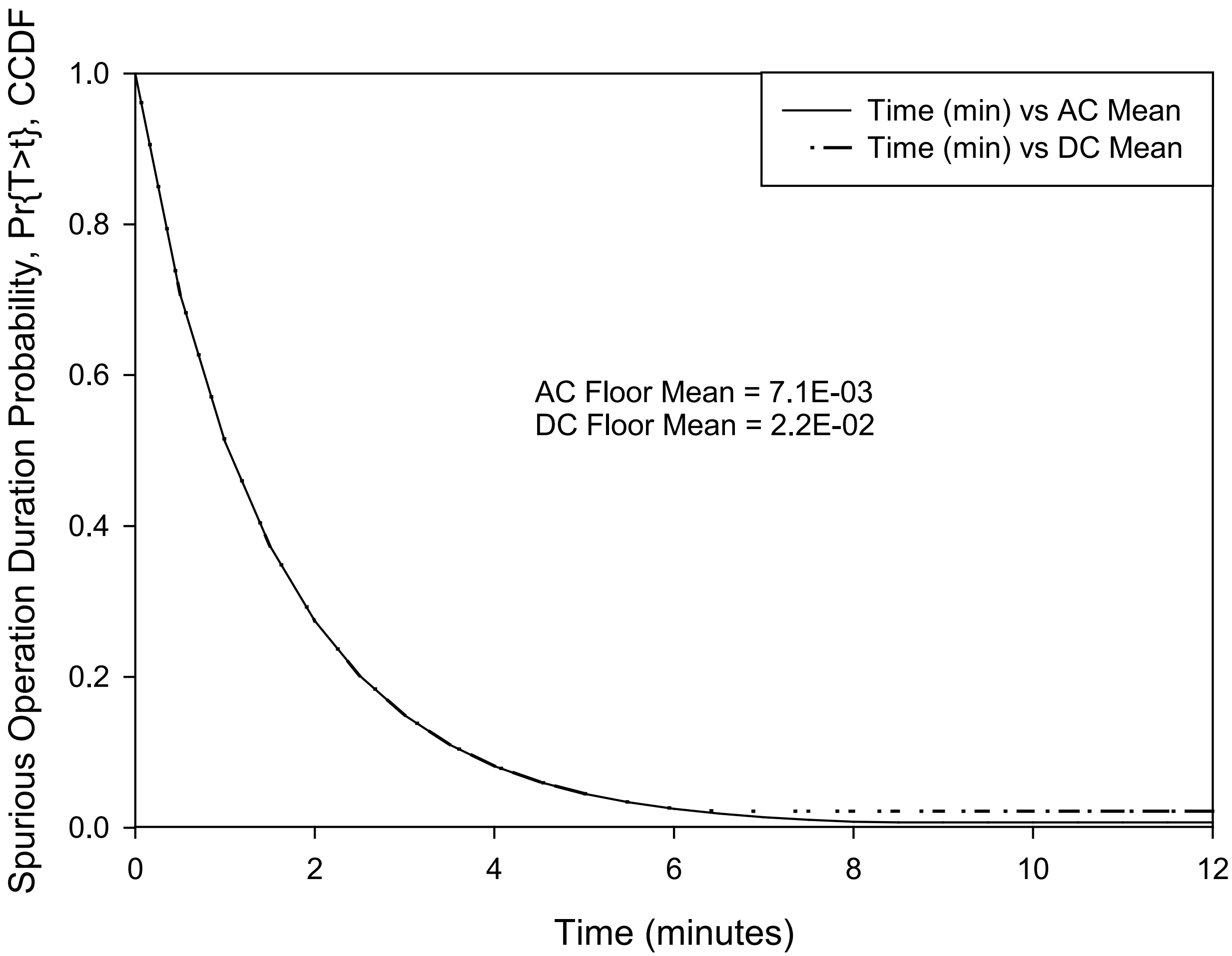

Figure 3. **AC and DC Spurious Operation Duration Mean Conditional Probability Plots**

3. EXAMPLES OF CONDITIONAL RISK CHANGES

This section provides three simplified case studies to illustrate the changes in conditional risk estimation between the original NUREG/CR-6850 Task 10 method and the new quantification estimate developed using expert judgment in the JACQUE-FIRE program.

Case 1a – Solenoid Operated Valve (SOV)

- Electrical schematic shown in Figure 4
- Failure mode of concern is a hot short induced spurious operation causing valve to spurious open
- Cable B is a multi-conductor thermoset-insulated cable containing electrical nodes (P00, N00, R00, G00, SV0, SV1, and a spare), located in a steel ladder back cable tray.

Results

Method	Data Source	Conditional Likelihood
NUREG/CR-6850	Table 10-2	0.62
NUREG/CR-7150	Table 1 (in this paper)	0.56
Conditional Risk Change		0.04 decrease (~6% risk reduction)

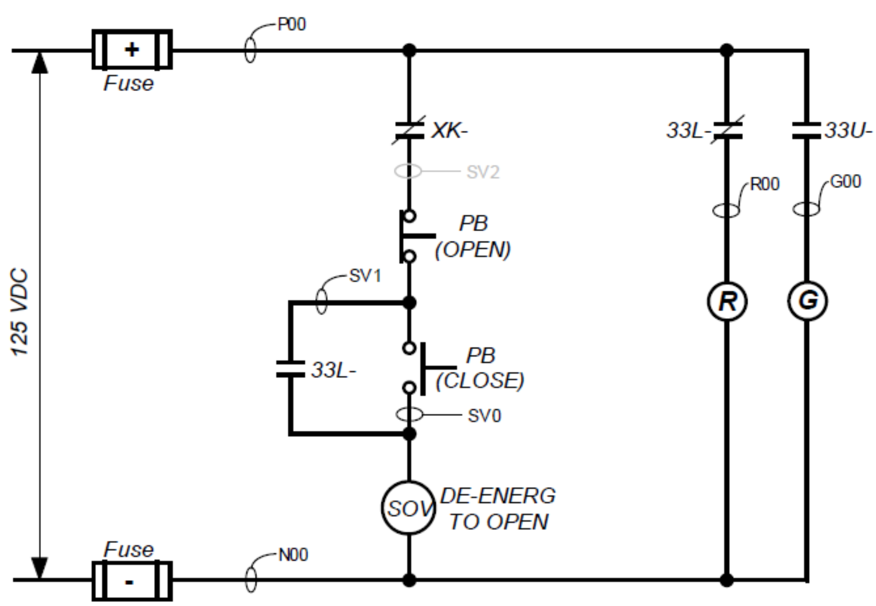

Figure 4. Electrical Schematic for Typical SOV Circuit

Case 1b – Solenoid Operated Valve (SOV)

- Same as Case 1a, except cable is armored.

Results

Method	Data Source	Conditional Likelihood
NUREG/CR-6850	Table 10-5	0.15
NUREG/CR-7150	Table 1 (in this paper)	0.86
Conditional Risk Change		0.71 increase (~factor of 6 risk increase)

Case 2a – Motor Operated Valve (MOV)

- Electrical Schematic Shown in Figure 5
- Failure mode of concern is a hot short induced spurious closure of valve
- Cable B is a multi-conductor thermoplastic containing electrical nodes (X00, S01, R00, G00, SC1, and two spares), located in a steel ladder back cable tray.

Results

Method	Data Source	Conditional Likelihood
NUREG/CR-6850	Table 10-3	0.32
NUREG/CR-7150	Table 1 (in this paper)	0.29
Conditional Risk Change		0.03 decrease (~10% risk reduction)

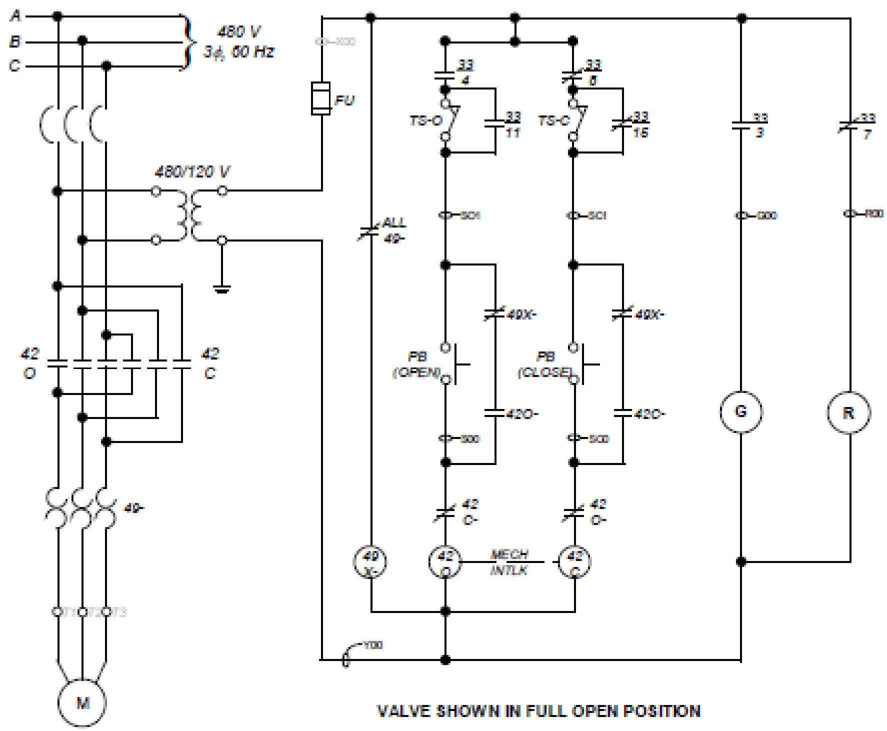

Figure 5. **Electrical Schematic for Typical MOV Circuit**

Case 2b, Motor Operated Valve (MOV)

- Same as Case 2a, except cable is armored.

Results

Method	Data Source	Conditional Likelihood
NUREG/CR-6850	Table 10-5	0.075
NUREG/CR-7150	Table 1 (in this paper)	0.034
Conditional Risk Change		0.041 decrease (~50% risk reduction)

Case 3a – Double Break DC MOV

- Electrical schematic is shown in Figure 6
- Failure mode of concern is spurious opening (Raise) of valve while in remote
- Cable B is a multi-conductor cable thermoplastic insulated cable containing electrical notes (P01, N01, F02, F03, and a spare) located in a steel ladder back cable tray.

Results

Method	Data Source	Conditional Likelihood
NUREG/CR-6850	Table 10-4	0.62
NUREG/CR-7150	Table 1 (in this paper)	0.21
Conditional Risk Change		0.41 decrease (~factor of 3 risk reduction)

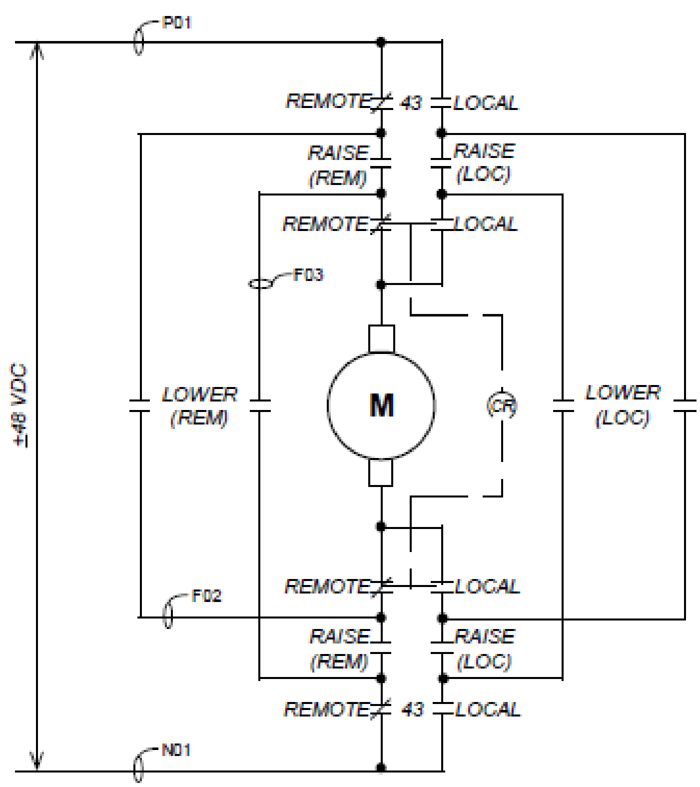

Figure 6. **Electrical Schematic for Double-Pole-Isolation DC MOV Control Circuit**

Case 3b Double Break DC MOV

- Same as Case 3a, except cable B is located in conduit

Results

Method	Data Source	Conditional Likelihood
NUREG/CR-6850	Table 10-5	0.16
NUREG/CR-7150	Table 1 (in this paper)	0.21
Conditional Risk Change		0.05 decrease (~30% risk reduction)

4. CONCLUSIONS

Data obtained from operating experience and tests are the main basis for developing estimates of probabilities and durations of fire induced circuit failures to be used in a PRA. For circumstances where limited, or no data, available, or where a consensus position on a technical issue is desired, the use of expert judgment can be a valuable tool. The use of two expert panels as described have shown, the PIRT and SSHAC methods in combination are useful for obtaining expert judgment on complex issues, in this case, to solve some of the problems faced in fire PRA.

The electrical expert PIRT panel results have provided technical consensus on several long time contentious safety issues related to fire PRA electrical circuit analyses. Specifically, the PIRT results categorized circuit configurations as being possible, implausible or incredible, which provided strong technical recommendations to support regulatory activities. Strong technical recommendations, as resulted from the two expert panels, provide knowledge for a better understanding of fire-induced hot short phenomena. In turn applying knowledge gained from such panels, enhance both deterministic and risk-informed fire analyses resulting in resolving long standing issues and implementing guidance to improve regulatory activities.

Additionally, the results of the PIRT panel identified areas where knowledge is low and suggested areas of future research prioritized based on risk insights. Finally, the PIRT results provided a strong technical basis and framework for the follow-on PRA expert elicitation panel to perform its analysis.

The PRA expert elicitation was conducted according to the SSHAC process, which provided the following main benefits: 1) well-defined roles for the experts engaged in the elicitation; 2) workshops with specific goals; and 3) a PPRP that reviewed and provided comments on the technical and process aspects of the elicitation. The continuous oversight of this PPRP team allowed for real time assurance that the SHAC process was being followed in order for the results to accurately represent the informed technical community The final output of this panel represents aggregated community distributions for the probabilities and durations of fire-induced spurious operations given cable damage due to fire.

The results of both panels are advancing the current state-of-the-art on probabilistic data for developing a Level-1 fire PRA. This data will provide more realistic results in fire PRAs based on test data supplemented by structured expert judgment. Further, these results will promote informed and stable regulatory decision making in U.S. NPP fire protection programs.

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