PRA Panel Proponent #3 Report

January 2013

NRC-RES/EPRI Fire PRA Expert Elicitation Regarding Fire-Induced Cable Failure and Resulting Spurious Operations

Introduction and Problem Statement

The views expressed here are mine and I have attempted to weigh factual information more heavily than any personal judgments that have been made at the PIRT and probabilistic risk assessment (PRA) expert elicitation panel meetings. It is my belief that topics covered during these PRA meetings that were not based on technical information should not influence my conclusions and as presented below I have attempted to present my expert judgment based on technical information or provide a technical basis to support any judgments. By completing the assessments in this manner, I believe that involvement in the project is adequately served to support representation of scientific view. However, there are several areas where little to no information is available and where I make judgments based on my best engineering experience. Under these circumstances, I specifically state either the lack of information and/or lack of knowledge. Although the views express here are mine, I was assisted in the data processing and analysis by two other associates.

The objective of this project as presented to me is to quantify the center, body and range of hot short-induced spurious operation likelihood and duration resulting from fire damaged cables. The precursor to these events is the cable being damaged. As such, any phenomena that influence the likelihood of cable damage was not used as a basis to support any shorting phenomena judgment. To facilitate the scoping of this work, the PIRT panel developed tables identifying influencing parameters that they felt affect the likelihood of a fire-induced damaged electrical cable experiencing a hot short-induced spurious operation. These tables are presented in Volume 1 of NUREG/CR-7150, “Joint assessment of Cable Damage and Quantification of Effects from Fire.” In general, I agree with this approach and have developed my assessment around the structure of using the tables developed by the PIRT as modified by the PRA panel. I’ve broken the documentation of my expert judgments into two sections. The first section presents my assessment of the conditional likelihood of fire-induced spurious operation to a solenoid operated valve (SOV) circuit, given cable damage. This value, along with other point estimates that I’ve proposed are used in event trees to derive the motor operated valve (MOV) spurious operation likelihood value. The latter section discusses my evaluation of the data to develop information related to duration of fire-induced spurious operations.

Table 2 on the subsequent page documents the conditional probabilities I’ve developed for consideration by the technical integration (TI) team. These values can be used for SOV cases. The text that follows provides supporting information as to how I developed these estimates and how these estimates could be used in the developed MOV event tree to derive estimates for MOV circuits.

Table 1. Conditional spurious operation probability estimates for single break SOV circuits

Power Source	AC						DC			
Bounding Value	0.60 (0.40, 0.75)						0.88 (0.60, 0.95)			
Circuit Grounding	Grounded AC			Ungrounded AC (on separate CPT)			Ungrounded DC (also applies to distributed ungrounded AC)			
Bounding Value	0.45 (0.25, 0.55)			0.60 (0.40, 0.75)			0.88 (0.60, 0.95)			
Hot Short – Failure Mode	Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	GFEHS	Aggregate
Bounding Value	0.45 (0.3, 0.5)	0.01 (1E-3, 0.05)	0.45 (0.25, 0.55)	0.60 (0.4, 0.7)	1E-3 (1E-3, 0.05)	0.60 (0.40, 0.75)	0.65 (0.40, 0.70)	0.01 (1E-3, 0.03)	0.50 (0.30, 0.65)	0.88 (0.60, 0.95)
TS Target Cable	**0.45** (0.4, 0.5)	**1E-3** (5E-4, 0.01)	**0.45** (0.40, 0.55)	**0.60** (0.5, 0.7)	**1E-4** (1E-5, 1E-3)	**0.60** (0.50, 0.75)	**0.50** (0.43, 0.57)	**1E-3** (5E-4, 0.01)	**0.20** (0.13, 0.27)	**0.60** (0.45, 0.75)
TP Target Cable		**0.01** (5E-3, 0.05)			**0.01** (5E-3, 0.05)			**0.01** (0.005, 0.03)		
Cable includes a grounded metal foil shield wrap	**0.20** (0.12, 0.28)		**0.20** (0.12, 0.28)	**0.55** (0.40, 0.70)		**0.55** (0.40, 0.70)	**0.55** (0.40, 0.70)		**0.35** (0.22, 0.48)	**0.70** (0.45, 0.95)
Armored Cable	**0.01** (0.005, 0.012)		**0.01** (0.005, 0.012)	**0.50** (0.45, 0.55)		**0.50** (0.45, 0.55)	**0.75** (0.70, 0.80)		**0.50** (0.35, 0.65)	**0.88** (0.70, 0.95)

Note: Point estimates (median) are given in bold text and 1st and 3rd quartiles are given in parentheses (1st quartile, 3rd quartile)

Judgment of Fire-Induced Spurious Operation Likelihood Estimates

<u>Proposed Approach</u>

The electrical expert PIRT report (NUREG/CR-7150 Vol. 1) provides empty tables that identify circuit attributes that the PIRT panel felt affected the likelihood of fire-induced spurious operations. This information is shown in Table 1 with slight modifications as agreed upon during the 2nd workshop of the PRA expert elicitation panel.

Prior to the start of my analysis, staff from the NRC sorted the data files and developed a roll-up table identifying the number of spurious operations and number of trials for each box in Table 1. Although this information is useful as a reference point, I didn't feel confident that this roll-up table provided sufficient information to conduct a thorough evaluation of the data set for the specific boxes identified in Table 1. Thus, for each cell within the Table 1, I reviewed the test data independently for corresponding configurations, identifying the number of possible spurious operations for each cell and also the number of actually occurring spurious operations for the corresponding cells.

Once the corresponding data was identified for the specific cell under evaluation, I conducted a simple Bayesian update using a non-informed Jeffreys prior. This serves as a first approximation and is later adjusted if necessary for consideration of various experimental and other influencing factors.

Using the Bayesian approximation as an anchor, I evaluated on a case-by-case basis the influence of various factors that affect the statistical result. These factors include,

- Wiring configuration
- Circuit grounding configuration
- Cable failure characteristics
- Comparison of experimental attributes to field application

<u>General insights on data analysis</u>

The insulation resistance measurement system data (IRMS) provides little valuable information for use in developing the probabilities of spurious operation. This is because the cable(s) connected to the IRMS are not distinguished as target and source conductors. Theoretically, it could be argued that various conductors could be considered target and sources and a detailed analysis could be conducted to estimate the associated spurious operation likelihood. However, the IRMS system response time is too slow to allow for the analysis results to be beneficial. Thus, I did not use any IRMS data in development of my estimates.

The surrogate circuit data has direct application related to determining the likelihood of spurious operation. All of the ac surrogate circuit test results are based off of a motor operated valve (MOV) circuit that has two[1] spurious operation targets. The dc circuit results used MOV and medium voltage breaker control circuit simulators which had two spurious operation targets.

[1] The EPRI tests used three spurious operation targets per surrogate circuit, two of the targets were within the same multi-conductor cable and the third spurious operation target was located in a single conductor cable which surrounded the multi-conductor cable.

The dc testing also used circuits that had only 1 spurious operation target, these included the small solenoid operated valve (SOV), 1-inch valve SOV, and the large coil circuit.

The medium voltage breaker is either in the closed or tripped position and as such, only a hot short to the trip or close coil, respectively, will result in a spurious operation. MOVs are typically not used for modulation and thus are typically either in the closed or open position. As such, a hot short to a conductor associated with the open MOV contactor will result in a spurious opening of a MOV initially in the closed position. However, a hot short to the conductor associated with the close contactor will not result in spurious operation of a MOV initially in the closed position. The reason for this lengthy discussion is that the surrogate circuit used in the testing did not reflect initial valve position and a hot short to either the open or closed contactor would be classified as a hot short-induced spurious operation. In addition, in the EPRI and CAROLFIRE testing the electrical and mechanical interlocks were removed or not used such that hot shorts to both contactors on the same MOV could be classified as spurious operations.

In typical MOV circuit designs, the limit and torque switches limit the direction in which the MOV can spurious operate. For instance, if the valve is in the closed position, the close torque and close limit switches are open in the portion the circuit that is 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 opening of the valve. One exception to this logic is related to the IN 92-18 concern, where a hot short that bypasses the limit and torque switches may actuate the valve in the open or closed position. Bypassing these switches could cause the valve to become permanently damaged or result in some other type of failure. However, the end 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 the data should be analyzed to adequately represent real case scenarios. After the 1st workshop, two of the panel members proposed an event tree method that utilizes various split fractions such as valve response, end position, and IN 92-18 protection. These event trees would use the values populated in Table 1 to develop a modified estimate. To support the use of these event trees, as presented in the 1st and 2nd workshop, the MOV data must be analyzed using the target approach as presented in NUREG-2128. That is, each MOV contractor target conductor is analyzed separately for spurious operation. To accomplish this, I analyzed the MOV data on a target specific basis. Doing so provided two benefits. For MOV circuits, the valve is typically either in the fully close or fully open position and the hot short-induced spurious operation that would cause the valve to change position is the failure mode of concern. Under this approach, I evaluated the appropriate data set for spurious operations of one of the contactors and then re-analyzed the same data set for spurious operations of the other contactor, thus doubling the data set (benefit #1) and only evaluating one spurious operation target at a time for the MOV data set. This method simplified the complexity of the MOV circuit response and more importantly allowed use of the MOV data to support evaluation of devices that only have one target conductor that can result in a spurious operation (benefit #2).

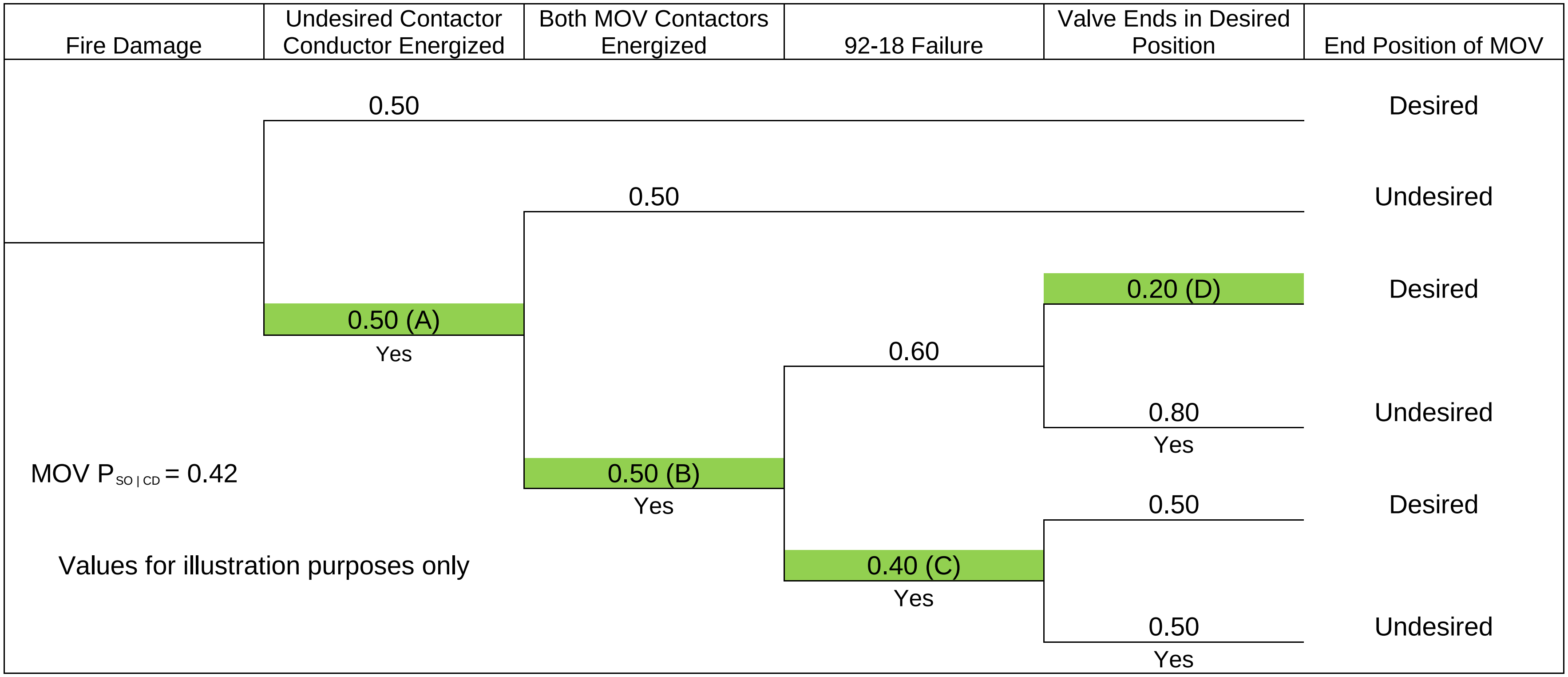

Figure 1. MOV Event Tree Structure (for Illustrative Purposes Only)

The event tree shown in Figure 1 was developed during the 2nd PRA expert elicitation workshop and requires 4 values (highlighted in green) from the proponents to arrive at a conditional probability of spurious operation given fire damage for a MOV. The following provides a description of what each decision point in the event tree represents.

<u>Undesired Contactor Conductor Energized</u>

The first value (identified as "A") 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 will be referred to as the "conductor of concern." This value is the same as the SOV conditional probability of spurious operation that are shown in Table 1 above. The up branch accounts for cases where the circuit failure mode is a fuse clear or any other failure mode that doesn't involve energizing the conductor of concern.

Both MOV Contactors Energized

The second value (identified as "B") evaluates 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 cases where only the conductor of concern experiences a hot short-induced spurious operation. If this is the case, it is assumed that the valve travels to its end position and the valve is assumed to fail in the undesired position. The bottom branch accounts for cases where both of the MOV contactors are energized regardless of order or timing of each hot short. The estimates that I propose for this event are based on test data where both contactors can become energized and then adjusted for factors that I felt differ from the test cases to actuality (e.g., conductor wiring configuration, grounding, cable construction, etc.).

92-18 Failure

The third value (identified as "C") 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 doesn't 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 valve position is dependent on when the hot short abates. The estimates that I propose for this event in the scenarios below are also based on test data (when available) and adjusted for factors that may influence difference between test data and actuality. However, I also considered that this particular event is highly scenario dependent on the circuit design, and specific cable being evaluated. As such, I've used some subjective judgments to also account for this variability.

Valve Ends in Desired Position

This decision point of the event tree (identified as "D") quantifies the valve end position. The end valve for the case where 92-18 failures could occur (torque or limit switches bypassed) simply assumes that there is an even probability of either MOV contractor being energized first and the valve strokes to the either the fully open or closed position and remains in that position. The first contactor to experience a hot short in combination with the 92-18 failure cause the valve to stroke in the direction of the MOV hot shorted contactor. For the case where the 92-18 failure doesn't occur, the value provided (green cell) quantifies the likelihood that the MOV doesn't cycle to the undesired position. Since this event tree doesn't take hot short duration into consideration, I propose that 80% of the time the valve will be in some position other than desired position for all scenarios documented below. Due to the wide variety of valve stroke times, without accounting for duration of hot shorts, and without knowing the success criteria for the specific valve being evaluated, I feel comfortable that the 80% value bounds real world cases. Since this aspect of the event tree is so dependent on the valve design, independent assessment by licensees would provide a more realistic value for a specific valve under evaluation.

Adjusting the estimates based on test wiring configurations

In order to provide the most realistic probabilities for different types of intra-cable hot shorts, it is desirable to account for the wiring or "conductor bias" used in the EPRI and NRC tests represent real world application. The PIRT panel determined that wiring configuration was the most influential parameter regarding spurious operation likelihood (see Volume 1 of NUREG/CR-7150). Since wiring configuration was found to be important, I felt it necessary to adjust the test result such that they better represent reality. As such, the following lengthy discussion documents the way that I choose to adjust my results. There are a few important assumptions that I must first identify. This approach is based on the use EPRI/NEI test data set where four wiring configurations were used. This gave some comparative advantages, but was also limited by grounding configurations, number of tests, and power supply voltage profile. As such, I've only applied this method to grounded ac intra-cable spurious operation cases and used expert judgment and engineering principles to account for wiring configuration for other cases.

The NRC circuit testing was conducted using a source centered (SC) bias, with a few exceptions. The source centered configuration was found to be somewhat conservative in some cases during the EPRI testing. The EPRI testing, discussed in EPRI TR1003326, was conducted using four different defined biases for which different hot short, short-to-ground, and spurious actuation probabilities were documented. Thus, the testing only represents a subset of possible wiring configurations used in the field. Although some architectural engineering and construction companies may have a detailed procedure for connecting circuits to conductors within a multi-conductor cable, there is no standard or industry best practice for assigning conductors when wiring a circuit. As such, for the assessment and ultimate adjustment of the statistical results, I have assumed a random cable conductor to circuit wiring configuration to represent what is in use in the field. Figure 2 provides an illustration of the conductor configurations used by EPRI. The NRC used the source centered configuration almost exclusively of their testing.

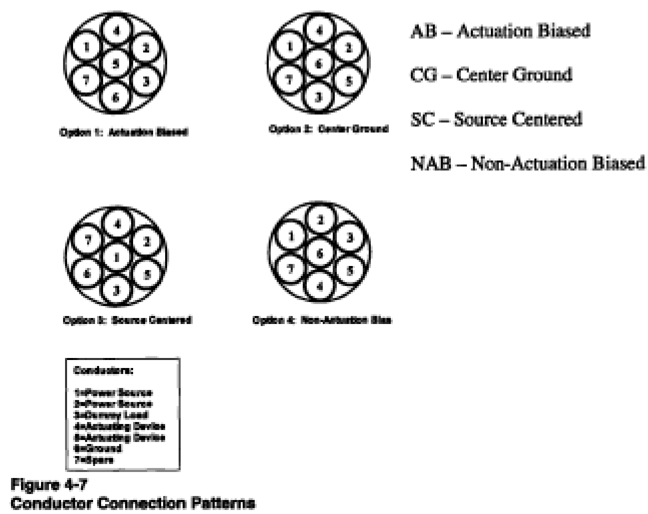

Figure 2. Illustration of wiring configuration used in EPRI testing (from EPRI TR1003326)

The biases for the four configurations presented in Figure 2 were only defined by the EPRI test report in terms of the exact circuit configurations used. For the purposes of this analysis, some definitions are expanded upon for clarification purposes. Assuming a randomly wired cable in a plant this analysis provides the expected ratios for different conductor biases comparable to those provided in the EPRI testing. A 7/c cable with 2 spares[2], 2 sources, 2 spurious operation targets, and 1 ground is evaluated because it is representative of the EPRI and NRC testing.

The conductor biases are defined here as:

Actuation Biased (AB): configuration where both target conductors are adjacent to at least one source and the center conductor is neither a ground nor a source.

[2] The two spares are represented in the EPRI circuit by one spare that is left ungrounded and one conductor that is connected to a burden resistor representing an indication lamp.

Center Ground (CG): configuration where the center conductor is grounded but the cable is NOT considered to be non-actuation biased. (See below.)

Source Centered (SC): center conductor is energized and considered a source for potential spurious actuations.

Non-Actuation Biased (NAB): target conductors are NOT located adjacent to source conductors.

Remainder: the remaining cases (e.g., target centered or spare centered, but with only one target adjacent to a source) are not tallied in any of the above categories but the ratio is still provided for completeness.

In order to determine the total possible number of unique configurations (or permutations), the center conductor is treated separately and is assumed to be a given type of conductor (i.e., source, target, spare, ground) such that the remaining six conductors can be considered a circle permutation. Note that external or inter-cable hot shorts are excluded for the purposes of this particular analysis.)

The formula for a circle permutation, or the number of ways to arrange n elements along a circle, with some identical elements, is given as:

——— (1)

where n=a+b+c+d and
a,b,c,d are the variable for spares, targets, sources, common return (grounds)

The “conductor type” for the center conductor is changed so that four cases are evaluated:

1. center conductor is grounded,
2. center conductor is a source,
3. center conductor is an ungrounded spare, and
4. center conductor is a spurious actuation target.

Thus, for the case where the ground is defined as the center conductor, there will only be 6 elements (with 2 spares, 2 targets, and 2 sources) in a circle such that:

—— —— permutations

For the case where a spare is located in the center, there will only be 6 elements (2 sources, 2 targets, 1 spare, and 1 ground) in a circle such that:

—— —— permutations

Similarly, both the target centered and source centered configurations will have 30 permutations each.

The total number of permutations for the 7/c cable is determined by adding the number of circle permutations for each of the four cases.

Thus, for a SC configuration the ratio is simply:

Similarly, the ratio for CG configuration would be:

However, this value would include one of the NAB conductor bias configurations. To account for this, the NAB cases will be determined and the center ground, NAB bias contribution will be removed to determine an independent ratio for CG bias.

The number of permutations for a non-actuation bias with a center ground can be found by:

permutation

The number of permutations for a non-actuation bias with a center spare can be found by:

permutations

Thus, for a NAB configuration the ratio is simply:

And the CG configuration ratio, excluding the 1 NAB configuration, becomes:

The calculations for the AB configuration are slightly more difficult and in some cases have simply been verified by inspection.

For the AB conductor bias configuration with a target center conductor, the outer target conductor simply needs to be located adjacent to one or more sources because the center target will always be adjacent to a source. For simplification, this problem is broken up into 3 steps. First, the combination of a target (T) and a source (S), in that order, is considered one single element and the total number of elements is reduced from 6 to 5. The number of permutations for this scenario is:

permutations

Similarly, from source (S) to target (T), the number of permutations is 12. The two values cannot simply be added because there is some overlap where the configuration may have a source, target, and second source in series (STS). The number of permutations for which include this arrangement is calculated in a similar manner to previous steps:

permutations

Thus, the total number of target-centered AB conductor bias configurations is given by:

If configurations with an ungrounded spare conductor as the center conductor are also considered to be AB, the total number of AB configurations, and the associated ratio, will need to be increased.

The total number of AB configurations for a spare-centered configuration is determined by looking at the number of possibilities for both targets to be adjacent to a source, in various configurations or steps, similar as to how the total was determined for the previous configuration. These steps were for arrangements with combinations of ST and ST, TS and TS, or ST and TS.

permutations

permutations

permutations

The total number of AB configurations is given by:

By process of elimination, the remaining fraction of values is given by:

This remainder accounts for target-centered and spare-centered cases where only a single target is adjacent to a source. Because the remainder ratio cannot be attributed to any one of the four EPRI wiring configurations, I choose to distribute this fraction equally among the four cases. This results in the ratio values shown below.

The ratios developed here (shown in bold) are used in specific scenarios identified below to adjust the experimental data to represent field wiring configurations, which I have assumed to be random. For the EPRI data, the test results were binned by wiring configuration and a representative spurious operation likelihood value was calculated from the data. Next the four likelihood values calculated were multiplied by the associated ratios identified above and the product were summed to arrive at an adjusted likelihood estimate for the EPRI data.

Since the NRC data set mostly consisted of test cables connected to a surrogate circuit in a source centered wiring configuration. This data was modified as shown below to represent the realm of possible wiring configuration.

Where,
- z = probability of spurious operation from NRC data (# SO / # Trials)
- y = probability of spurious operation from EPRI data for non-source center configurations
- x = probability of spurious operation from EPRI data for source center configurations

<u>The Aggregate</u>

I was also asked by the TI team to come up with an aggregate value for the various configurations. After reviewing several options, I determined that a simple Boolean "OR" combination of the intra-cable, inter-cable and multiple shorts to ground results (if applicable). I've also assumed independence of these failure modes. For every case, I explored any possibilities that the independence assumption be void, but did not identify any scenarios where I found this to be the case. Thus, the "Aggregate" column in Table 1 above was populated, without further discussion using the following formula;

Aggregate = A + B + C – [(A*B) + (A*C) + (B*C) – (A*B*C)]

Where,
- A = Intra-Cable Spurious Operation Probability
- B = Inter-Cable Spurious Operation Probability
- C = Ground Fault Equivalent Hot Short Spurious Operation Probability

A. Grounded ac configurations

This sections looks at the likelihood of a grounded AC circuit experiencing a spurious operation. Conditional spurious operation likelihood estimates given fire-induced cable damage are developed for the SOV case and then values for use in the MOV event tree are developed. The progression of each case follows the same theme of reviewing the data set, adjusting the data to account for testing-to-reality effects and then adjusting the value based on any expert judgment or engineering principles.

Intra-cable TS Target Cable (ROW 1, COLUMN 1)

Statistical Analysis

Using the grounded ac data from the CAROLFIRE, DESIREE-FIRE and NEI/EPRI projects, all data with the following attributes were removed;

- Thermoplastic insulation (TP)
- Armor
- Metal foil shield wrap
- Ungrounded
- Cable failure due to water spray

Table 2 below provides a summary of the collected data from the EPRI and NRC tests. The EPRI and NRC MOV data is reported on separated rows and a composite (summation) of these two rows is also provided. The surrogate SOV information was populated as discussed in the introductory sections, by evaluating the MOV data on a single spurious operation target basis, completed twice. This table also provides information on the number of times both spurious operation targets of the MOV circuit experienced hot shorts. This information is used when developing estimates for the MOV event tree.

Table 2. Spurious Operation Data Results for Grounded AC Intra-Cable TS insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
EPRI MOV	8 / 24	9 / 24	10 / 24	7 / 24
NRC MOV	15 / 26	16 / 26	18 / 26	13 / 26
MOV Composite	23 / 50	25 / 50	29 / 50	**20 / 50**
Surrogate SOV	**48 / 100**			

Expert Judgment

If the cable under consideration contains grounded conductors other than a drain wire (e.g., grounded spares), as identified above, there is a higher probability that the energized sources will short to the grounded spares. Since the circuit is of the grounded configuration, this increases the likelihood of the circuit protective device (fuse) clearing and reducing the likelihood of hot short-induced spurious operation. As such, I suggest reducing the likelihood number above by a fraction of the number of grounded spares within the cable. For example, if a cable contains one grounded conductor in a 7 conductor cable, I suggest subtracting

P_{c2c_short} : probability of a conductor to conductor short circuit failure mode

Performing a scoping study using common multi-conductor control cable configurations, I evaluated the above equation, varying the conductor count (5/C to 19/C) and number of grounded conductors (0 to 2) resulted in values between 0.00 and 0.25. Without knowledge of the specific cable conductor configuration and without knowledge of the number of grounded conductors in a particular cable, I'm proposing a value of 0.05 to be used as a realistic generic value to account for grounded spare conductors.

The second adjustment that I made is due to the conductor wiring configuration. The ratios developed in the introduction are used to proportion the NRC and EPRI data. The adjusted EPRI data results are 24/48 and the NRC adjusted data results are 28/52, for a combined SOV estimate of approximately 52/100.

Thus, proportioning the test results combined with the grounding adjustment and rounding I propose the estimates presented in Table 3. Figure 3 present these values in an event tree.

Table 3. Adjusted Expert Judgment Spurious Operation Values for SOV Grounded AC Intra-cable TS insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.45**	0.40	0.50
MOV ET Both Targets Hit	0.30	0.20	0.40
MOV ET 92-18 Failure	0.50	0.35	0.65
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.40**		

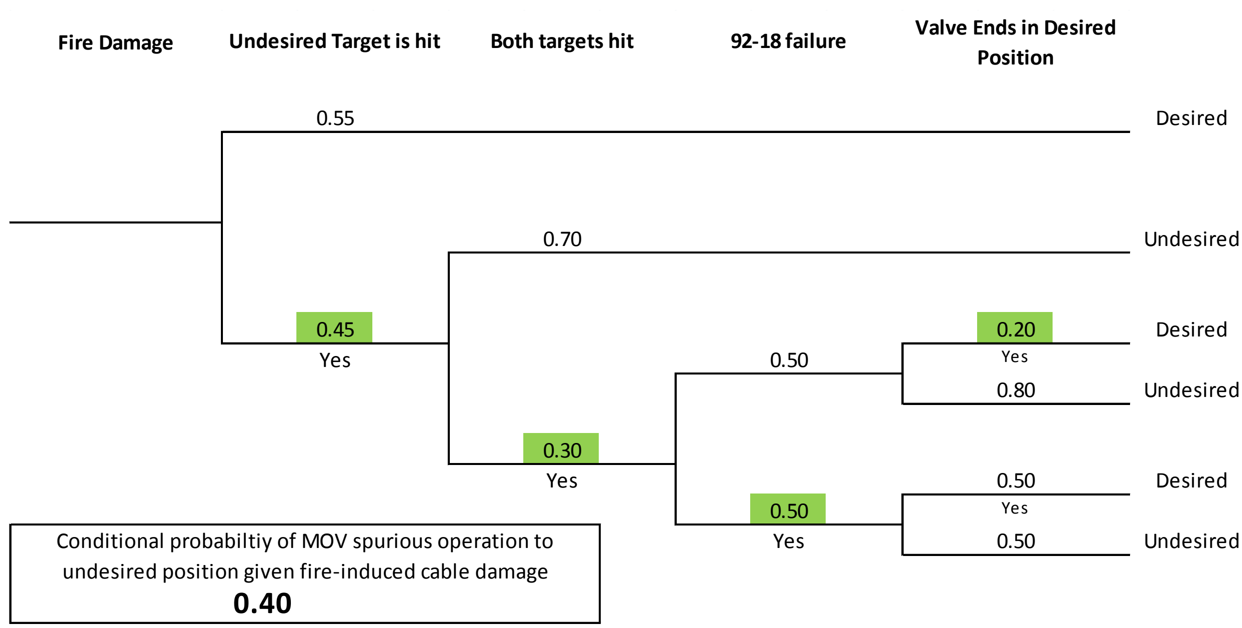

Figure 3. MOV Event Tree for Grounded AC Intra cable TS insulated

Inter-cable TS Target Cable (ROW 1, COLUMN 2)

Statistical Analysis

EPRI Test Data

From the EPRI data, the following observations were made;

- Data should provide a conservatively high spurious operation likelihood value due to experimental setup (three 1/C cables surrounding 7/C cable)
- Only TS M/C and 1/C test data was used, namely;
  - Test 2, 3, 5, 7, 8, 9, 10, 11, 12, 15, and 17, Test 10 and 17 were vertical orientation
- The 1/C cable in all TS tests was constructed with a jacket (Hypalon)
- The EPRI test configuration consisted of three spurious operation target conductors (two within the multi-conductor cable and one connected to one of the three external 1/C cables). With regard to counting the possible inter-cable possible spurious operation targets, I count three possible per test cable, thus a test with 4 test cables has the opportunity for 12 inter-cable spurious operations.

From the EPRI data I determined that there are a total of 126 spurious operations possible, and 8 inter-cable spurious operations actually occurred.

CAROLFIRE Data

Two types of inter-cable information can be used from CAROLFIRE data set. The first is from the intermediate scale testing where the Inter-cable surrogate circuit diagnostic unit (SCDU) configuration was used. This configuration consists of instrument individual cables within a bundle to either source or target paths of a single SCDU. Although this configuration will not be able to observe intra-cable failure modes, it does provide insights into the inter-cable failure modes and for the grounded circuits (SCDU 2-4) a source conductor short to ground will still result in a fuse clear failure. Review of Tests IT-2 through IT-5 revealed that none of the inter-cable configuration provided any data for TS-TS with a grounded circuit. These configurations have some applicability for ungrounded as well as inter-cable interactions between TS and TP insulated cables.

IT-2 : SCDU – 1 connected to TS bundle, but ungrounded circuit = not applicable
IT-3 : SCDU – 1 connected to TS bundle, but ungrounded circuit = not applicable
IT-4 : No applicable tests
IT-5 : No applicable tests

The second type of inter-cable information that can be used from the CAROLFIRE testing are configurations using the MOV-1 wiring scheme and having cable adjacent to one another in the cable raceway. This configuration allows for indication of intra- as well as inter-cable interactions. The results are summarized below;

IT-1 : Location A, SCDU 1-4 used, SCDU 1 ungrounded, No SO due to inter-cable identified.
IT-6 : Location A, Cables B and C are TS insulated, however Cable B is on SCDU – 1 which is ungrounded and thus any inter-cable SO would have to be a result of direct

cable to cable plus a short to ground on the common return of the ungrounded circuit. Due to the grounding differences, I decided not to use this data point.

IT-7 : Location A, Cable A & B are TS insulated and connected to SCDU 3 and 2 respectively. I include this data set and zero inter-cable SO occurred.

IT-8 thru IT-12 : No applicable data

IT-13 : Location F, Cable A and C are TS insulated, Cable C is connected to SCDU-2 which is grounded while, Cable A is connected to SCDU-1 which is ungrounded and thus any inter-cable SO would have to be a result of direct cable to cable plus a short to ground on the common return of the ungrounded circuit. Due to the ground differences, I decided not to use this data.
Location G, Cable A and C are TS insulated and connected to SCDU-3 and -4, respectively. No inter-cable SO occurred.

IT-14 : Location F, Cable A and G are TS insulated, Cable B is connected to SCDU-2 which is grounded while, Cable A is connected to SCDU-1 which is ungrounded and thus any inter-cable SO would have to be a result of direct cable to cable plus a short to ground on the common return of the ungrounded circuit. Due to the ground differences, I decided not to use this data.
Location G, Cable A and B are TS insulated and connected to SCDU-3 and -4, respectively. No inter-cable SO occurred.

DESIREE-FIRE Data

All of the ac MOV SCDUs used in DESIREE-Fire were grounded. Intermediate scale tests 4, 11 and 12 bundled the ac SCDU cables in configuration that are applicable to a grounded TS-TS inter-cable interaction. The report identifies no spurious operations as a result of inter-cable interactions on the ac MOV SDCU circuits.

Summary of all Data

Table below provides a summary of the data, with the CAROLFIRE and DESIREE-FIRE test results combined.

Table 4. Spurious Operation Data Results for Grounded AC Inter-Cable TS insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	SO Target 3 (EPRI ONLY)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
EPRI MOV	1 / 42	1 / 42	6 / 42	7 / 42	1 / 42
NRC MOV	0 / 19	0 / 19	N/A	0 / 19	0 / 19
MOV Composite	1 / 61	1 / 61	6 / 42	7 / 61	**1 / 51**
Surrogate SOV	**8 / 164**				

Expert Judgment

Since the EPRI test set-up only represents one uncommon configuration found in plants, I believe the data results present a high likelihood estimate. CAROLFIRE and DESIREE-FIRE tests did not provide any SO failures. In addition, the ground plane interactions must be taken into consideration and the likelihood of having grounded spares in the M/C cable are possible and likely. The tests did not ground any spare conductors. As such, I believe that all of the calculated values are high, and because of this I suggest adjusting the statistical results lower as shown in Table 5.

Table 5. Adjusted Expert Judgment Spurious Operation Values for SOV Grounded AC Inter-cable TS insulated and MOV Event Tree Values

Parameter	Median	1^{st} Quartile (25^{th} %tile)	3^{rd} Quartile (75^{th} %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**1E-3**	5E-4	1E-2
MOV ET Both Targets Hit	0.05	0.04	0.07
MOV ET 92-18 Failure	0.10	0.05	0.14
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**9.9E-4**		

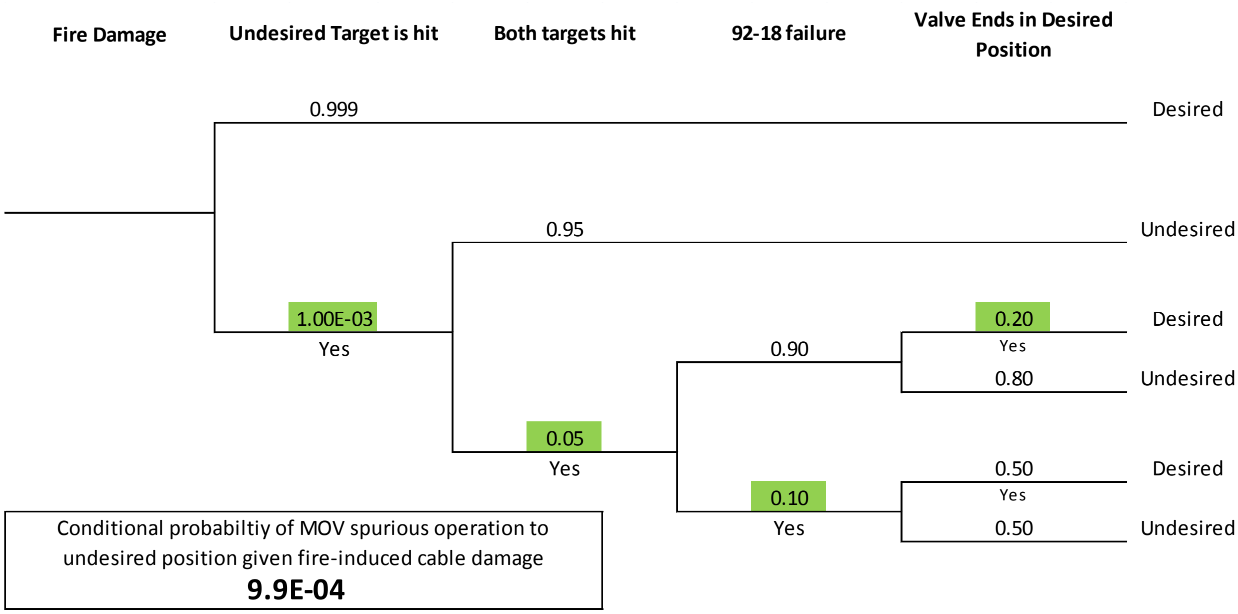

Figure 4. MOV Event Tree for Grounded AC Inter-cable TS insulated

Intra-cable TP Cable (ROW 2, COLUMN 1)

Statistical Analysis

Using the grounded ac data from the CAROLFIRE, DESIREE-FIRE and NEI/EPRI projects, all data with the following attributes were removed;

- Thermoset insulation (TS)
- Armor
- Un-insulated grounded drain wire
- Metal foil shield wrap

Table 6 below provides a summary of the collected data from the EPRI and NRC tests and the highlighted cells are used as the anchor points for the MOV ET and surrogate SOV cases.

Table 6. Spurious Operation Data Results for Grounded AC Intra-Cable TP insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
EPRI MOV	4 / 13	5 / 13	5 / 13	4 / 13
NRC MOV	10 / 20	8 / 20	10 / 20	8 / 20
MOV Composite	14 / 33	13 / 33	15 / 33	**12 / 33**
Surrogate SOV	**27 / 66**			

Expert Judgment

The test data only consists of one circuit common return grounded conductor, and no spares were grounded during testing. Although not exclusive across the industry, it is common practice to ground any unused spares. With the grounded circuit configuration, having grounded conductors within the multi-conductor cable should increase the likelihood of an energized conductor coming in contact with a grounded conductor. As such, having grounded spares in the cable should decrease the likelihood of hot short-induced spurious operation caused by fire damage.

I conducted the same wiring configuration analysis on the influence on the EPRI and NRC data sets, as was done for the grounded AC intra-cable TS case. The adjusted EPRI data result in 13/26 and the NRC adjusted data results in 16/40, for a combined SOV estimate of approximately 29/66. Taking common return / ground plan interaction into consideration, and considering the PIRT panels conclusions that insulation type has little to no effect on spurious operation likelihood, I've adjusted the statistical results as shown in Table 7. My adjusted results for the MOV event tree and Surrogate SOV cases are shown in the Table 7.

Table 7. Adjusted Expert Judgment Spurious Operation Values for SOV Grounded AC Intra-cable TP insulated and MOV Event Tree Values

Parameter	Median	1^{st} Quartile (25^{th} %tile)	3^{rd} Quartile (75^{th} %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.45**	0.40	0.50
MOV ET Both Targets Hit	0.30	0.20	0.40
MOV ET 92-18 Failure	0.50	0.35	0.65
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.40**		

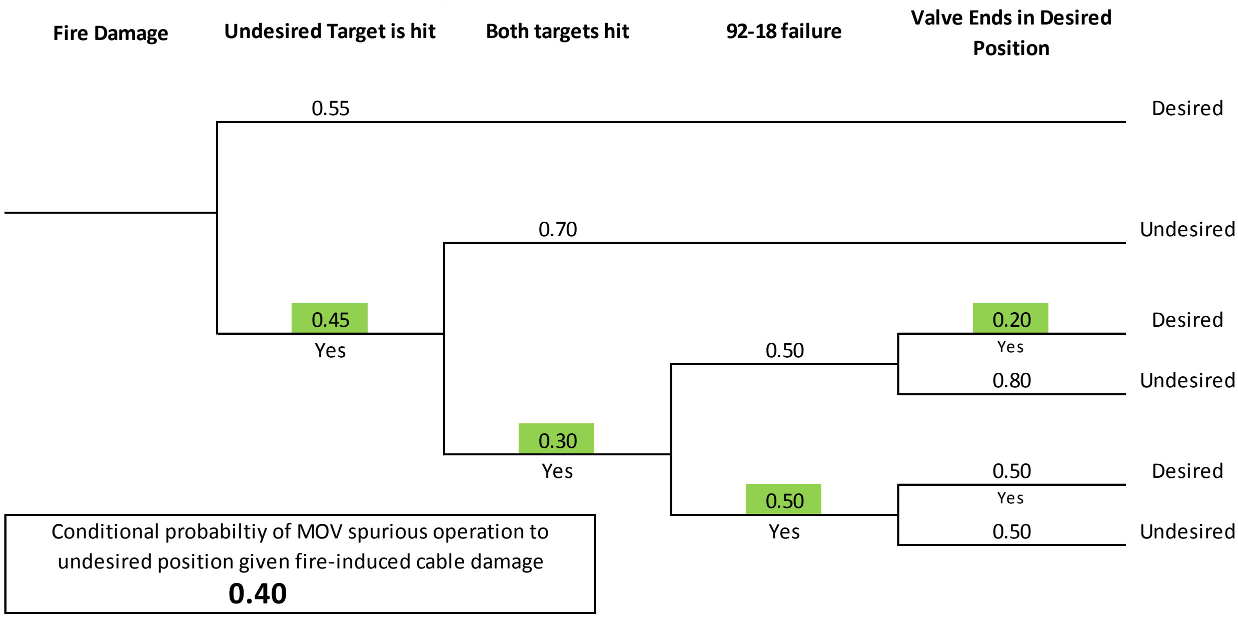

Figure 5. MOV Event Tree for Grounded AC Intra-cable TP insulated

Inter-cable TP Target (ROW 2, COLUMN 2)

Statistical Analysis

EPRI Test Data

From the EPRI data, the following observations are made;

- Data should provide a conservatively high spurious operation likelihood value due to experimental setup.
    - M/C cable would have higher likelihood of intra-cable short causing a fuse clear failure than a single conductor cable that cannot fail internally prior to the external interaction
- Only TP M/C and 1/C test data used
    - Test 4, 6, and 16, Test 17 was a vertical orientation
- The 1/C cable in all TP tests did not have a jacket.
- The EPRI test configuration consisted of three spurious operation target conductors (two within the multi-conductor cable and one connected to one of the three external 1/C cables). With regard to counting the possible inter-cable possible spurious operation targets, I count three possible per test cable, thus a test with 4 test cables has the opportunity for 12 inter-cable spurious operations.

From the EPRI data I determined that there are a total of 39 spurious operations possible, and 7 inter-cable spurious operation actually occurred. Using binomial w/normal approximation median = 0.179487, 1st quartile 0.108819, 3rd quartile 0.250156. All of the above interactions were between two TP cables. There was no test data from the EPRI tests where a TS cable shorted to and energized a TP insulated cable to cause a spurious operation.

CAROLFIRE data

Two types of inter-cable information can be used from CAROLFIRE data set. The first is from the intermediate scale testing where the Inter-cable SCDU circuit configuration was used. This configuration consists of incrementing individual cables within a bundle to either source or target paths of a single SCDU. Although this configuration will not be able to observe intra-cable failure modes, it does provide insights into the inter-cable failure modes and for the grounded circuits (SCDU 2-4), a source conductor short to ground will still result in a fuse clear failure. Review of Tests IT-2 through IT-5 revealed the following;

<u>TP source to TP target</u>

IT-2 : SCDU 2 is connected to one TP and one TS as source conductors, and one TP cable as target conductor T6. No SO occurred as a result of inter-cable.
IT-3 : No applicable data.
IT-4 : SCDU-1 is ungrounded and will not be included. SCDU 2-4 are configured for one TP and one TS cable connected as sources and one TP as a target conductor. No SO occurred as a result of inter-cable.
IT-5 : SCDU-4 is connected to one TS and one TP as sources and one TP as target. No SO occurred as a result of inter-cable.

<u>TS source to TP target</u>

IT-2 : SCDU – 2 connected to mixed bundle with SO target T6 connected to a TP cable and source conductors connected to two TS cables. No SO occurred.
IT-3 : SCDU-2 connected to mixed bundle with all SO targets in a TP cable and source conductors in a TS and TP cable. No SO occurred as a result of inter-cable interactions. SCDU-3 was connected identically as SCDU-2 and No SO occurred.

IT-4 : SCDU-2, 3, and 4 were all connected with SO targets in a TP cable, and source conductors in TS and TP cables. No SOs occurred in any case.

IT-5 : SCDU-4 was connected with all SO targets in a TP cable and source conductors in a TS and TP cable. There were no SO due to inter-cable interactions.

The second type of inter-cable information that can be used from the CAROLFIRE testing are configurations using the MOV-1 wiring scheme and having cable adjacent to one another in the cable raceway. This configuration allows for indication of intra- as well as inter-cable interactions. Review of Tests IP-4, IT-1, and IT-6 through IT-13 revealed that only one of these tests were configured in a manner that would allow for inter-cable interactions between two thermoplastic cables. That test was IP-4. There were several opportunities for a TS insulated cable to short to a TP insulated cable and is summarized below.

<u>TP source to TP target</u>

IP-4 : SCDU 1-4 are connected to four TP cables in a bundle. SCDU 1 is ungrounded. Although SCDU 2 and 3 experienced inter-cable hot shorts, they were not of sufficient quality to produce a spurious operation.

<u>TS source to TP target</u>

IT-6 : Location A, SCDU -2 connected to Cable B (TP) and SCDU-4 connected to Cable C (TS). No SO occurred as a result of inter-cable interactions.

IT-8 : Location A, SCDU – 3 connected to Cable A (TS) and SCDU-2 connected to Cable A (TP). No SO occurred as a result of inter-cable interactions.

IT-9 : Location A, SCDU – 2 connected to Cable A (TS) and SCDU-3 connected to Cable B (TP). No SO occurred as a result of inter-cable interactions.
Location G, since SCDU-1 is ungrounded and SCDU 4 is grounded, I didn't use this data set even though one was connected to a TP cable and the other a TS cable.

IT-10 : Location A, SCDU-2 connected to Cable E (TS) and SCDU-3 connected to Cable C (TP). No SO occurred as a result of inter-cable interactions.
Location G, since SCDU-1 is ungrounded and SCDU 4 is grounded, I didn't use this data set even though one was connected to a TP cable and the other a TS cable.

IT-11 : Location A, since SCDU-1 is ungrounded and SCDU 4 is grounded, I didn't use this data set even though one was connected to a TP cable and the other a TS cable.
Location G, SCDU-3 connected to Cable B (TP) and SCDU-2 connected to Cable E (TP). No SO occurred as a result of inter-cable interactions.

IT-12 : same experimental set-up as IT-11 and same results with regard to inter-cable spurious operations.

DESIREE-FIRE Data

All of the ac MOV SDCUs used in DESIREE-FIRE were grounded. Intermediate scale test 8 was the only test where TP insulated cables were located adjacent to one another and the possibility of inter-cable interactions were possible. The results indicated that no inter-cable spurious operations occurred. There were no instances where a thermoset insulated cable could have energized a TP insulated cable.

Summary of all Data

Table 8 provides a summary of the test data results from the various programs. The CAROLFIRE and DESIREE-FIRE testing has been combined into one group. As done previously, the MOV data has been also evaluated on a target basis to provide information for the surrogate SOV category.

Table 8. Spurious Operation Data Results for Grounded AC Inter-Cable TP insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	SO Target 3 (EPRI ONLY)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
EPRI MOV	1 / 13	1 / 13	5 / 13	5 / 13	1 / 13*
NRC MOV	0 / 18	0 / 19	N/A	0 / 19	0 / 18
MOV ET	1 / 31	1 / 31	5 / 13	5 / 32	**1 / 31**
Surrogate SOV	**7 / 76**				

* Device Actuation Circuit 4 experienced SO on all targets

Expert Judgment

Since the EPRI test set-up with the 1/C unjacketed cables surrounding the M/C cable, I believe the these results are conservative because unjacketed 1/C cables are uncommon, and any M/C cable would likely fail internally or short to ground causing a fuse clear. It would be very uncommon to find this configuration in the plant. Although the jacket provides only a utilitarian purpose, it does provide some thermal mass and electrical insulation qualities. I would suspect that had a jacketed 1/C cable been used instead, there would have been a lower number of inter-cable spurious operations observed. In addition, the ground plane interactions must be taken into consideration and the likelihood of having grounded spares in the M/C cable is possible. The tests did not ground any conductors. As such, I believe that all of the calculated values are high, and because of this I suggest adjusting the data values shown in the Table 9.

Table 9. Adjusted Expert Judgment Spurious Operation Values for SOV Grounded AC Inter-cable TP insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.01**	5E-3	0.05
MOV ET Both Targets Hit	0.05	0.01	0.10
MOV ET 92-18 Failure	0.10	0.03	0.13
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.01**		

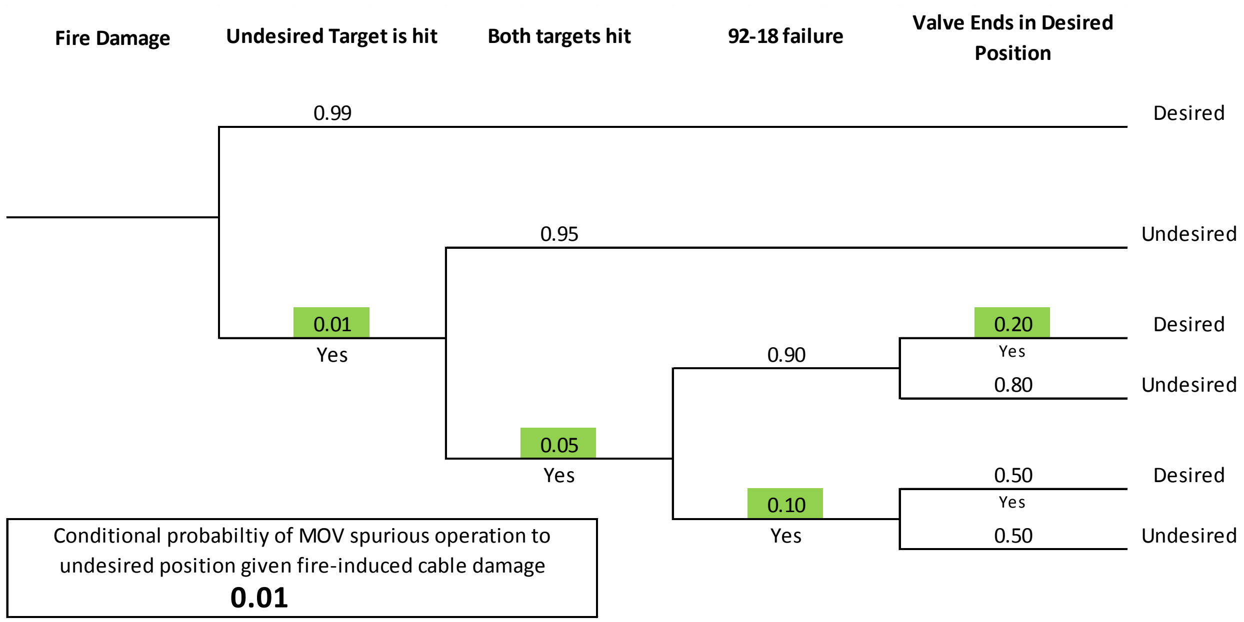

Figure 6. MOV Event Tree for Grounded AC Inter-cable TP insulated

Intra-cable Metal Foil Wrap (ROW 3, COLUMN 1)

Statistical Analysis

Using the grounded ac data from the CAROLFIRE, DESIREE-FIRE, and NEI/EPRI projects, only data that tested cables with a metal foil shield wrap were used. During testing the metal foil wrap was grounded as would typically be done in plant configurations. Table 10 presents a summary of the test results. From this test data pool for grounded ac, the following was observed;

- Only MOV circuits
- 2 of the five metal foil wrap tested cables were Japanese copper shielded cable (1 out of 2 spuriously operated), 6/C, w/ one passive target
- 3 of the five metal foil wrap tested cables were Kerite tin/lead shielded cables (1 out of 3 spurious operated), 5/C, w/o passive target

Table 10. Spurious Operation Data Results for Grounded AC Intra-Cable Metal Foil Wrap

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	0 / 5	2 / 5	2 / 5	0 / 5
Surrogate SOV	2 / 10			

Expert Judgment

It could be arguable that the grounded ac test data for armored cables could be a suitable complementary data set for the metal foil shield configuration. Since both armor and the metal foil shield are grounded, the configurations are similar in that both provide an enhanced ground plane for conductor interactions during cable degradation. However, I decided against combining the armored cable grounded AC results with the metal foil shield wrap. My primary reasoning relates to the differences in cable construction. The steel interlocked armor only makes point contact with the exterior conductor insulation while the metal foil wrap make line contact with the exterior conductor insulation. This configuration differences affect the heat transfer to the conductors at the time of conductor failure from the thermal effects. Because of the physical configuration differences, I believe that the metal foil wrap will provide less of a ground plan interaction at time of conductor failure from fire effects than that of the armored cable case. Because of the lack of data I decided to weigh my expert judgment higher than the data statistical results. As such, I believe that the median for both the MOV and SOV cases should be lower than the Bayesian estimate. My adjusted estimates are presented in the table below.

Table 11. Adjusted Expert Judgment Spurious Operation Values for SOV Grounded AC Intra-cable Metal Foil Wrap and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.20**	0.12	0.28
MOV ET Both Targets Hit	0.20	0.12	0.28
MOV ET 92-18 Failure	0.30	0.20	0.40
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.19**		

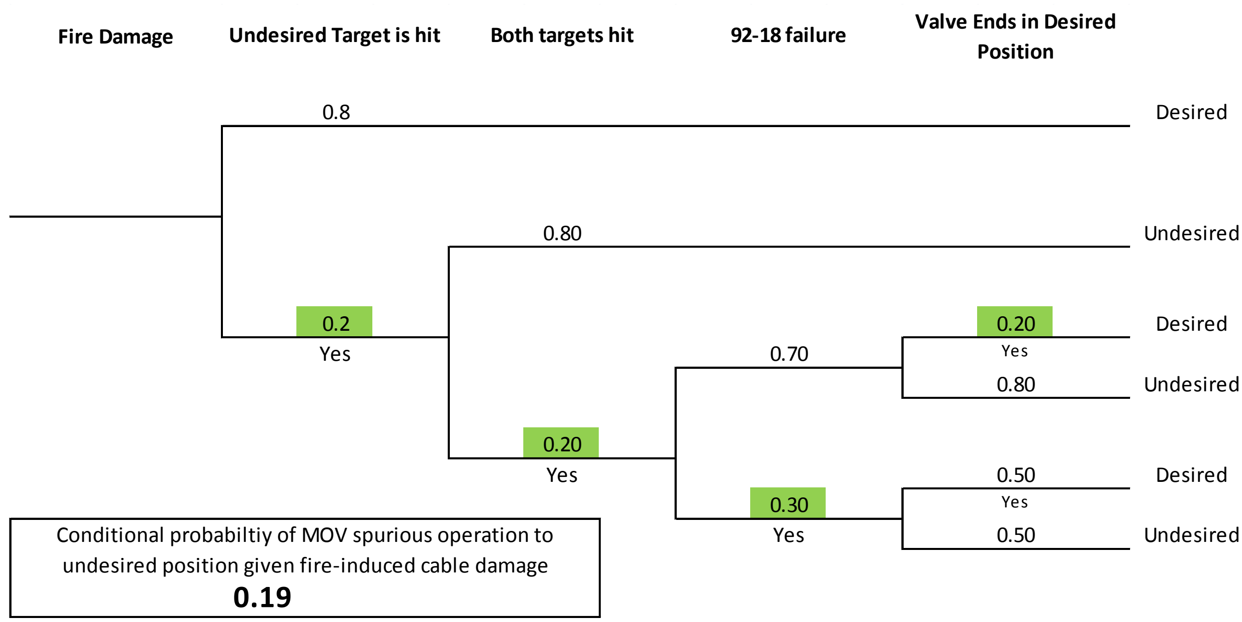

Figure 7. MOV Event Tree for Grounded AC Intra-cable Metal Foil Wrap

Intra-cable Armored Cable (ROW 4, COLUMN 1)

Statistical Analysis

The only data available from this configuration (grounded ac circuit with an armored cable) is from the EPRI, Duke, and DESIREE-FIRE testing.

From the EPRI results:

All of the EPRI armored tests involved an XLPE insulated, CSPE jacketed cable with 8/C and a grounded armor. Of the seven armored cables tested in the grounded ac MOV configuration, only one armored cable failed with both forward and reverse coils receiving a hot short-induced spurious operation (no interlocks were used). However, in this case, the minimum bend radius of the cable was exceeded, which may have influenced the failure.

From the Duke results:

The Duke armored tests that used the grounded ac MOV test configuration used two different cable constructions. One was the same XLPE insulated, CSPE jacketed cable with 8/C and a grounded armor as the EPRI tests. The second was a 37/C trunk cable with the same insulation and jacket material as the 8/C armored cable. Since the results were the same for the 8/C and 37/C I didn't separate the data by conductor count.

From the DESIREE-FIRE results:

Penlight test #19 provided two additional data points for grounded armored cable. Using the same 8/C cable as identified above, the results indicated 0 spurious operations for two trials of an ac grounded MOV circuit.

All of the data identified above used a grounded ac MOV circuit. The following information was collected.

Table 12. Spurious Operation Data Results for Grounded AC Armored Intra-cable

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
EPRI MOV	1 / 7	1 / 7	1 / 7	1 / 7
NRC MOV	0 / 2	0 / 2	0 / 2	0 / 2
MOV ET	1 / 9	1 / 9	1 / 9	**1 / 9**
Surrogate SOV	**2 / 18**			

Note: do the proprietary nature of the DUKE testing, Table 12 does not present any of those results; however, they were taking into consideration when developing the likelihood estimates below.

Expert Judgment

Given that steel interlocked armor is used and grounded, and that there is a grounded ac circuit connected to the cable, I would expect the conductors to physically short to the grounded armor prior to shorting to themselves. The data showed that only one spurious operation occurred in a circuit where the cable exceeded its minimum bend radius. These general results were valid even for large armored trunk cables. Since the wiring configuration for the majority of the testing was in the conservative source centered configuration and due to the physical construction of a steel interlocked armored cable, I believe that median value provided in the above statistical analysis section are conservatively high and I suggest lowering them as a result of the test arrangements. I also propose that this configuration is not represented by a normal approximation and I would propose that the 1^{st} and 3^{rd} quartiles should be adjusted from those presented statistically. Specifically, I believe that the upper quartile band should be closer to the median and the lower quartile should be farther away from the median. As such, I suggest adjusting the quartile estimates as shown below.

Table 13. Adjusted Expert Judgment Spurious Operation Values for SOV Grounded AC Armored Intra-cable and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.01**	0.005	0.012
MOV ET Both Targets Hit	0.01	0.005	0.015
MOV ET 92-18 Failure	0.05	0.03	0.07
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.01**		

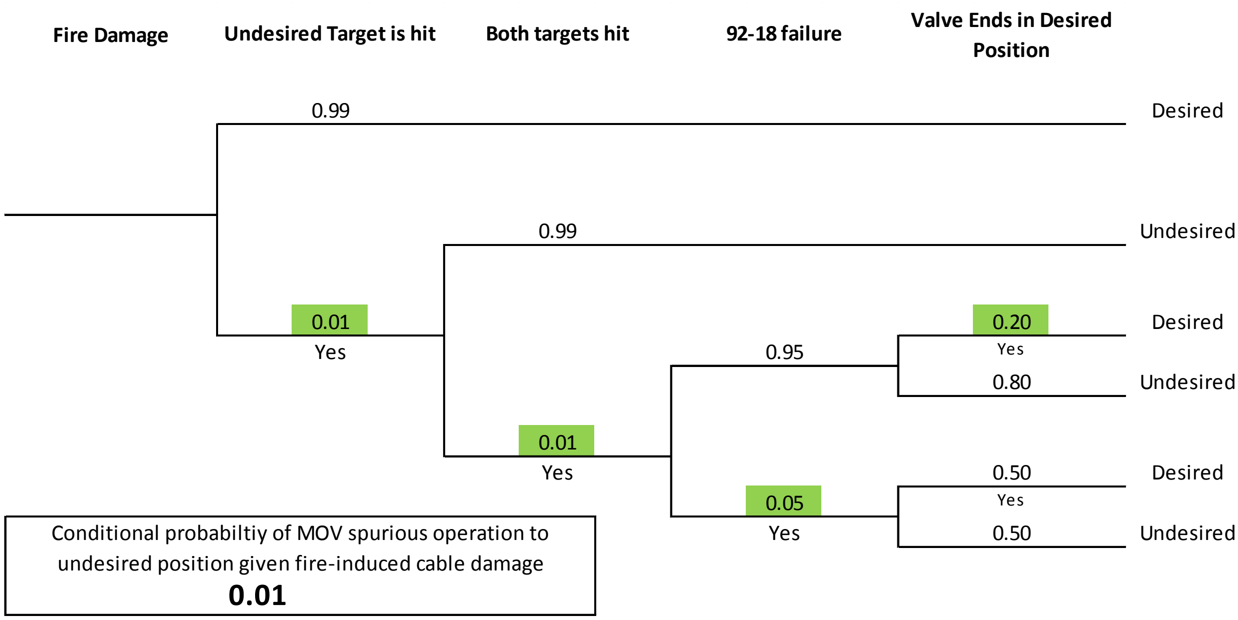

Figure 8. MOV Event Tree for Grounded AC Armored Intra-cable

B. Ungrounded ac configurations

This sections looks at the likelihood of an ungrounded AC circuit experiencing a spurious operation. Conditional spurious operation likelihood estimates given fire-induced cable damage are developed for the SOV case and then values for use in the MOV event tree are developed. The progression of each case follows the same theme of reviewing the data set, adjusting the data to account for testing-to-reality effects and then adjusting the value based on any expert judgment or engineering principles.

Intra-cable TS Target Cable (ROW 1, COLUMN 4)

Statistical Analysis

Using the ungrounded ac data from the CAROLFIRE projects, all data with the following attributes were removed;

- Thermoplastic insulation (TP)
- Armor
- Un-insulated grounded drain wire
- Metal foil shield wrap

In addition, the test data only considers cables without any conductors grounded (i.e., no grounded drain wires or grounded spares). Because of the circuit ungrounded configuration, having grounded conductors within the multi-conductor cable does not decrease the likelihood of spurious operation as was the case for a grounded circuit. The following information was collected.

Table 14. Spurious Operation Data Results for Ungrounded AC Intra-Cable TS insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	6 / 8	6 / 8	6 / 8	6 / 8
Surrogate SOV	**12 / 16**			

Expert Judgment

The data results show a high likelihood of spurious operations. Since it is an ungrounded circuit, energized conductors shorting to a ground plane will not in and of themselves result in a fuse clear. As such, the only phenomena that I believe needs to be conserved for this case are the wiring configuration. Although, there is not data from the EPRI tests to proportion the NRC source centered configuration, I believe that the ungrounded source centered configuration resulted in a conservative results related to spurious operation. As such, I propose adjusting the data results as presented in Table 15.

Table 15. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded AC Intra-cable TS insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.60**	0.50	0.70
MOV ET Both Targets Hit	0.50	0.42	0.65
MOV ET 92-18 Failure	0.75	0.68	0.83
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.47**		

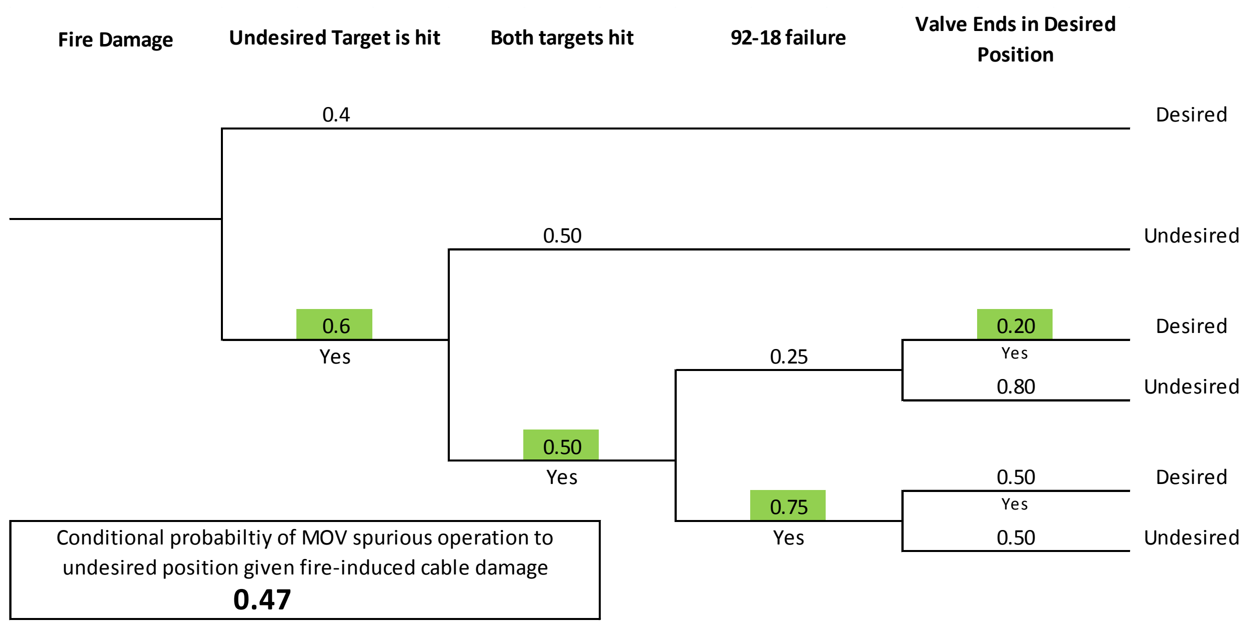

Figure 9. MOV Event Tree for Ungrounded AC Intra-cable TS insulated

Inter-cable TS Target Cable (ROW 1, COLUMN 5)

Statistical Analysis

No data available for this case.

Expert Judgment

For this case, I believe there is one key point that needs to be understood. That is, for this failure mode to cause a spurious operation two proper polarity inter-cable shorts are needed for a spurious operation to occur when the circuits are ungrounded and powered from separate control power transformers (CPTs). Alternatively, a spurious operation of an ungrounded circuit may occur with a grounded circuit when the proper conductors of an ungrounded circuit shorts to ground and to the grounded circuit concurrently. The only case where this isn't true is when you have one CPT powering multiple circuits. However, the reduced reliability in that design results in it not being commonly used.

Thus as a starting point, I used the grounded ac inter-cable TS insulated results and since two inter-cable shorts are needed for this ungrounded ac inter-cable configurations, I multiplied them together (0.01 x 0.01 = 1 E-4). However, for the spurious operation to occur, there is a need to have the two inter-cable shorts concurrent and on the proper target conductors for the cases involving two ungrounded circuits. Alternatively, the source cable could be associated with grounded circuits, in such cases, the target cable could experience a inter-cable spurious operation from one inter-cable short and a proper short to ground. As such, I believe that this case should be lower than 1 E-4 by at least one order of magnitude. Conversely, the lack of the circuit being of the grounded variety, may allow for a higher likelihood of inter-cable interactions in general than if the circuit were to be of the grounded variety. As such, I believe these two phenomena balance and I've chosen to use the statistical estimate to represent my expert judgment. A similar approach was taken for the TP insulated ungrounded ac case.

Table 16. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded AC Inter-cable TS insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**1E-4**	1E-5	1E-3
MOV ET Both Targets Hit	0.05	0.03	0.10
MOV ET 92-18 Failure	0.10	0.07	0.13
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**9.9E-6**		

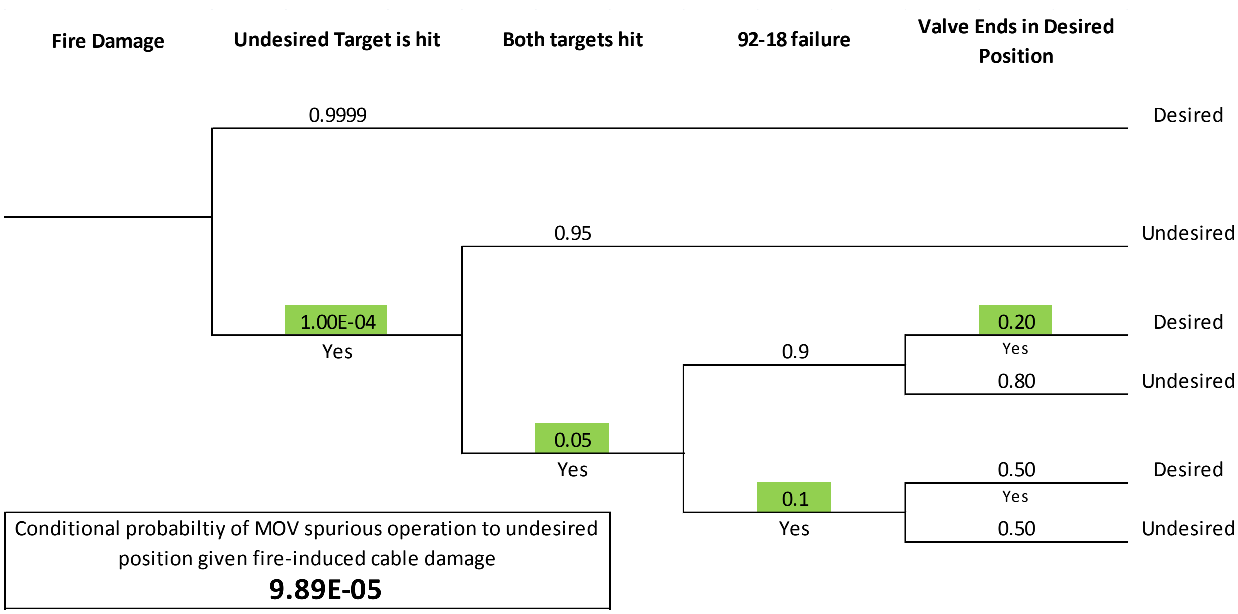

Figure 10. MOV Event Tree for Ungrounded AC Inter-cable TP insulated

Intra-cable TP Cable (ROW 2, COLUMN 4)

Statistical Analysis

Using the ungrounded ac data from the CAROLFIRE projects, all data with the following attributes were removed;

- Thermoplastic insulation (TS)
- Armor
- Un-insulated grounded drain wire
- Metal foil shield wrap

The following information was collected.

Table 17. Spurious Operation Data Results for Ungrounded AC Inter-Cable TP insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	3 / 5	4 / 5	5 / 5	2 / 5
Surrogate SOV	**7 / 10**			

In addition, the test data only considers cables without any conductors grounded (i.e., no grounded drain wires or grounded spares). Because of the circuit ungrounded configuration, having grounded conductors within the multi-conductor cable does not decrease the likelihood of spurious operation as was the case for a grounded circuit.

Expert Judgment

Similar to the argument made for the TS intra-cable case, I've adjusted the data results as presented in Table 18.

Table 18. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded AC Intra-cable TP insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.60**	0.50	0.70
MOV ET Both Targets Hit	0.50	0.42	0.65
MOV ET 92-18 Failure	0.75	0.68	0.83
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.47**		

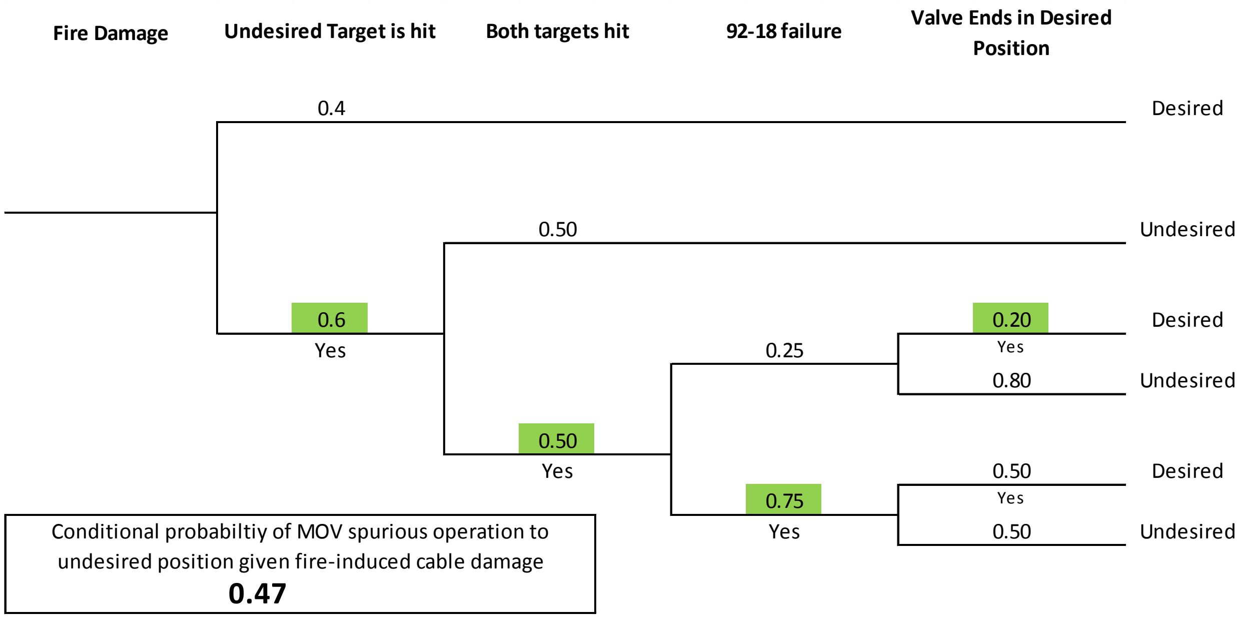

Figure 11. MOV Event Tree for Ungrounded AC Intra-cable TP insulated

Inter-cable TP Target (ROW 2, COLUMN 5)

Statistical Analysis

No data available for this case.

Expert Judgment

Following the same approach that was taken for the ungrounded ac TS insulated case, using the grounded ac inter-cable results as a starting point, I calculate an anchor of (0.1 x 0.1 = 1 E-2). Using the same logic documented for the Inter-cable TS ungrounded AC case, I propose the following estimates.

Table 19. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded AC Inter-cable TP insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.01**	0.005	0.05
MOV ET Both Targets Hit	0.05	0.03	0.10
MOV ET 92-18 Failure	0.10	0.07	0.13
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**9.9E-4**		

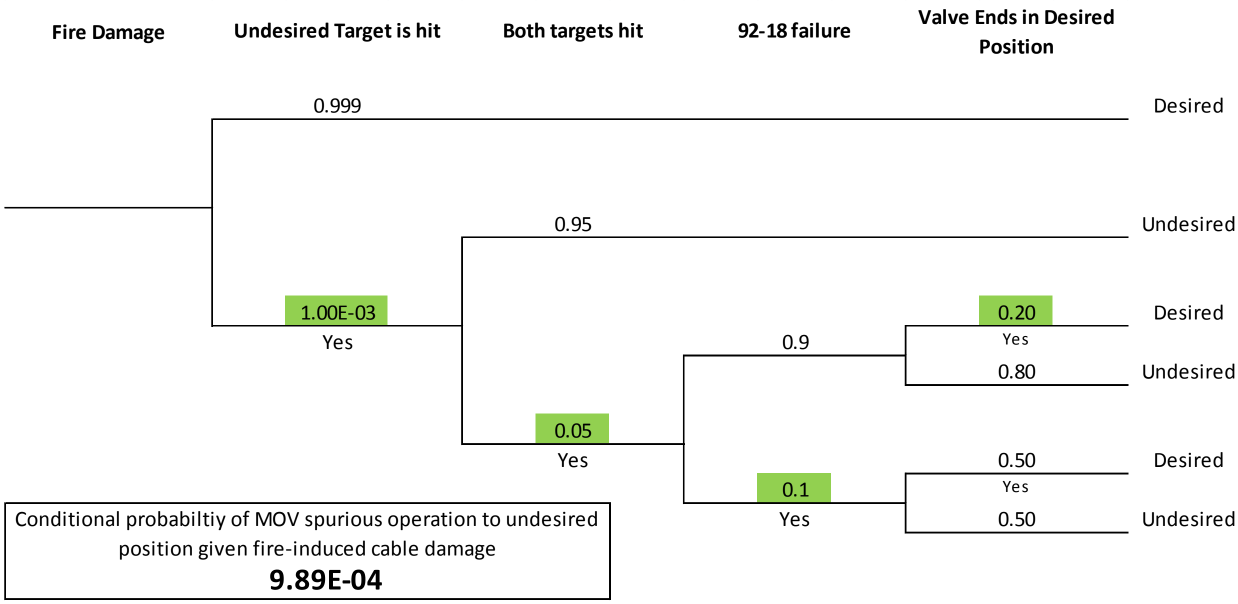

Figure 12. MOV Event Tree for Ungrounded AC Inter-cable TP insulated

Intra-cable Metal Foil Wrap (ROW 3, COLUMN 4)

Statistical Analysis

No test data is available for this case.

Expert Judgment

This case is similar to the ungrounded ac armor case in that the metal foil, although grounded, can aid in intra-cable shorting. However, as discussed previously, I do not believe that the metal foil will have as predominate of an effect as the armored cable. As such, I propose the likelihood of this case fall somewhere between the base case and the armored case for ungrounded circuits.

Table 20. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded AC Metal Foil Wrap and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.55**	0.40	0.70
MOV ET Both Targets Hit	0.45	0.37	0.53
MOV ET 92-18 Failure	0.80	0.73	0.87
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.44**		

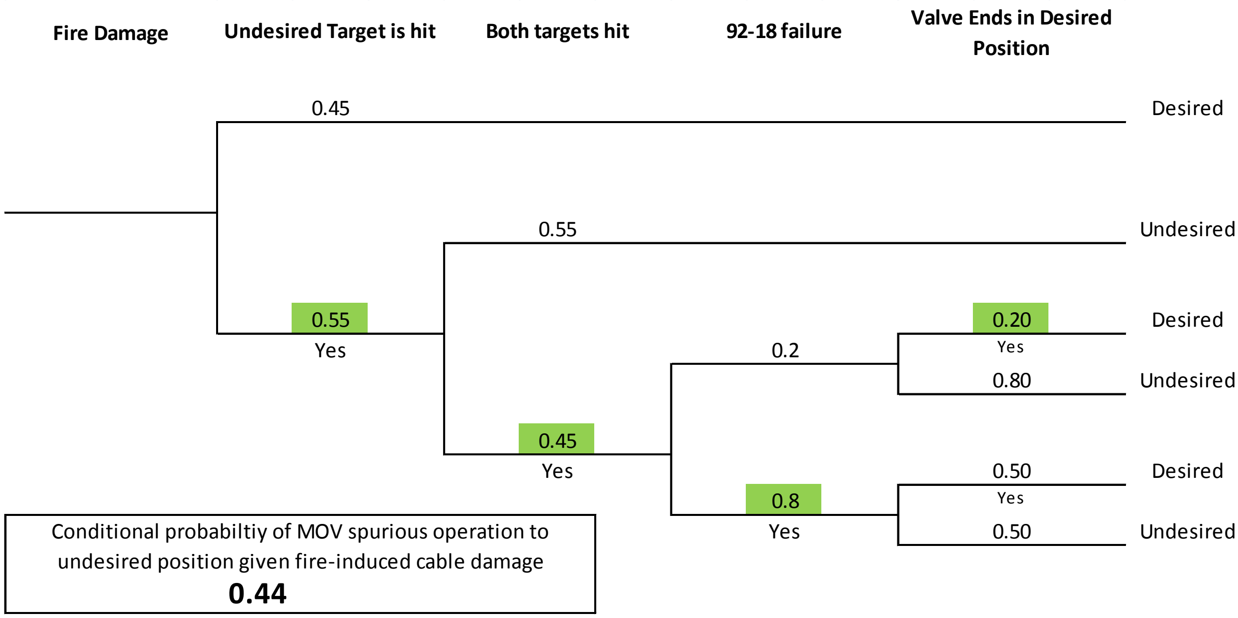

Figure 13. MOV Event Tree for Ungrounded AC Metal Foil Wrap

Intra-cable Armored Cable (ROW 4, COLUMN 4)

Statistical Analysis

The only data available from this configuration (ungrounded ac circuit with an armored cable) is from the Duke testing.

From the Duke results:

The Duke armored tests that used the ungrounded ac MOV test configuration used two different cable constructions. One was the same XLPE insulated, CSPE jacketed cable with 8/C and a grounded armor as the EPRI tests. The second was a 37/C trunk cable with the same insulation and jacket material as the 8/C armored cable. Since the results were the same for the 8/C and 37/C I didn't separate the data by conductor count.

Expert Judgment

Given that steel interlocked armor is used and grounded, and that there is an ungrounded ac circuit connected to the cable, I believe that median value obtained from the data analysis is an adequate representation of the true value.

Table 21. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded AC Armored Cable and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.50**	0.45	0.55
MOV ET Both Targets Hit	0.45	0.37	0.53
MOV ET 92-18 Failure	0.80	0.73	0.87
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.40**		

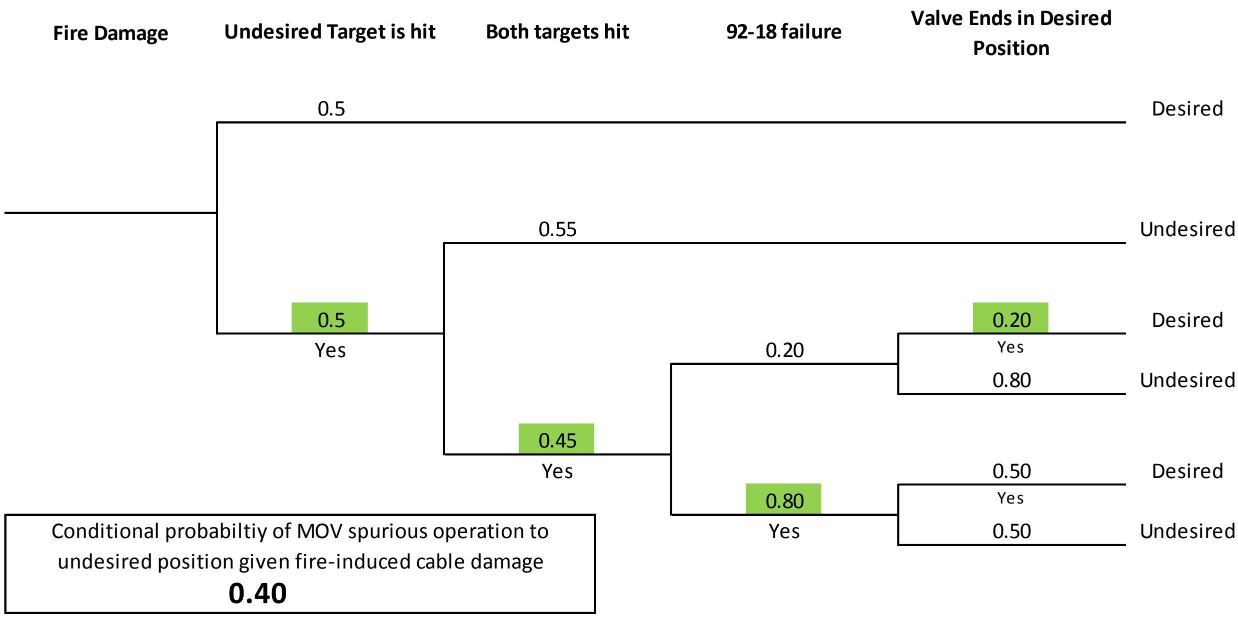

Figure 14. MOV Event Tree for Ungrounded AC Armored

C. Ungrounded dc configurations

This sections looks at the likelihood of an ungrounded DC circuit experiencing a spurious operation. Conditional spurious operation likelihood estimates given fire-induced cable damage are developed for the SOV case and then values for use in the MOV event tree are developed. The progression of each case follows the same theme of reviewing the data set, adjusting the data to account for testing-to-reality effects and then adjusting the value based on any expert judgment or engineering principles.

Also, I choose not to use the medium voltage breaker data to evaluate the SOV spurious operation likelihood. I felt that the way the circuit was instrumented in the test program and the manner in which the data results were reported, the data couldn't be used without significant time reviewing the individual circuit voltage and current plots. As such, the previous section is the only place where I used the medium voltage breaker data. The spurious operation data used in the remainder of my analysis only uses the small SOVs, 1" valve SOV, Large Coil and MOV data. To supplement the SOV data, similar to what was done in for AC MOV circuits, the DC MOV data was doubled to increase the data set and limit the spurious operation target to one conductor per circuit.

Intra-cable TS Target Cable (ROW 1, COLUMN 7)

Statistical Analysis

Using the ungrounded dc data from the DESIREE-FIRE project, I first removed all data with the following attributes;

- Thermoplastic insulation (TP)
- Armor
- Un-insulated grounded drain wire
- Metal foil shield wrap
- Cables that failed via ground fault equivalent hot short (GFEHS)

Kerite-FR cables free of any shield were maintained in the data set, as NUREG/CR-2128 did not identify any substantial differences in the spurious operation likelihood compared to other TS insulated cable materials. In addition, the test data only considers cables without any conductors grounded (i.e., no grounded drain wires or grounded spares). Table 22 summaries the test data results for this scenario.

Table 22. Spurious Operation Data Results for Ungrounded DC Intra-Cable TS insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	12 / 27	11 / 27	20 / 27	3 / 27
NRC SOV	22 / 40			
Surrogate SOV	**45 / 94**			

Expert Judgment

Unlike the AC grounded circuits cases where the EPRI data could be used to proportion likelihood of spurious operation among the four different wiring configurations, there is no such data for ungrounded DC circuits. Additionally, I'm not confident that the same ratios could be used for this ungrounded case because of the influence from external grounds. Given that the source centered wiring configuration remains likely to provided conservative results with regard to spurious operation likelihood, I'm uncertain to the extent that wiring configuration play for ungrounded circuits. Additionally, the ground effects identified for the grounded ac cases are not applicable here due to the ungrounded nature of DC circuits. In actuality, any grounded conductor within a multi-conductor cable may increase the likelihood of intra-cable shorting. As such, I'm proposing that the statistical results obtained from the information above be used as the estimates with wider uncertainty.

Table 23. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC Intra-cable TS insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.50**	0.43	0.57
MOV ET Both Targets Hit	0.15	0.10	0.20
MOV ET 92-18 Failure	0.80	0.68	0.84
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.47**		

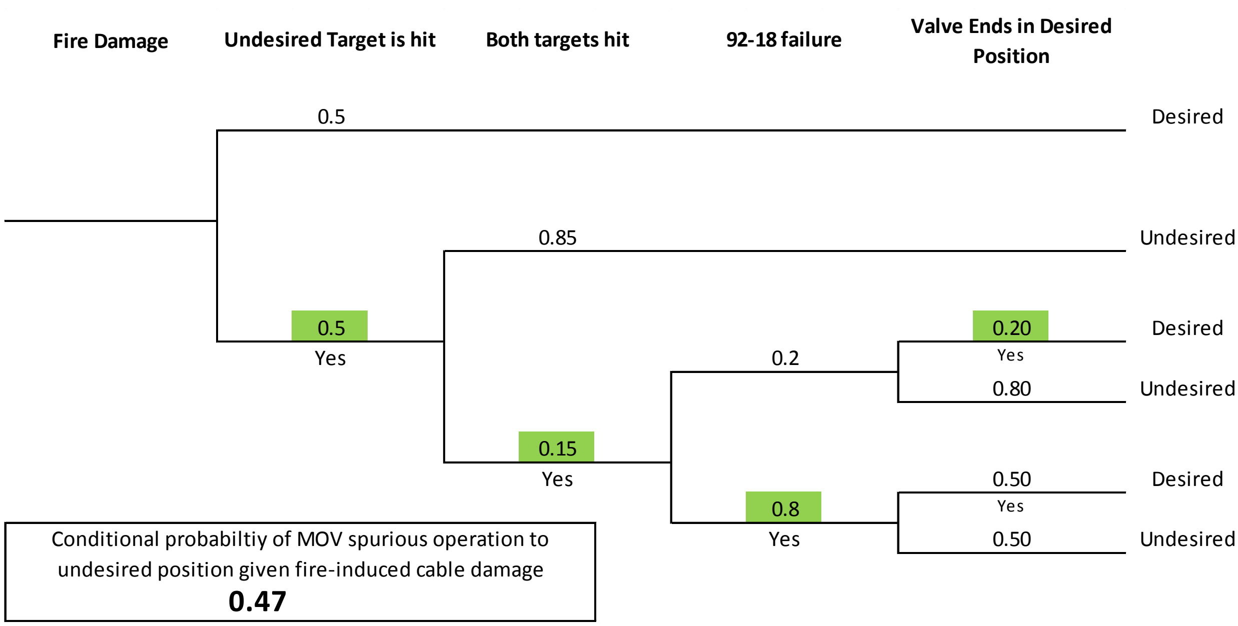

Figure 15. MOV Event Tree for Ungrounded DC Intra-cable TS insulated

Inter-cable TS Target Cable (ROW 1, COLUMN 8)

Statistical Analysis

Using the ungrounded dc data from the DESIREE-FIRE project, I first removed all data with the following attributes;

- Thermoplastic insulation (TP)
- Armor
- Un-insulated grounded drain wire
- Metal foil shield wrap
- Cables that failed via ground fault equivalent hot short (GFEHS)
- Penlight data due to cable locations within test chamber

Reviewing draft NUREG-2128, I determined that there were 36 opportunities for thermoset insulated cable-to-cable (inter-cable) interaction to occur during the DESIREE-FIRE intermediate-scale testing. NUREG-2128 identified all of the spurious operation interactions that occurred within these tests, to involve the ground plane. The analysis didn't find any cases where spurious operations occurred cable-to-cable without the ground plane interaction. As such, I've collected the following information.

Table 24. Spurious Operation Data Results for Ungrounded DC Inter-Cable TS insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	N/A	N/A	0 / 12	0 / 12
NRC SOV	0 / 24			
MOV ET			**0 / 12**	0 / 12
Surrogate SOV	**0 / 24**			

Expert Judgment

After reviewing the data, I propose that this likelihood figure for this case to be the same as the grounded ac base case. This scenarios failure mode is similar to the grounded ac base case, I see no other fire-induced circuit failure phenomena that would provide strong enough of an influence to cause this scenario to differ from the grounded ac base case. As such, I've proposed adjusting the statistical estimate as shown below.

Table 25. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC Inter-cable TS insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**1E-3**	5E-4	1E-2
MOV ET Both Targets Hit	0.01	0.005	0.03
MOV ET 92-18 Failure	0.05	0.04	0.07
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**9.98E-4**		

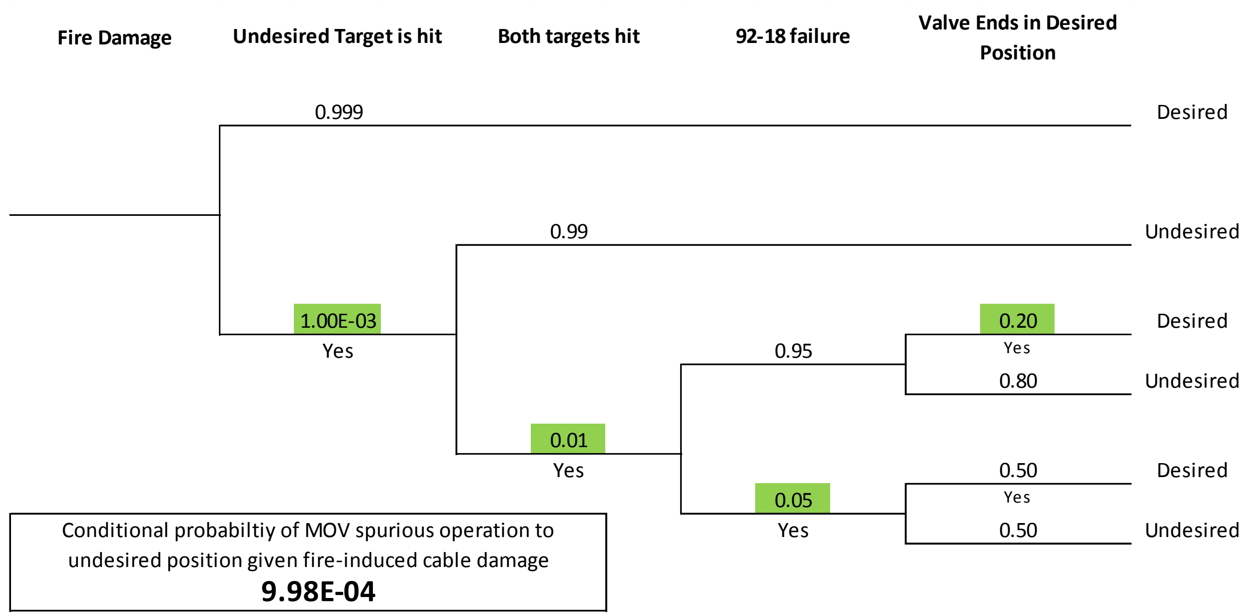

Figure 16. MOV Event Tree for Ungrounded DC Inter-cable TS insulated

GFEHS TS Target Cable (ROW 1, COLUMN 9)

Statistical Analysis

Using the ungrounded DC data from the DESIREE-FIRE testing program, I reviewed each test for applicable TS to TS interactions via the ground plane. The following tests were identified to be applicable;

- IS-Pre1
- IS-1
- IS-2
- IS-3
- IS-4
- IS-11
- IS-12

Table 26. Spurious Operation Data Results for Ungrounded DC GFEHS TS insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	2 / 12	1 / 12	2 / 12	1 / 12
NRC SOV	6 / 24			
Surrogate SOV	**9 / 48**			

Expert Judgment

I feel that the data provides an adequate estimate of the likelihood for this case and have only suggested rounding the estimates.

Table 27. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC GFEHS and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.20**	0.13	0.27
MOV ET Both Targets Hit	0.10	0.06	0.13
MOV ET 92-18 Failure	0.50	0.44	0.56
MOV ET Valve Ends in Desired Position	0.20	0.12	0.27
MOV Conditional Spurious Operation Probability	**0.19**		

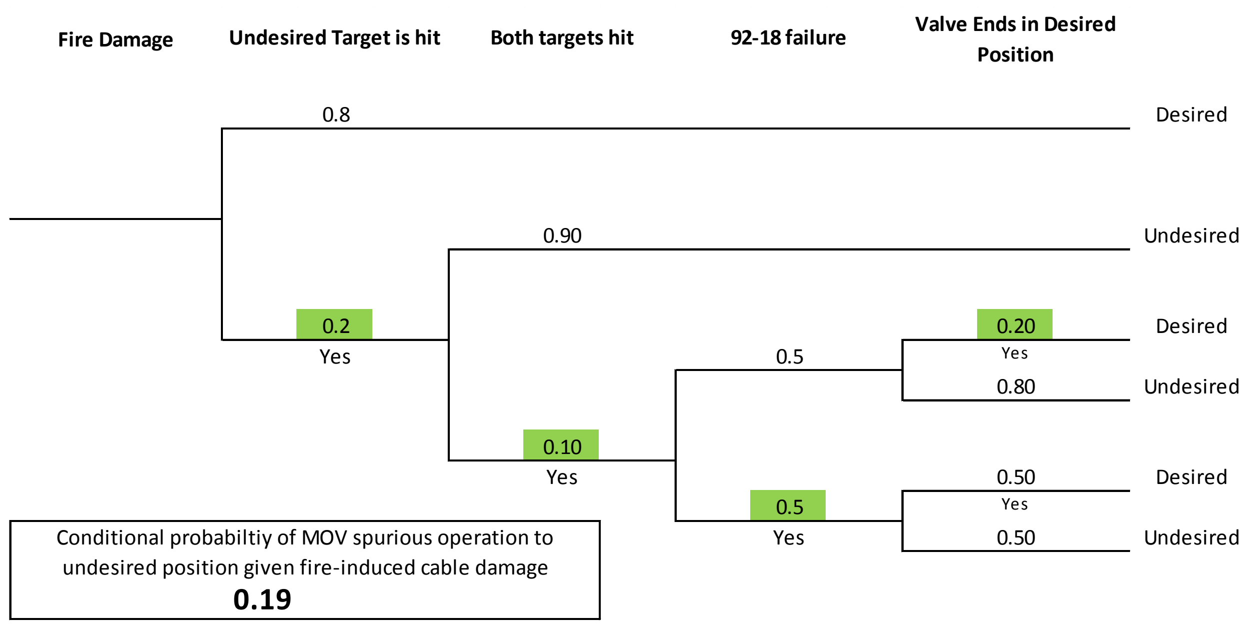

Figure 17. MOV Event Tree for Ungrounded DC GFEHS TS insulated

Intra-cable TP Cable (ROW 2, COLUMN 7)

Statistical Analysis

Using the ungrounded dc data from the DESIREE-FIRE project, I first removed all data with the following attributes;

- Thermoset insulation
- Armor
- Un-insulated grounded drain wire
- Metal foil shield wrap
- Cables that failed via ground fault equivalent hot short (GFEHS)
- Kerite-FR

The following information was collected.

Table 28. Spurious Operation Data Results for Ungrounded DC Intra-Cable TP insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	7 / 20	10 / 20	14 / 20	3 / 20
NRC SOV	17 / 29			
Surrogate SOV	**34 / 69**			

Expert Judgment

Following the same argument made for the ungrounded DC Intra-cable TS case, I suggest using the data estimates and rounding higher to make the results agree with the PIRT panel recommendations that insulation type does not influence spurious operation likelihood.

Table 29. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC Intra-cable TP insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.50**	0.43	0.57
MOV ET Both Targets Hit	0.15	0.10	0.20
MOV ET 92-18 Failure	0.80	0.68	0.84
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.47**		

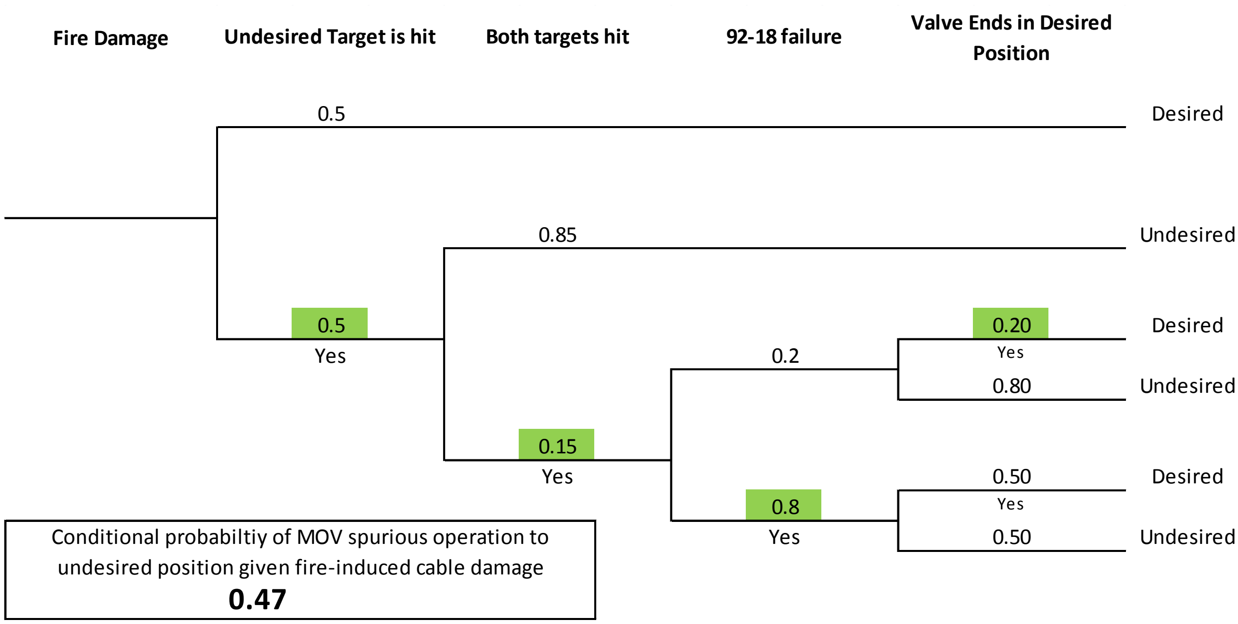

Figure 18. MOV Event Tree for Ungrounded DC Intra-cable TP insulated

Inter-cable TP Target (ROW 2, COLUMN 8)

Statistical Analysis

Using the ungrounded dc data from the DESIREE-FIRE project, I first removed all data with the following attributes;

- Thermoset insulation (TS)
- Armor
- Un-insulated grounded drain wire
- Metal foil shield wrap
- Cables that failed via ground fault equivalent hot short (GFEHS)
- Penlight data due cable locations within test chamber

Reviewing draft NUREG-2128, I determined that there were 24 opportunities for thermoplastic insulated cable-to-cable (inter-cable) interaction to occur during the DESIREE-FIRE intermediate-scale testing. NUREG-2128 identified all of the spurious operation interactions that occurred within these tests, to involve the ground plane. The analysis didn't find any cases where spurious operations occurred cable-to-cable without the ground plane interaction. As such, I've collected the following information.

Table 30. Spurious Operation Data Results for Ungrounded DC Inter-Cable TP insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	N/A	N/A	0 / 8	0 / 8
NRC SOV	0 / 16			
MOV ET			**0 / 8**	0 / 8
Surrogate SOV	**0 / 16**			

Expert Judgment

Following the same argument presented for the TS insulated case, I've proposed adjusting the estimates as shown below.

Table 31. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC Inter-cable TP insulated and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.01**	0.005	0.03
MOV ET Both Targets Hit	0.01	0.005	0.03
MOV ET 92-18 Failure	0.05	0.04	0.07
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.01**		

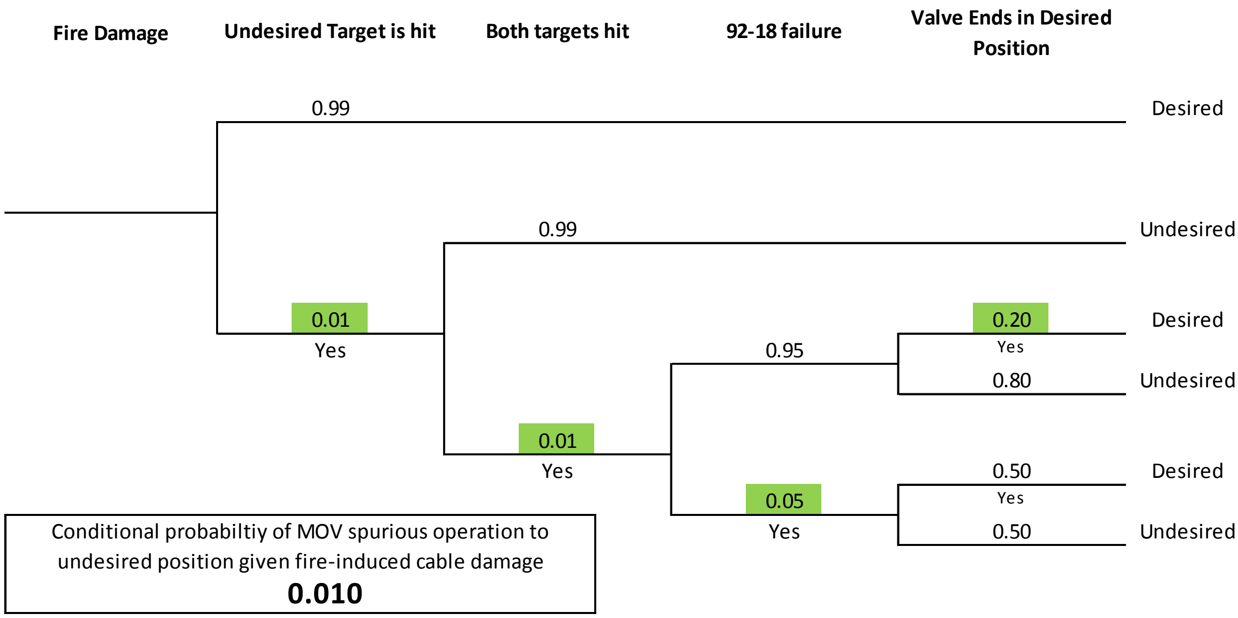

Figure 19. MOV Event Tree for Ungrounded DC Inter-cable TP insulated

GFEHS TP Target (ROW 2, COLUMN 9)

Statistical Analysis

Using the ungrounded DC data from the DESIREE-FIRE testing program, I reviewed each test for applicable TP to TP interactions via the ground plan. The following tests were identified to be applicable;

- Preliminary 2
- IS-5
- IS-6
- IS-7
- IS-8

Table 32. Spurious Operation Data Results for Ungrounded DC GFEHS TP insulated

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	2 / 10	1 / 10	2 / 10	1 / 10
NRC SOV	0 / 18			
Surrogate SOV	**3 / 38**			

Expert Judgment

Compared to the ungrounded DC thermoset ground fault equivalent hot short case, the data contradicts the PIRT conclusions that TS likelihood for inter-cable should be lower than the TP cases. I believe that there are other variable associated with the testing that are at play here and as such I'm proposing that both TS and TP ground fault equivalent hot short have the same likelihood of occurrence as shown in Table 33.

Table 33. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC GFEHS and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.20**	0.13	0.27
MOV ET Both Targets Hit	0.10	0.05	0.20
MOV ET 92-18 Failure	0.50	0.35	0.65
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.19**		

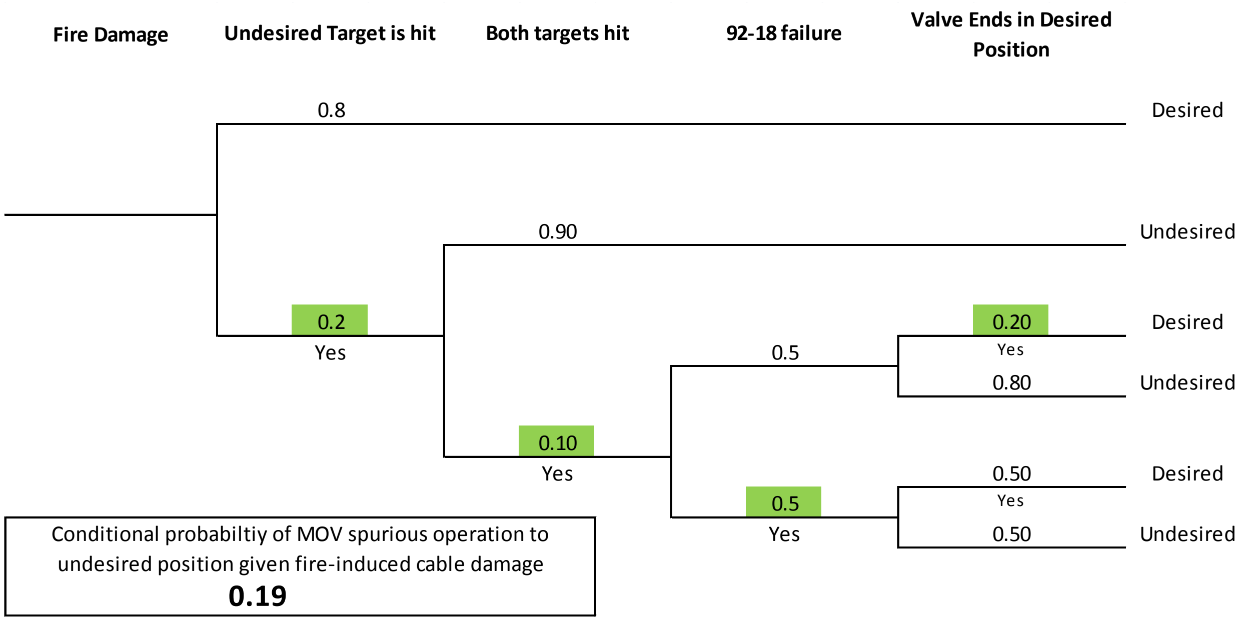

Figure 20. MOV Event Tree for Ungrounded DC GFEHS

Intra-cable Metal Foil Wrap (ROW 3, COLUMN 7)

Statistical Analysis

Using the ungrounded dc data from the DESIREE-FIRE project, I used only the data where a grounded metal foil wrap was used. This consisted of seven test circuits which all used the Kerite FR insulation. Kerite-FR cables free of any shield were maintained in the data set (total of 5 tests), as NUREG/CR-2128 did not identify any substantial differences in the spurious operation likelihood compared to other TS insulated cable materials. In addition, the test data only considers cables without any conductors grounded (i.e., no grounded drain wires or grounded spares).

Table 34. Spurious Operation Data Results for Ungrounded DC Intra-Cable Metal Foil Wrap

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	0 / 2	0 / 2	0 / 2	0 / 2
NRC SOV	2 / 3			
Surrogate SOV	**2 / 5**			

Expert Judgment

For the ungrounded DC circuit configuration, the grounded metal foil shield should increase the likelihood of hot-short induced spurious operations. However, the limited set of data doesn't suggest this. From a relative comparison approach, I believe that this configuration should fall somewhere between an ungrounded armor and the base case (ungrounded dc TS insulated). I don't believe the grounded metal foil shield will have as dominant of an effect as the armor, but would have more of an effect than a cable with a smaller ground influence plane. As such, I suggest adjusting the statistical analysis results as follows;

Table 35. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC Metal Foil Wrap and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.55**	0.40	0.70
MOV ET Both Targets Hit	0.30	0.20	0.40
MOV ET 92-18 Failure	0.80	0.73	0.87
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.48**		

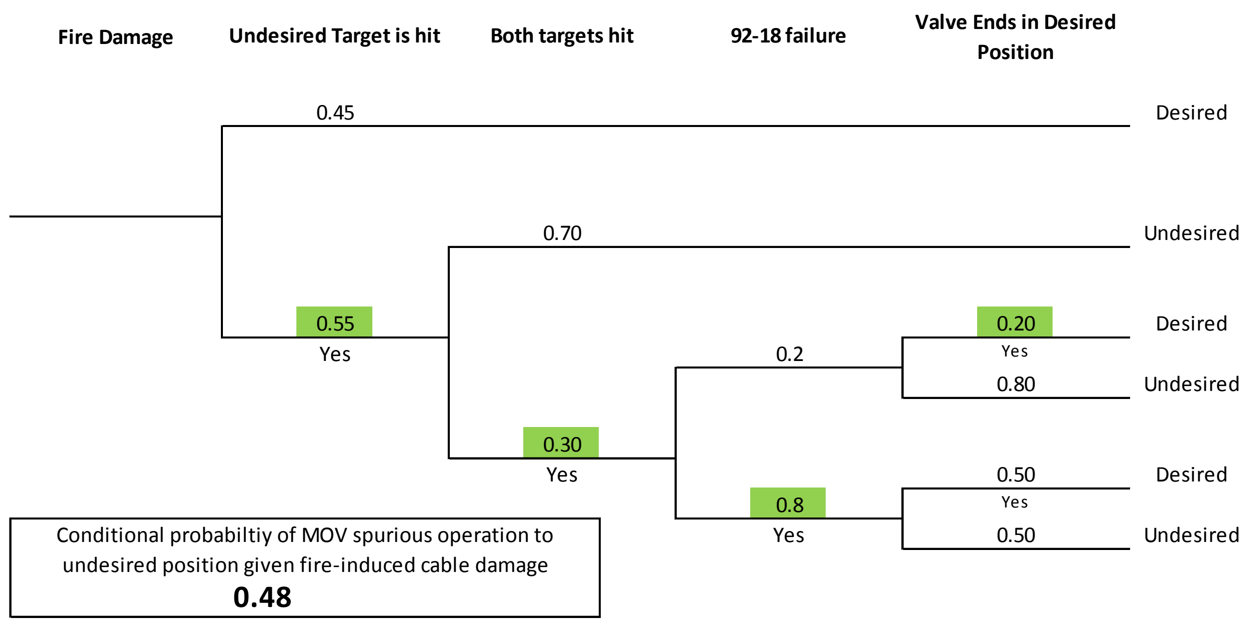

Figure 21. MOV Event Tree for Ungrounded DC Metal Foil Wrap`

GFEHS Metal Foil Wrap (ROW 3, COLUMN 9)

Statistical Analysis

Using the ungrounded DC data from the DESIREE-FIRE testing program, I reviewed each test for applicable grounded metal foil wraps. The only configurations were from intermediate-scale tests 9 and 10. The collected information is shown in Table 36.

Table 36. Spurious Operation Data Results for Ungrounded DC GFEHS Metal Foil Wrap

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	1 / 2	2 / 2	2 / 2	1 / 2
NRC SOV	0 / 4			
Surrogate SOV	**3 / 8**			

Expert Judgment

Due to the lack of data, I choose to provide my best judgment based on the theory that this estimate should fall somewhere between the GFEHS TS, TP cases and the armored cable case. Thus, I've provided the following conditional probabilities presented in Table 37.

Table 37. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC GFEHS Metal Foil Wrap and MOV Event Tree Values

Parameter	Median	1^{st} Quartile (25^{th} %tile)	3^{rd} Quartile (75^{th} %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.35**	0.22	0.48
MOV ET Both Targets Hit	0.30	0.20	0.40
MOV ET 92-18 Failure	0.50	0.35	0.65
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.31**		

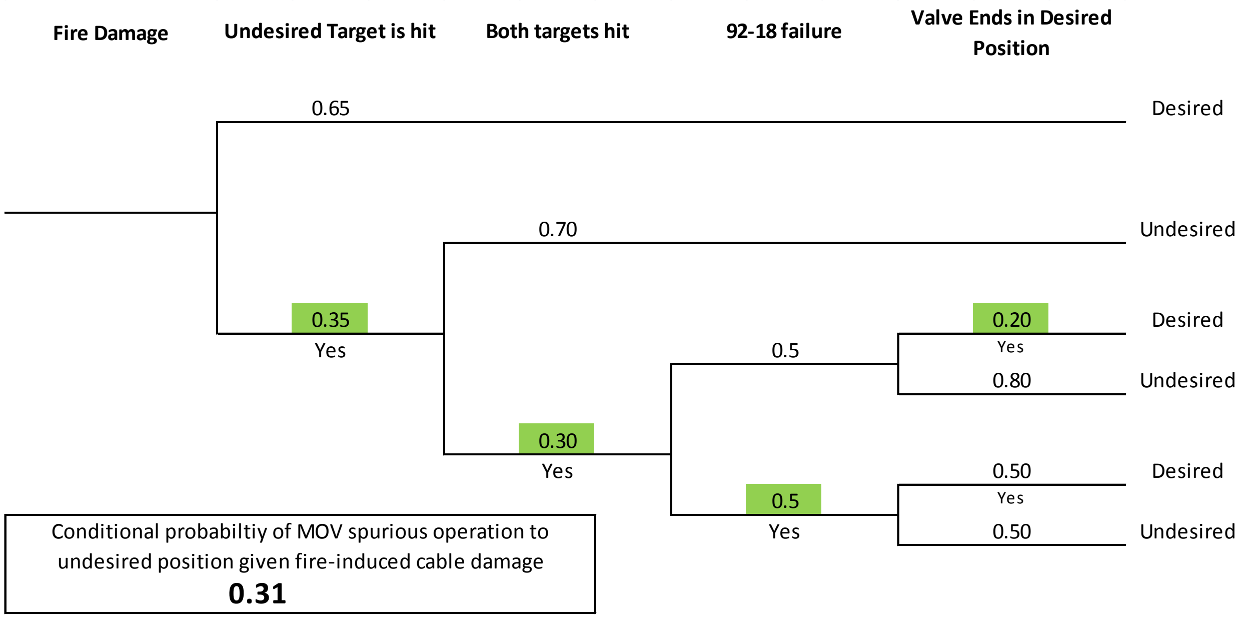

Figure 22. MOV Event Tree for Ungrounded DC GFEHS Metal Foil Wrap

Intra-cable Armored Cable (ROW 4, COLUMN 7)

Statistical Analysis

Using the ungrounded dc data from the DESIREE-FIRE and Duke testing where a grounded interlocked armor was used, I compiled the following information.

Table 38. Spurious Operation Data Results for Ungrounded DC Armored Intra-Cable

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	1 / 3	3 / 3	3 / 3	1 / 3
NRC SOV	8 / 9			
MOV Composite			14 / 16	**7 / 16**
Surrogate SOV	**12 / 15**			

Note: do the proprietary nature of the DUKE testing, Table 12 does not present any of those results; however, they were taking into consideration when developing the likelihood estimates below.

Expert Judgment

The data shows a high likelihood of fire-induced spurious operation give cable damage. However, all of this testing was conducted using the source centered wiring configuration, which I believe provide conservative results. Unfortunately, the test results didn't vary the wiring configuration for ungrounded dc, as was done for grounded AC. Without this data, I'm not confident that wiring configuration will have as dominant of an effect on the ungrounded DC as it did for the grounded ac circuits, especially for this case with the armor. As such, I propose no reduction in likelihood from the wiring configuration and propose an increase for grounded conductors in the cable.

Table 39. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC Armored Intra-cable and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.75**	0.70	0.80
MOV ET Both Targets Hit	0.45	0.37	0.53
MOV ET 92-18 Failure	0.80	0.74	0.88
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.60**		

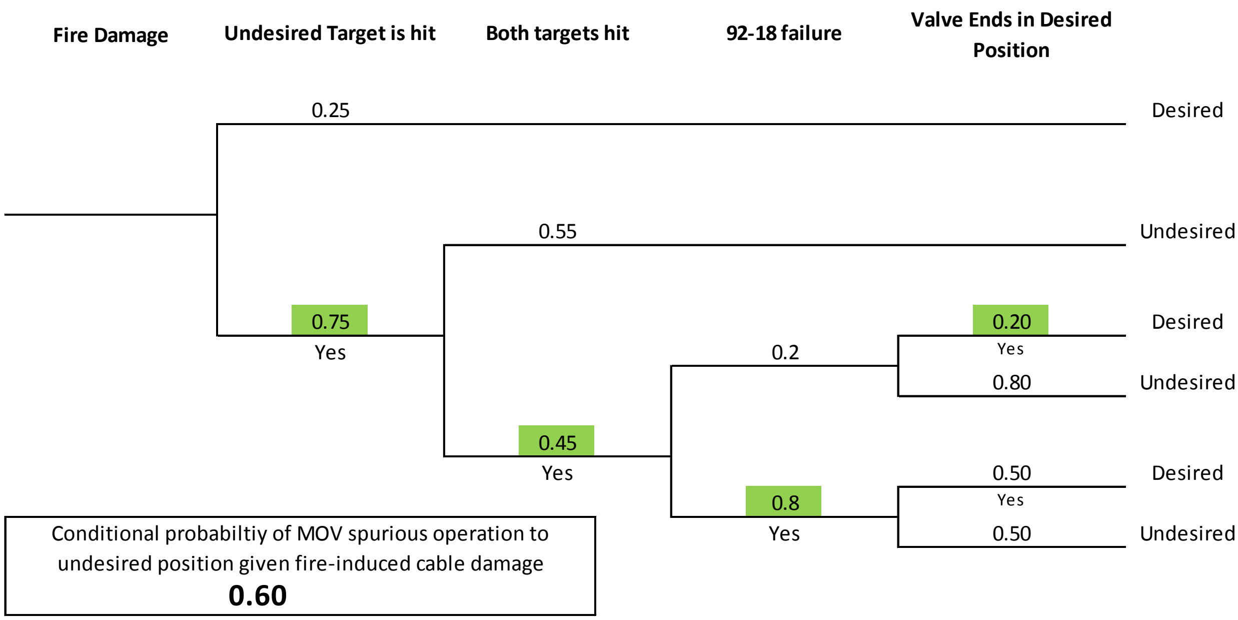

Figure 23. MOV Event Tree for Ungrounded DC Intra-cable Armored Cable

GFEHS Armored Cable (ROW 4, COLUMN 9)

Statistical Analysis

Duke test data couldn't be used to determine if spurious operations were GFEHS or intra-cable due to their electrical instrumentation system response time. Using the ungrounded DC data from the DESIREE-FIRE testing program, I reviewed each test for applicable armored cables. The following tests were identified to be applicable;

- PT-20
- PT-22
- IS-9

Table 40. Spurious Operation Data Results for Ungrounded DC GFEHS Armored Cable

Circuit	SO Target 1 (MOV – YC/C5)	SO Target 2 (MOV – YO/C6)	At least 1 SO (YC or YO)	Double Count Both (YC & YO)
NRC MOV	2 / 2	2 / 4	2 / 3	2 / 3
NRC SOV	0 / 3			
MOV ET			**2 / 3**	2 / 3
Surrogate SOV	**4 / 9**			

Expert Judgment

Consistent with previous arguments for adjusting the ungrounded DC result, I once again have little basis to adjust the test results and only suggest rounding up for possible grounded conductor influences.

Table 41. Adjusted Expert Judgment Spurious Operation Values for SOV Ungrounded DC GFEHS Armored Cable and MOV Event Tree Values

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
SOV Conditional Spurious Operation Probability & MOV ET Undesired Target Hit	**0.50**	0.35	0.65
MOV ET Both Targets Hit	0.65	0.54	0.76
MOV ET 92-18 Failure	0.50	0.35	0.65
MOV ET Valve Ends in Desired Position	0.20	0.13	0.27
MOV Conditional Spurious Operation Probability	**0.39**		

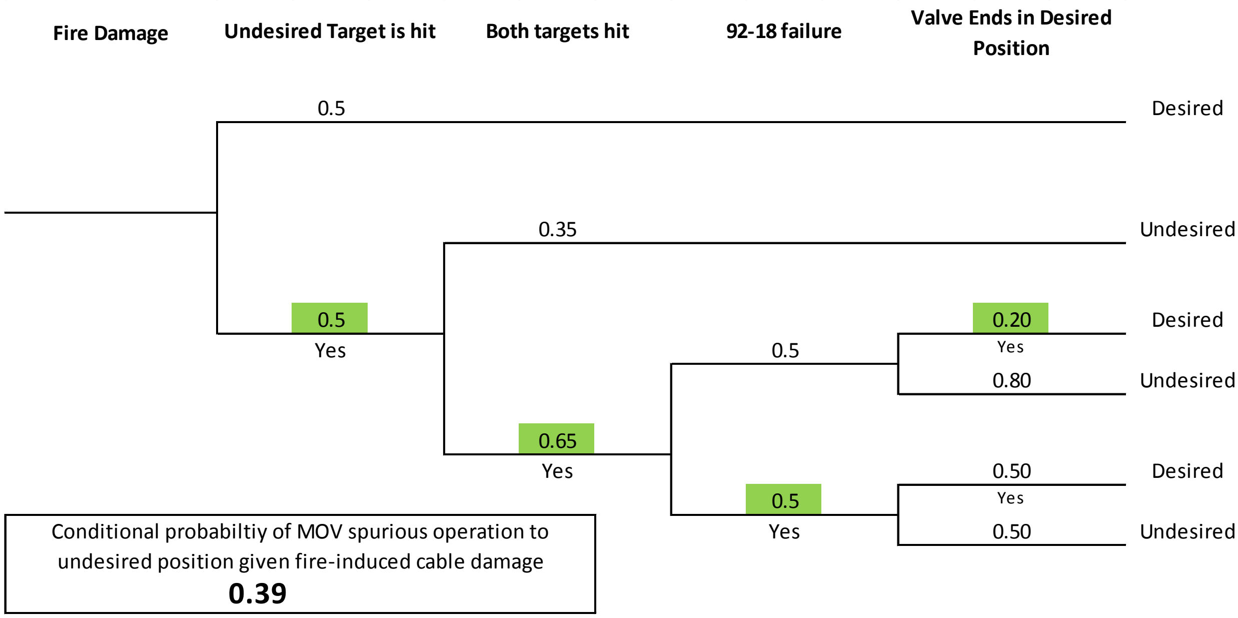

Figure 24. MOV Event Tree for Ungrounded DC GFEHS Armored Cable

D. Breaker Analysis

The medium voltage circuit breaker control circuit will be analyzed here separately. From the DESIREE-FIRE test data all but one test implemented a control cabling scheme where the trip and close circuit conductors were in separate cables. That one test was Intermediate scale Test #10. The Table 42 below provides a summary of the shorting behavior that occurred in the small-scale penlight and intermediate scale circuit breaker testing. The test results for each test are presented in two parts. The first part represents the observed test results, identifying the initial breaker position, 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 the breaker to return to the initial position. The second part of the table present the hypothetical circuit response, assuming that the breaker would have been initially placed in the opposite position than what was tested. The test hypothetical S.O. results are based on the real data by analyzing the timing of hot shorts on the S.O. target conductors that would cause a S.O..

Table 42. Medium voltage circuit breaker control circuits S.O. Test Results

Insulation Type	Test #	Observed test results			Hypothetical test results		
		Breaker Initial Position	1st S.O (seconds)	2ND S.O. (seconds)	Breaker 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
	Int. 1	OPEN	-	-	CLOSE	1361	
	Int. 3	OPEN	1460	-	CLOSE	1363	1460
	Int. 4	OPEN	-	-	CLOSE	5237	
	Int. C1	CLOSE	410	-	OPEN	-	-
	Int. 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	-
	Int. 5	OPEN	1424	-	CLOSE	546	1424
	Int. 6	CLOSE	850	1603	OPEN	158	850
	Int. 7	CLOSE	1095	-	OPEN	185	1095
	Int. C2	CLOSE	334	354	OPEN	354	-

The results in Table 42 show that the likelihood of a medium voltage switchgear control circuit experiencing a spurious operation, provided that cable damage was to occur, is on the order of 80.6% (29/36). Although the data shows a slightly higher likelihood of spurious operation for TP insulated cables than TS, I could not substantiate this based on the limited number of data points and the fact that the other circuits analysis for insulation material influences didn't indicate a difference. I next choose to bin the results into four bin, 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

Using these binning configurations and the data, the following event tree was developed. There was no attempt to take into account the effects of the anti-pump circuit, the transient nature of the breaker opening and closing, or the duration between spurious operations if multiples were to occur. In fact, I do not believe that the anti-pump circuit should be credited in any way as a means of keeping a breaker tripped for failure modes that result from fire-induced cable damage. This is because for the anti-pump circuit to work as designed, the hot short in the closed portion of the circuit would have to be maintained continuous for the duration of the fire transient on the corresponding cable. In actuality, I find it highly unlikely that such a hot short would persist on the correct conductors without momentary interruptions. 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 supports this conclusion.

Given the limited test data and variations used to test the breaker, I propose the estimates shown in Table 43.

Table 43. Expert Judgment Spurious Operation Values for Medium Voltage Switchgear

Parameter	Median	1st Quartile (25th %tile)	3rd Quartile (75th %tile)
Conditional probability of breaker end state differs from initial state (Spurious Operation Only)	**0.48**	0.41	0.55
Conditional probability of breaker end state same as initial state (Spurious Operation + Non-Spurious)	0.52	0.47	0.57

E. Spurious Operation Double Break Design

This section presents the conditional spurious operation likelihood estimates developed for circuit of a double break design. A description of the double break circuit design is presented in the PIRT report (NUREG/CR-7150 Vol. 1). Note that the double break design is similar to a circuit whose fuses have been pulled or have cleared previously. There are two basic circuit types that double break estimates are provided for, namely, ungrounded AC and ungrounded DC.

Figure 3-8 “Double break ungrounded AC schematics,” of NUREG/CR-7150, Vol. 1, provide simple circuit schematics of double break design for ungrounded AC control circuits. After reviewing the various scenarios, I believe all are independent, except the “intra-cable + intra-cable” scenario. The dependency here is that the conductors can be in the same cable that is damaged by the fire. As such, for the “Intra + Intra cable short” column I’ve used the single break values and divided by 2 to account for the fact that two shorts are needed and these two shorts need to be to the correct conductors. The remainder of the cases, I believe to be independent and I’ve proposed using Boolean logic to arrive at point estimates. The resultant point estimates (median) and uncertainty (1st and 3rd quartiles) are presented in Table 44 for the ungrounded AC scenarios. For the ungrounded ac cases that involved ground fault equivalent hot short failure modes, I’ve used insight from the ungrounded DC test results to arrive at an estimate for the ungrounded ac.

Table 44. Conditional spurious operation probability estimates for double break SOV circuits

<table>
<tr><th colspan="7">Double Break Ungrounded AC Powered from a CPT*</th></tr>
<tr><th rowspan="3">Cable Configuration</th><th colspan="6">Conductor shorting modes of interest</th></tr>
<tr><th>Intra + Intra cable short</th><th>Intra + Inter cable short</th><th>Inter + Inter cable short</th><th>Intra + ground cable short</th><th>Inter + ground cable short</th><th>Aggregate result</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td>TS insulated cables</td><td rowspan="2">0.30
(0.25, 0.35)</td><td>5E-5
(1E-6, 8E-5)</td><td></td><td>0.10
(0.05, 0.15)</td><td></td><td>0.37
(0.28, 0.46)</td></tr>
<tr><td>TP insulated cables</td><td>0.005
(0.001, 0.08)</td><td>1E-4
(5E-5, 3E-4)</td><td>0.15
(0.10, 0.20)</td><td>1E-3
(5E-4, 3E-3)</td><td>0.41
(0.30, 0.52)</td></tr>
<tr><td>Grounded metal foil shield wrap</td><td>0.28
(0.15, 0.43)</td><td></td><td></td><td>0.20
(0.13, 0.27)</td><td></td><td>0.42
(0.27, 0.57)</td></tr>
<tr><td>Armored 7/C cable</td><td>0.25
(0.15, 0.40)</td><td></td><td></td><td>0.25
(0.15, 0.35)</td><td></td><td>0.44
(0.24, 0.64)</td></tr>
<tr><td colspan="7">*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.
◊ Intra cable shorts that mimic the fault mode of ground fault equivalent hot shorts are included under the intra + intra cable short column.</td></tr>
</table>

Note: Point estimates (median) are given in bold text and 1st and 3rd quartiles are given in parentheses (1st quartile, 3rd quartile)

A similar analysis was performed for the ungrounded DC scenarios. There results of this work are presented in Table 45.

Table 45. Conditional spurious operation probability estimates for double break ungrounded DC SOV circuits

Double Break Ungrounded AC Powered from a CPT*						
Cable Configuration	Conductor shorting modes of interest					
	Intra + Intra cable short	Intra + Inter cable short	Inter + Inter cable short	Intra + ground cable short	Inter + ground cable short	Aggregate result
	1	2	3	4	5	6
TS insulated cables	**0.25** (0.20, 0.30)	**5E-4** (1E-4, 8E-4)		**0.10** (0.05, 0.15)		**0.33** (0.23, 0.43)
TP insulated cables		**0.005** (0.001, 0.008)	**1E-4** (5E-5, 3E-4)	**0.15** (0.10, 0.20)	**0.002** (8E-4, 4E-3)	**0.37** (0.27, 0.47)
Grounded metal foil shield wrap	**0.28** (0.15, 0.43)			**0.20** (0.13, 0.27)		**0.42** (0.32, 0.52)
Armored 7/C cable	**0.38** (0.30, 0.46)			**0.40** (0.30, 0.50)		**0.57** (0.45, 0.69)

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

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

Note: Point estimates (median) are given in bold text and 1st and 3rd quartiles are given in parentheses (1st quartile, 3rd quartile)

F. Spurious Operation Duration

In addition to providing the conditional spurious operation probability estimates, I was also tasked to provide spurious operation duration information. This section attempts to summarize the analysis of the test data and the engineering judgment used to develop my estimates.

I began the task by reviewing Section 16 “Hot Short Duration (FAQ 08-0051)” of NUREG/CR-6850 Supplement 1, “Fire Probabilistic Risk Assessment Methods Enhancements.” The interim position provided by the FAQ was to provide the probability of spurious operation duration for a hot short lasting longer than or equal to time, t, in minutes. The interim position solution was a complementary cumulative distribution function of a Weibull distribution, and of the form:

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

Where the λ and β factors are 0.963 and 0.579, respectively and specified the minimum recommended probability to be used in fire PRA to be 0.01 due to significant uncertainties with the duration probabilities.

FAQ 08-0051 also make following important statement;

> When accounting for hot short duration in a fire PRA, the duration is paired with the occurrence of the spurious actuation. It should be emphasized that the probability that the hot short duration equals or exceeds a particular time, i.e. $P(T \geq t)$, is used to characterize the likelihood that a hot short condition persists beyond the specified time. Therefore, in the context of an event tree, the failure path or downward branch would be characterized by $P(T \geq t)$, and the complement, $1 - P(T \geq t)$, is used to characterize the success path or upward branch. In practice, the duration time of interest would be a characteristic of the PRA scenario.

Finally, FAQ 51 identified 4 conditions which the interim position should not be used, they were;

1. The hot short duration probabilities should not be applied to spurious actuation of equipment caused by grounding of one or more conductors (i.e., for those spurious actuations not caused by hot shorts). For these cases, no credit should be given for hot short duration.
2. The hot-short duration probability should not be applied if the spurious actuation produced by the hot short would not clear once the cable is grounded. For this case, no credit should be given for hot short duration. A review should be completed to ensure that clearing the hot short will clear the spurious actuation, including identification of the device (e.g., fuse or circuit breaker) that would clear the hot short given cable grounding.
3. Given a short to ground on an auxiliary or “off-scheme” circuit, credit for recovery of a spurious actuation needs to include a functional circuit analysis demonstrating the effect of a short to ground on the auxiliary circuit. For cases where functional circuit analysis cannot demonstrate recovery, no credit can be given for hot short duration since the short to ground will not clear by itself.
4. The spurious operation duration probabilities should not be used for DC circuits.

With an understanding of solution provided in FAQ 51, I began by reviewing the hot short duration data from the AC and DC tests. From the results presented in NUREG-2128, the duration data was presented for hot shorts and hot short-induced spurious operations separately, with the hot short durations typically lasting longer than the spurious operation duration. Since it is not entirely clear the root cause of the longer duration hot shorts and since the purpose of this task is to quantify the duration probabilities of spurious operations, I choose to use only the spurious operation data (i.e., did not use any hot short duration data). I analyzed the AC and DC data separately.

I first separated the AC data into the following bins;

- Grounded AC Flame Thermoset
- Grounded AC Flame Thermoplastic
- Ungrounded AC Flame Thermoset
- Ungrounded AC Flame Thermoplastic
- Grounded AC Hot Gas Layer Thermoset
- Grounded AC Hot Gas Layer Thermoplastic
- Ungrounded AC Hot Gas Layer Thermoset
- Ungrounded AC Hot Gas Layer Thermoplastic
- Grounded AC Plume Thermoset
- Grounded AC Plume Thermoplastic
- Ungrounded AC Plume Thermoset
- Ungrounded AC Plume Thermoplastic

Using Matlab R2012a and it's "kstest2" function for the two variable Kolmogorov-Smirnov (k-s) goodness of fit test, I found that circuit-grounding configuration and cable insulation didn't affect the poolability of the AC spurious operation duration data. Additional k-s tests indicated that the plume and hot gas layer AC data sets were marginally poolable, but the data from the flame regions of the testing would not pool with either of the two other categories. This is because of the severe thermal exposure conditions of the flame region causing the cable being damaged to rapidly progress through its failure mode sequences, resulting in typically short spurious operation durations.

Next, I separated the DC duration data into the following bins;

- DC Ungrounded Flame Thermoset
- DC Ungrounded Flame Thermoplastic
- DC Ungrounded Hot Gas Layer Thermoset
- DC Ungrounded Hot Gas Layer Thermoplastic
- DC Ungrounded Plume Thermoset
- DC Ungrounded Plume Thermoplastic
- DC Ungrounded Radiant Thermoset
- DC Ungrounded Radiant Thermoplastic

Following the same procedure of using Matlab as was done for the AC duration data, I found that all but the radiant data sets could be pooled. One last k-s test was run to evaluate if the AC pooled data set could be combined with the DC pooled data set. The k-s test results for this comparison resulted in a p-value of 0.1034 equating to a pass when using an alpha of 0.05. Finally, Matlab was used to fit a Weibull distribution was fit to the final data set.

All of the previous discussion focuses on the data alone and doesn't take experimental configurations into consideration. It is important to note that the CAROLFIRE and DESIREE-FIRE testing, which constitute the majority of these results were tested to severe thermal exposure conditions such that the cable would be damaged in 20-30 minutes, a time frame that was felt to be risk significant during the design stages of the CAROLFIRE program. In addition, the cable tray loading was limited in most cases, and had more loaded tray been tested, the time to damage and durations would likely have been extended. So the question that needs to be posed, is how do these exposure conditions correlate to real fires experienced in the plant that are severe enough to cause cable damage. Given the limited number of well documented fires that have caused cable damage and the wide variety of fire scenarios that can be encountered in the plants, this question is not an easy one to answer.

Given this information, I believe that data represents a lower portion of the actual duration probability distribution curve. For the AC and DC case, I'm proposing a Weibull distribution with the following parameters;

$$\lambda = 0.9544 \qquad \beta = 0.4805$$

However, for the DC case, because there were several tests where the fuses didn't clear, I propose that a minimum duration probability of 0.03 be used to capture these cases. In addition, the AC minimum should be 0.01. Figure 25 presents these results graphically along with the interim solution provided in FAQ 51.

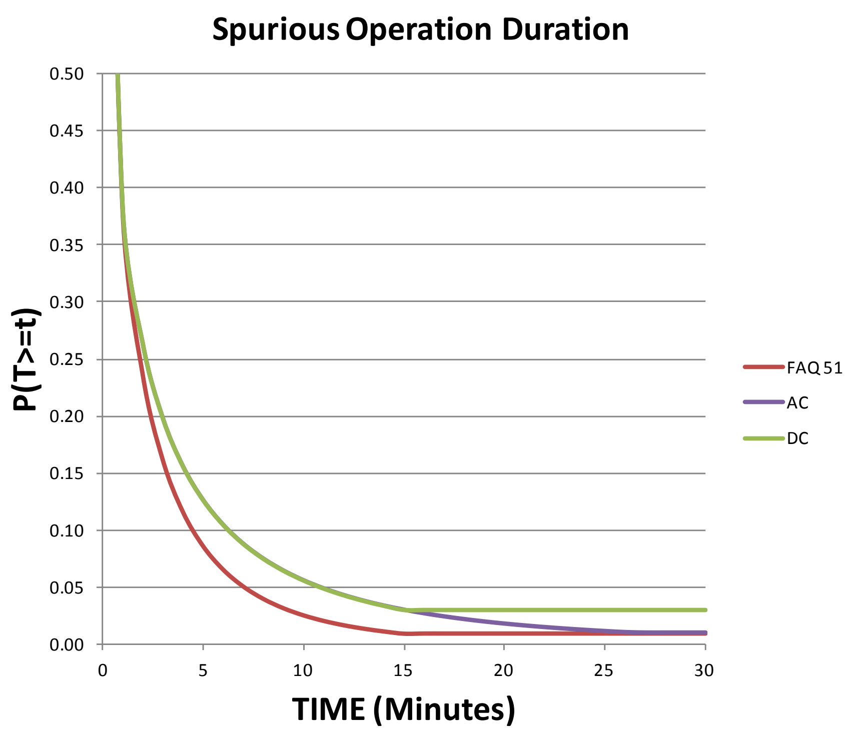

Figure 25. Duration of spurious operations (showing FAQ 51, proposed AC and DC cases)

Table 46 provides the corresponding probabilities of spurious operation duration from a hot short lasting greater than or equal to time, t, in minutes.

Table 46. Probability of duration ≥ TIME (Minutes) for spurious operation

TIME (Minutes)	P(T≥t)	
	AC	DC
0	1.00E+00	1.00E+00
1	3.85E-01	3.85E-01
2	2.64E-01	2.64E-01
3	1.98E-01	1.98E-01
4	1.56E-01	1.56E-01
5	1.26E-01	1.26E-01
6	1.05E-01	1.05E-01
7	8.79E-02	8.79E-02
8	7.49E-02	7.49E-02
9	6.44E-02	6.44E-02
10	5.58E-02	5.58E-02
11	4.88E-02	4.88E-02
12	4.29E-02	4.29E-02
13	3.79E-02	3.79E-02
14	3.36E-02	3.36E-02
15	3.00E-02	0.03
20	2.69E-02	
21	1.62E-02	
22	1.48E-02	
23	1.35E-02	
24	1.23E-02	
25	1.13E-02	
26	1.04E-02	
27	0.01	
28		
29		
30		
>30		