Probability Distributions for Multiple Fire-Induced Cable Faults Causing Spurious Component Operations

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Abstract: Given the uncertainty associated with spurious operations, combined with their risk significance, it is important that fire probabilistic safety assessments (PSA) explicitly model this uncertainty so it can be considered during risk-informed decision-making. NUREG/CR-7150 develops probability distributions for hot short-induced spurious operations, as well as spurious event durations, for various control circuit types and configurations. The circuit failure mode likelihood analysis task of a fire PSA assigns these probability distributions to fire scenario- and cable-specific failures.

If a single cable failure results in spurious component operation, the NUREG/CR-7150 distributions can be used directly in the uncertainty quantification; however, if two independent cable failures can cause the same spurious component operation, a new distribution must be estimated to represent the aggregate failure probability. This paper describes a probabilistic sampling study performed to estimate spurious operation probability distributions associated with two cable faults. Additionally, new distributions were calculated for two cables failing along with the consideration of the spurious event duration. The resulting distributions can be exported to the PSA model database, which enables the uncertainty associated with spurious operation by multiple cable faults to be quantitatively included in plant fire risk uncertainty quantification.

Keywords: Fire PSA, Uncertainty, Circuit Analysis, Monte Carlo, CFMLA, Spurious

1. INTRODUCTION

The United States Nuclear Regulatory Commission [1] has emphasized the importance of quantitatively evaluating the uncertainty of probabilistic safety assessment (PSA) results, in particular for risk-informed decision-making. Uncertainty quantification has been a challenge for fire PSAs, which often rely heavily on modeling outside of the PSA model logic.

In this paper, we focus on one aspect of spurious component operation uncertainty important to fire PSAs. We present a probabilistic sampling study used to estimate distributions associated with spurious component operation caused by two independent hot shorts, including consideration of spurious event duration. The resulting distributions can be incorporated into the fire PSA database, which enables uncertainty surrounding these events to be quantitatively considered in the fire PSA uncertainty quantification. This represents an improvement to current practice, which often relies on sensitivity studies.

Circuit failure mode likelihood analysis, described in NUREG/CR-6850 Task 10 [2], assigns conditional hot short probabilities to individual target cables. NUREG/CR-7150, Volume 2 [3] provides the conditional spurious operation probabilities for different types of circuits, such as AC versus DC, grounded versus ungrounded, and SOV versus MOV. For example, Tables 4-1 and 4-3 in [3] provide beta distributions representing spurious operation likelihood for SOV and MOV single-break control circuits, respectively.

The authors of NUREG/CR-7150 [3], as discussed in the document, chose to represent spurious operation probability as a beta random variable since its range is [0,1], and it is a relatively flexible distribution that is built into common PSA software. Equation 1 is the probability density function of a beta random variable X.

$$f(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1} \qquad \text{Equation 1}$$

Where $\Gamma(n) = (n-1)!$ is the gamma function, and the α and β terms are the distribution shape parameters. In this application, the random variable X represents the conditional probability of spurious operation given cable damage. Equation 2 and Equation 3 calculate the expected value (mean) and variance of the beta distribution, respectively.

$$E[X] = \frac{\alpha}{\alpha+\beta} \qquad \text{Equation 2}$$

$$var[X] = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \qquad \text{Equation 3}$$

Fire PSA uses the mean probabilities from NUREG/CR-7150 [3] to develop the point-estimate core damage frequency (CDF) and large early release frequency (LERF). The uncertainty quantification requires the probability distribution for each basic event be fully characterized (mean and variance) to estimate the overall CDF and LERF distribution by sampling studies.

The probability of a component spuriously operating as a result of fire exposure depends on its circuit design, and the number, type and failure modes of cables required to cause the spurious operation. FAQ 08-0047 in NUREG/CR-6850 Supplement 1 [4] explains how dependence between these factors can impact the conditional probability of spurious operation occurring. If the fire scenario damages a single cable that is capable of inducing a spurious operation, the corresponding probability distribution from NUREG/CR-7150 [3] is used for uncertainty quantification. However, if fire-induced failure of two cables are independently capable of inducing the same spurious component operation, Equation 4 is used to calculate the total failure probability (see Section 10.5.3.1 in [2]).

$$P_{Component\ Failure} = (P_{Failure\ Cable\ A}) + (P_{Failure\ Cable\ B}) - (P_{Failure\ Cable\ A}) * (P_{Failure\ Cable\ B}) \qquad \text{Equation 4}$$

Note that Equation 4 assumes independence between the cable failure events. NUREG/CR-7150 [3] provides a discussion on the assumption of independence and concludes that it yields a “moderately conservative” estimate of spurious operation probability, and that without testing it would be difficult to justify an alternate approach that considers dependence.

When generating the point estimate CDF and LERF for a fire scenario where multiple cables could independently induce the same basic event, the mean failure probabilities are used in the exclusive OR

(Equation 4) calculation. The resulting spurious operation probability for the specific component is used during quantification. This step is typically performed outside the PSA model logic, often in the fire PSA database, since the addition of cable-specific events to the model logic can quickly increase quantification burden, especially if the circuit failure mode likelihood analysis is applied broadly across many components and fire scenarios.

However, performing this calculation outside the model logic creates a challenge for uncertainty quantification, which generally requires cutsets where all uncertain events are explicit. Furthermore, there is no convenient closed-form solution to the sum of independent non-identically distributed beta random variables, and approximations are therefore required. For example, Nadarajah et. al [5] develop a saddle point approximation of the sum of beta random variables and compare its performance to a normal approximation. The normal approximation to the sum of beta random variables is often used in project management to estimate total project duration, where the individual task durations are beta distributed.

In the next section, we describe a probabilistic sampling study, followed by fitting normal distributions to the sampling results, to approximate the distributions of fire scenario- and component-specific spurious operation events.

2. ANALYSIS

Table 1 classifies a sample of fire-induced circuit failure types evaluated by NUREG/CR-7150 [3] into Cases 1 through 5. Note this study was performed only for configurations identified in Table 1, and all for thermoset cables, since they were most relevant to a fire PSA being performed at the time of this paper. The fire PSA was for a four-loop Westinghouse pressurized water reactor. A similar study could be performed for the remaining configurations considered by NUREG/CR-7150 [3].

Table 1: Circuit Failure Types and Associated Spurious Operation Probability Distributions per NUREG/CR-7150 [3]

Case	Valve	Failure(s)	AC/DC	Grounded	Distribution
1	MOV	Inter-cable	AC	Yes	Beta(α = 0.36, β = 40.31)
2	MOV	Intra-cable, Inter-cable	AC	Yes	Beta(α = 5.80, β = 15.16)
3	MOV	Intra-cable, Inter-cable	AC	No	Beta(α = 4.81, β = 7.68)
4	SOV	Inter-cable, GFE	DC	No	Beta(α = 2.43, β = 11.76)*
5	SOV	Intra-cable, Inter-cable, GFE	DC	No	Beta(α = 12.76, β = 10.18)

* Note the Case 4 distribution was estimated as the sum of the two random variables in Table 4-1 of NUREG/CR-7150 [3] representing inter-cable hot short and ground fault equivalent probabilities. This was accomplished by sampling the two distributions, summing each pair of observations, and then fitting a beta distribution to the histogram of sums.

NUREG/CR-7150 [3] also provides a probabilistic model representing the duration of spurious operations. The model is a composite of a Weibull distribution survival function up to a certain point in time, at which point there a floor probability that is modeled as a beta random variable. The floor distributions and associated times for AC and DC circuits are reproduced in Table 2.

Table 2: Spurious Operation Duration Floor Probabilities and Associated Times per NUREG/CR-7150 [3]

	Floor Probability	Floor Time
AC Control Circuits	Beta(α = 0.27, β = 36.99)	9 minutes
DC Control Circuits	Beta(α = 0.88, β = 39.28)	7 minutes

Table 3 summarizes the results of a sampling study (sample size of 100,000) that estimated probability distributions for spurious operations caused by various pairs of circuit failure configurations from Table 1. The random variables in Table 3, denoted $X_{i,j}$, each represent a spurious component operation that could occur by either one of two independent faults. For example, $X_{1,2}$ represents a motor operated valve with a thermoset insulated AC grounded control circuit spuriously operating due to either a Case 1 (inter-cable) fault in one portion of the circuit, or a Case 2 (either an intra- or inter-cable) fault in a separate part of the circuit.

In some cases, the reported distribution includes the likelihood of the duration exceeding the floor values reported in Table 2 (9 minutes for AC circuits and 7 minutes for DC circuits). For example, $X_{4,5,7min}$ represents a solenoid operated valve with a thermoset insulated DC ungrounded control circuit spuriously operating for at least 7 minutes due to either a Case 4 (inter-cable, GFE) fault in one part of the circuit or a Case 5 (intra-cable, inter-cable, GFE) fault in a separate part of the circuit. Note that the spurious duration is considered only for SOVs that reseat to their desired position after the hot short(s) clears. This spurious event duration cannot be applied to MOVs, which fail in their 'as-is' position even after any hot shorts clear.

These distributions were generated by sampling from the constituent fault type distributions (Table 1, Cases 1-5) and taking the exclusive OR sum (Equation 4) of the paired observations. For cases where duration is considered, the exclusive OR representing spurious operation probability was multiplied by corresponding observations sampled from the Table 2 beta distributions representing the floor probabilities associated with exceeding 9 and 7 minute durations for AC and DC circuits, respectively. Finally, a normal (Gaussian) distribution was fit to the resulting histogram for each case and the associated mean, μ, and standard deviation, σ, reported.

Table 3: Normal Distributions Approximating the Probability of Spurious Component Operation that can be Induced by Either One of Two Independent Cable Failures

Random Variable	μ	σ
$X_{1,1}$	1.8E-02	2.0E-02
$X_{1,2}$	2.8E-01	9.6E-02
$X_{1,3}$	3.9E-01	1.3E-01
$X_{1,4}$	1.8E-01	9.7E-02
$X_{1,5}$	5.6E-01	1.0E-01
$X_{2,2}$	4.8E-01	9.8E-02

Random Variable	μ	σ
$X_{2,3}$	5.6E-01	1.1E-01
$X_{2,4}$	4.0E-01	1.1E-01
$X_{2,5}$	6.8E-01	8.5E-02
$X_{3,3}$	6.2E-01	1.2E-01
$X_{3,4}$	4.9E-01	1.3E-01
$X_{3,5}$	7.3E-01	8.7E-02
$X_{4,4}$	3.1E-01	1.1E-01
$X_{4,5}$	6.3E-01	9.5E-02
$X_{5,5}$	8.0E-01	6.5E-02
$X_{4,7min}$	3.7E-03	4.9E-03
$X_{5,7min}$	1.2E-02	1.3E-02
$X_{4,4,7min}$	6.8E-03	8.0E-03
$X_{4,5,7min}$	1.4E-02	1.5E-02
$X_{5,5,7min}$	1.8E-02	1.8E-02

3. IMPLEMENTATION CONSIDERATIONS

The fire PSA to which the analysis was applied used a large fault tree approach with cutset generation to estimate fire CDF and LERF for each fire scenario. The sampling study was performed with MATLAB®, and the resulting distributions were incorporated in the plant fire PSA database. This allowed, following cutset generation, the distributions associated with spurious operation events to be considered during uncertainty quantification.

A full fire PSA can have 1,000s of fire scenarios, each affecting 100's of cables, and many scenarios can involve spurious operations of multiple components. Applying the sampling study described in this paper to all fire scenarios can require generation of many new distributions, each representing the unique combination of faults that could be induced by a given scenario. Consistent with the overall circuit failure mode likelihood analysis task, it is therefore practical that the sampling study proposed here be considered only for the more risk significant scenarios. Alternatively, the sampling process could be incorporated into the fire PSA database and automatically applied to all components to which circuit failure mode likelihood analysis is performed.

A final note on implementation is regarding spurious operations that contribute to initiating events, as opposed to mitigation failures. For example, spurious opening of a pressurizer power operated relief valve might cause a small loss of coolant accident (SLOCA) initiating event. In such cases, it is important that the spurious operation probability be applied to the initiating event frequency, and not simply as a basic event in the cutset. This is important because the initiating event frequency is factored out prior to estimating conditional core damage probability. This could be implemented by developing a fire scenario frequency distribution, using a similar sampling approach to that described in this paper, where random variables representing the base ignition frequency and any modifiers (non-suppression probability, severity factor, etc.) multiplied by the random variable representing spurious operation. This would introduce the (realistic) possibility that a particular initiating event does not occur, through its compliment. This could be handled using the process described in this paper to develop the relevant distributions, along with a pre-tree to ensure the proper accident sequence analysis and event tree is used for the associated initiating event. Risley et Al. [6] discuss this and issues surrounding the apportioning of fire ignition frequency to induced initiating events.

4. CONCLUSION

Given the uncertainty associated with spurious operations, combined with their risk significance, it is important that fire PSAs explicitly model this uncertainty so that it can be properly considered during risk-informed decision-making. However, point estimates for spurious operation probabilities are often used during uncertainty quantification, rather than distributions, and this is due to complexities and model burden associated with creating scenario- and cable-specific events into the PSA model logic.

This paper has proposed a feasible process for estimating scenario-specific spurious operation probability distributions, including contribution from multiple failure mechanisms and the consideration of duration. This approach can be automated in the fire PSA database and overall model infrastructure. Implementation at a Westinghouse four-loop pressurized water reactor showed that modeling of spurious operations has the potential to contribute significantly to scenario-specific fire CDF and LERF uncertainty, as well as to the overall CDF and LERF uncertainty if spurious operation has a high risk importance. Using only mean values for hot short probabilities, a relaxation often made to avoid over-complicating the fault tree logic and fire PSA database, can therefore underestimate fire CDF and LERF uncertainty.

Finally, one alternative to each plant incorporating the proposed sampling process into their fire PSA infrastructure would be for an industry organization, such as the Electric Power Research Institute (EPRI), the pressurized water or boiling water reactor owners' groups, or the Nuclear Energy Institute (NEI) to develop the distributions for all foreseeable risk-significant spurious operation events. While this may involve developing a very large set of distributions, the process could be easily automated and published such that plants would not have to perform this analysis individually.

5. REFERENCES

[1] NUREG-1855, Revision 1, "Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision Making."

[2] NUREG/CR-6850, "Fire PRA Methodology for Nuclear Power Facilities – Volume 2: Detailed Methodology," EPRI 1011989.

[3] NUREG/CR-7150, Volume 2, "Joint Assessment of Cable Damage and Quantification of Effects from Fire – Volume 2: Expert Elicitation Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure," EPRI 3002001989.

[4] NUREG/CR-6850 Supplement 1, "Fire Probabilistic Risk Assessment Methods Enhancements – Supplement 1 to NUREG/CR-6850 and EPRI 1011989," EPRI 1019259.

[5] Nadarajah S., Jiang X, Chu, J, "A saddlepoint approximation to the distribution of the sum of independent non-identically beta random variables," Statistica Neerlandica 2015;69:102–114.

[6] Risley P., Worrell C., Christiansen K., "An approach for apportioning fire scenario frequencies to induced initiating events," American Nuclear Society PSA 2019 Conference, April 28, 2019, Charleston, SC.

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