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How to Treat SOKC Effects in PSA Quantification

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1. Introduction

In carrying out the uncertainty evaluation in NPP PSAs, it is important to consider the state of knowledge correlation (SOKC) between events. The SOKC arises because, for identical or similar components, the state-of-knowledge about their failure parameters is the same. In other words, the data used to obtain mean values and uncertainties of the parameters in the basic event models of these components may come from a common source and, therefore, are not independent, but are correlated.

When the basic event mean values and uncertainty distributions are propagated in the PSA model without accounting for the SOKC, the calculated mean value of the relevant risk metric and the uncertainty about this mean value will be underestimated. The values can be underestimated due to the effect of the SOKC directly, as well as due to incorrect screening out of cutsets in truncation due to neglect of the SOKC in calculating cutset frequencies.

This paper studies the requirements and identifies essential outputs taking into account SOKC effects on PSA results.

2. State-of-knowledge Correlation (SOKC)

Two of the fundamental premises on which probabilistic analyses are constructed are that: 1) the basic events of the logic model are random, independent variables, and 2) the mean values can be propagated through the logic models. There are at least two challenges to these premises: correlated data and common-cause failures.

The correlated data effect is a statistical effect that occurs when a pool of data is used to characterize the uncertainty distribution for all components of a certain type. Correlated data implies that the same distribution applies to all of these components when they are sampled using a Monte Carlo approach. The effect of correlated variables is a higher mean value than the point estimate value.

EPRI 1009652[1] notes that a significant number of internal events PSAs have propagated the parametric uncertainties through the model including the state-of knowledge correlation. The analyses have resulted in very small differences between the point estimate calculation and the Monte Carlo evaluation, as shown in Table I.

There are two reasons SOKC tends to be of low importance in the total risk metric calculation. First, there tends to be a large number of diverse contributors to core damage frequency (CDF). As shown empirically, the lower the participation fraction of correlated variables in the risk metric, the lower the impact of SOKC. Second, the addition of plant-specific data to the PRA results in reducing the number of correlated data variables in the model. Therefore, extensive use of plant-specific data suppresses SOKC impact by eliminating the number of correlated variables in the model.

Table I. Comparison of mean and point estimate values

Plant	Data Available	Point Estimate Core Damage Frequency	Monte Carlo Simulation of Core Damage Frequency	Ratio of Difference
LaSalle (2003A) [F-2]	Plant-specific	6.64E-6	6.88E-6	1.04
Oyster Creek (IPE)[1] [F-3]	Generic	3.69E-6	4.67E-6	1.26
NUREG-1150				
Peach Bottom[2] [F-4]	Generic	3.62E-6	4.5E-6	1.24
Zion[2] [F-5]	Generic	2.8E-4	3.4E-4	1.21
Surry[2] [F-6]	Generic	3.3E-5	4.01E-5	1.22
Sequoyah[2] [F-7]	Generic	5.31E-5	5.76E-5	1.08
Grand Gulf[2] [F-8]	Generic	2.07E-6	4.05E-6	1.95
NUREG/CR-4832				
LaSalle[2] [F-9]	Generic	3.14E-5	4.41E-5	1.40

3. Guidance on Treatment of SOKC

The ASME/ANS standard on PRA [2] requires that both parameter and model uncertainties be addressed. For example, parameter uncertainties are addressed via the quantification process of the core damage and large early release frequencies and model uncertainties also have to be identified and characterized. Regarding SOKC, the ASME/ANS standard notes as Table II.

Table II. ASME/ANS PRA Standard Supporting Requirements Related to SOKC

	Capability Category II	Capability Category III
QU-A3	ESTIMATE the mean CDF accounting for the “state-of-knowledge” correlation between event probabilities when significant.	CALCULATE the mean CDF from internal events by propagating the uncertainty distributions, ensuring that the "state-of-knowledge" correlation between event probabilities is taken into account.
QU-E3	ESTIMATE the uncertainty interval of the CDF results. ESTIMATE the uncertainty intervals associated with parameter uncertainties (DA-D3, HR-D6, HR-G8, IEC15) taking into	PROPAGATE parameter uncertainties (DAD3, HR-D6, HR-G8, IE-C15), and those model uncertainties explicitly characterized by a probability distribution using the Monte Carlo approach or other comparable means. PROPAGATE uncertainties

	account the "state-of-knowledge" correlation.	in such a way that the "state-of-knowledge" correlation between event probabilities is taken into account.

NUREG-1855 [3] provides on how to address the treatment of parameter uncertainty when using PSA results for risk-informed decision-making. NUREG-1855 addresses the characterization of parameter uncertainty; propagation of uncertainty; assessment of the significance of the state-of-knowledge correlation (SOKC); and comparison of results with acceptance criteria or guidelines.

The section 6.3 of NUREG-1855 provides the NRC position on the supporting requirements of the ASME/ANS standard related to the SOKC as follows:

Quantifying the uncertainty of the risk metric resulting from propagating the parameter uncertainty could, in the simplest approach, i.e., used in Capability Category(CC) I, take the form of an interval (e.g., a range of results within which the actual risk metric value lies). However, it is more typical to characterize the uncertainty in terms of a probability distribution on the value of the quantity of concern. For CCs II and III, the mean and the distribution for the risk metric results are usually obtained by propagating the parameter uncertainties of the PRA inputs through the analysis using the Monte Carlo or similar sampling method.

The calculation of the risk metrics and characterization of their associated parameter uncertainty is also dependent on the CC, as described below. However, regardless of the CC, it is necessary to determine if the SOKC is important in significant sequences and/or cut sets.

• <u>Capability Category I</u>

When the SOKC is unimportant in significant sequences or cut sets a point estimate is calculated for the risk metric. When addressing the uncertainty interval or probability distribution, an estimate of the uncertainty interval and its basis is sufficient.

If the SOKC is important in significant sequences or cut sets, the calculation of the risk metric and the characterization of its associated parameter uncertainty is carried out to meet CC II requirements.

• <u>Capability Category II</u>:

If the SOKC is important in significant sequences or cut sets, a mean value(This is actually an approximation of the true mean since only significant contributors in significant sequences/cutsets are included.) is calculated for the risk metric by propagating the uncertainty distributions for the significant contributors through all significant accident sequences or cut sets using the Monte Carlo approach (or other comparable means) through the PRA model, ensuring that the SOKC between event frequencies or probabilities is taken into account. The uncertainty distribution of the risk metric is calculated by propagating the uncertainty distributions of the significant contributors through all significant sequences or cut sets using the Monte Carlo or similar approach and taking the SOKC into account.

If the SOKC is not important in significant sequences or cut sets, a mean value is calculated for the risk metric using the mean values of significant contributors, and the uncertainty interval of the risk metric can be quantified taking into account the uncertainty distributions of the significant contributors to the risk metric(This is actually an approximation of the true mean since only significant contributors in significant sequences/cutsets are included and the SOKC is not taken into account.).

• <u>Capability Category III</u>:

A mean value is calculated for the risk metric by propagating the uncertainty distributions of all the input parameters (both significant and non-significant contributors) using the Monte Carlo approach (or other comparable means) through the PRA model, ensuring that the SOKC between event frequencies or probabilities is taken into account. The uncertainty distribution of the risk metrics is calculated by propagating the uncertainty distributions of all the contributors through all retained sequences or cut sets using the Monte Carlo or similar approach and taking the SOKC into account.

The sec. 6.2 of NUREG-1855 provides the NRC position on significant sequences and cut sets as follows:

The ASME/ANS PRA standard defines a significant accident sequence as the following:

" One of the set of accident sequences resulting from the analysis of a specific hazard group, defined at the functional or systematic level, that, when rank-ordered by decreasing frequency, sum to a specified percentage of the core damage frequency for that hazard group, or that individually contribute more than a specified percentage of core damage frequency…(for the referenced version of the standard) the summed percentage is 95 percent and the individual percentage is 1 percent of the applicable hazard group…For hazard groups that are analyzed using methods and assumptions that can be demonstrated to be conservative or bounding, alternative numerical criteria may be more appropriate, and, if used, should be justified."

Similarly a significant cut set is defined as the following:

" One of the set of cut sets resulting from the analysis of a specific hazard group that, when rank ordered by decreasing frequency, sum to a specified percentage of the core damage frequency (CDF) (or large early release frequency (LERF)) for that hazard group, or that individually contribute more than a specified percentage of CDF (or LERF)…(for the referenced version of the standard) the summed percentage is 95 percent and the individual percentage is 1 percent of the applicable hazard group. Cut set significance may be measured relative to overall CDF (or LERF) or relative to an individual accident sequence CDF (or LERF) of the applicable hazard group…For hazard groups that are analyzed using methods and assumptions that can be demonstrated to be conservative or bounding, alternative numerical criteria may be more appropriate, and, if used, should be justified."

Regarding the significance of SOKC, NUREG-1855 notes in the section 2.1.2 as follows:

The SOKC is important when the same data is used to quantify the individual probabilities of two or more basic events. The uncertainty associated with such basic event probabilities must be correlated to correctly propagate the parameter uncertainty through the risk calculation. Most PRA software in current use has the capability to propagate parameter uncertainty through the analysis while taking into account the SOKC to calculate the probability distribution for the results of the PRA. EPRI report 1016737 [4] provides guidance for ascertaining the importance of the SOKC.

The section 2.4 of EPRI report 1016737 provides the following guidance:

Guideline 2a: Ensure that the state of knowledge correlation is appropriately represented for all relevant events and perform a detailed Monte Carlo (or similar) calculation with enough samples to demonstrate convergence to calculate the mean. or

Guideline 2b: If the risk metric used for the application is determined by cutsets that do not involve basic events with state-of-knowledge correlations in the development of the PRA (i.e. all events within the same cutset for the dominant contributors do not involve a state-of-knowledge correlation), then use the point estimate directly.

4. Accounting for the SOKC

4.1 Minimum Requirement to Meet the Guidance

Based on ASME/ANS standard on PRA and NUREG-1855, the followings are required at a minimum. They are pre-requisists to know how to address the treatment of SOKC.

a.1) Identification of SOKC correlated sets
a.2) Identification of significant sequences or cut sets
a.3) Determination of importance of SOKC

Regardless of the CC, it is necessary to identify SOKC sets and determine if the SOKC is important in significant sequences and/or cut sets.

4.2 Expected Outputs from Uncertainty Analysis

The calculated mean value of the relevant risk metric and the uncertainty about this mean value are affected by the SOKC effects. In order to account for the SOKC effects in PSA results, the followings affected by the SOKC would be needed to quantify.

b.1) Mean value of risk metrics accounting for SOKC
b.2) Uncertainty distribution of risk metrics accounting for SOKC
b.3) Mean value of each cut set accounting for SOKC
b.4) Importance measures accounting for SOKC
b.5) Impact of the SOKC in truncated cut sets
b.6) Impact of each SOKC group on the mean value of risk metrics

4.3 Uncertainty Analysis Accounting for SOKC

Using the Monte Carlo approach, the SOKC effects on PSA results could be evaluated. To-be-developed Monte Carlo methods or other comparable means may have the capability to evaluate b.1) through b.6) prescribed in sec. 4.2.

The Monte Carlo approach developed by Choi [5] provided the capability to calculate the mean risk metrics accounting for the SOKC between basic events (including CCFs) using efficient random number generators and to meet Capability Category III of the ASME/ANS PRA standard.

5. Conclusions

This paper summarized the minimum requirements and identified the essential outputs in order to account for the SOKC effects on PSA results. To meet the ASME/ANS standard and NRC position on the treatment of the SOKC, the efficient uncertainty analysis methods is needed.

REFERENCES

[1] Guideline for the Treatment of Uncertainty in Risk-Informed Applications", EPRI 1009652, EPRI, 2004.
[2] Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, ASME/ANS RA-Sa-2009, ASME/ANS, 2009.
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[5] J. Choi, Improved Monte Carlo Method for PSA Uncertainty Analysis, KNS Spring Meeting, Gyeongju, Oct. 27-28, 2016.