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Seismic Probabilistic Risk Assessment for Nuclear Safety: Effect of the number of seismic ground motion levels (seismic bins) on risk quantification

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INTRODUCTION

Quantifying the risk associated with a nuclear facility's exposure to a seismic event enables us to assess the safety level of nuclear installations. This quantification is carried out in Probabilistic Risk Assessments (PRA), widely used in the nuclear industry, and contributes today to the various life stages of nuclear power plants: design, operation and decommissioning. The use of a model with Event Trees and Fault Trees of the studied installation is common for quantifying seismic risk, and this requires the calculation of the failure probabilities of the Basic-Events of each backup mission of the system under analysis, which are derived from the convolution product of the seismic hazard and the equipment fragilities.

These two functions are expressed as a function of the ground motion intensity level by means of a properly selected IM (Intensity Measure). The fragilities are usually log-normal functions of the IM, but as the literal expression of the seismic hazard is not known, discretization of this hazard curve is necessary, and calculations are carried out for several ground motion intensity levels (or seismic bins).

For each bin, the boolean calculations associated with the fault trees are carried out with the failure probabilities of the Basics Events associated with each bin, thus ensuring the preservation of the physics of the system described by the derived tree, and the dependencies between each equipment involved in the safety missions.

This number of seismic bins is therefore a key factor in a Seismic PSA study, since it corresponds to the number of times the risk quantification calculation will have to be carried out, which is an important numerical issue for a full-scale model of a complete installation.

This paper proposes to study the effect of the number of seismic bins on the quantification of seismic risk with a Fault Tree Analysis (FTA) on a reduced scale installation. The Cutsets list of the selected Fault Tree and its quantification are carried out using the SCRAM software, Rakhimov (2015-2018), recently updated within the framework of the Horizon 2020 European Project METIS – *Methods and tools innovation for seismic risk assessment*. Droszcz, (2023), using a BDD-based quantification. These calculations are carried out within the framework of the development of a software tool that enables an integrated approach of the successive calculation stages involved in the quantification of seismic risk of a nuclear facility (these steps are namely: a) assessment of the seismic hazard, b) calculation of fragility functions of structures and equipment, c) system analysis and quantification), and the effect of the number of seismic bins on the final risk will be compared with the effect of other model assumptions such as whether or not dependencies between basic events are taken into account, or whether or not redundancy is taken into account.

SEISMIC HAZARD CURVES

Seismic hazard curves are taken from the 2020 update of the European Seismic Hazard Model - ESHM20, Danciu L. *et al* (2021). The location considered is in Italy, at 12.38°N – 43.1°E, see Figure 1. Hazard curves are retrieved for the Peak Ground Acceleration (PGA) as Intensity Measure (IM), and for the 16 %, 50 % and 84 % percentiles. Probabilities of Exceedance (PoE) in 50 years are given in Figure 2.

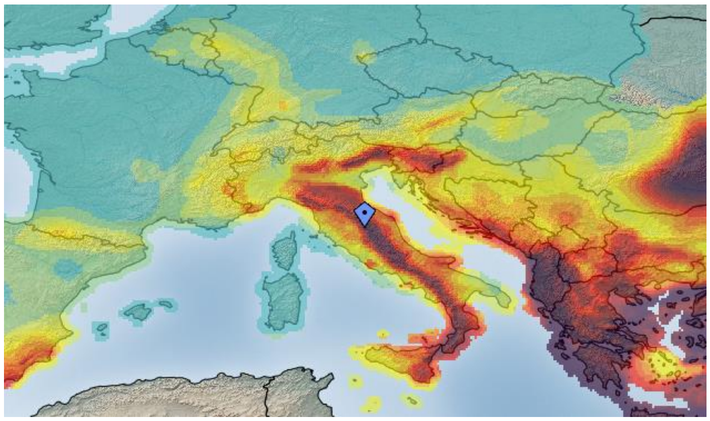


Figure 1. Hazard map from the European Seismic Hazard Model - ESHM20.

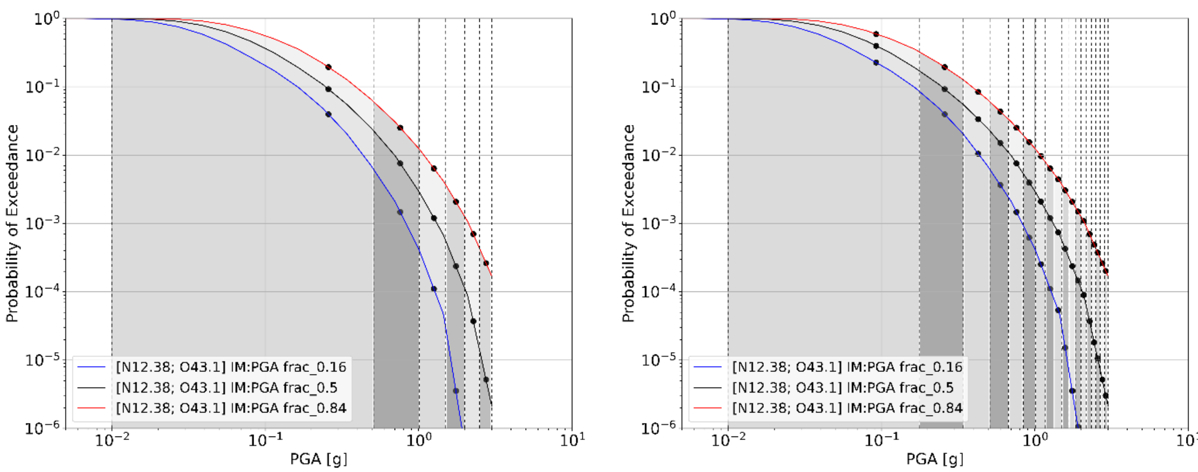


Figure 2. Hazard Curves from ESHM20, Probability of Exceedance in 50 years (Lon. 12.38, Lat.43.1, IM: PGA, percentiles 16%, 50% and 84%) split into 6 bins (left) and 18 bins (right)

LOSS OF CORE COOLING MODEL

Loss Of Core Cooling System and Fault Tree

We use a simplified fault tree to model the Loss of Core Cooling in a nuclear facility, starting from the failure of basic components such as Emergency Diesel Generators (EDG), electrical cabinets, feedwater and wellwater supply systems (with pumps and piping), and a steam generator. The Loss of Core Cooling event (top gate) is an AND-gate connecting two intermediate fault trees related to the Loss of Shutdown paths 1 and 2. This fault tree is presented in Figure 3. This configuration allows for system redundancy to be taken into account, where each parallel path provides cooling in case of failure on the other path. Each of the two paths is modeled by its own fault tree, Figures 4 and 5, each consisting of a logic OR-gate between events which are sufficient in themselves to cause the failure of the Path.

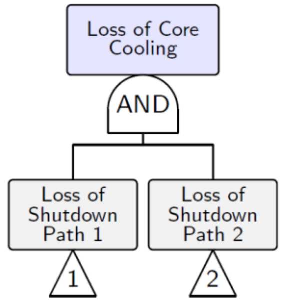


Figure 3. Fault Tree for the Loss of Core Cooling (LoCC)

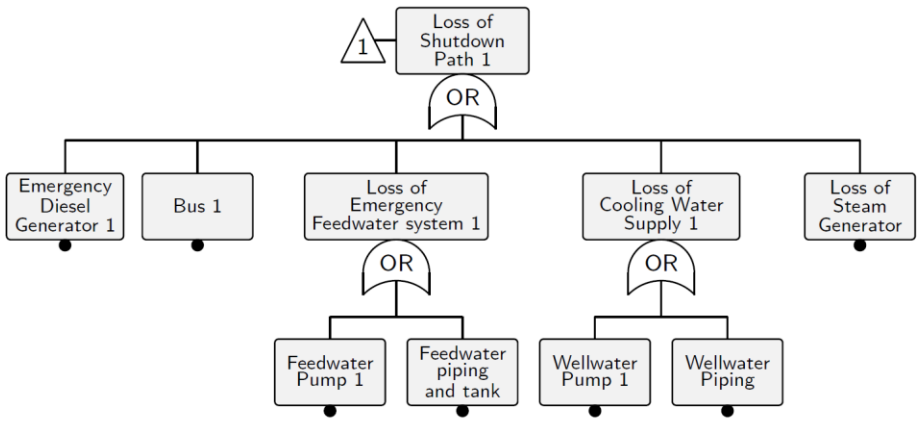


Figure 4. Fault Tree for the Loss of Shutdown Path 1

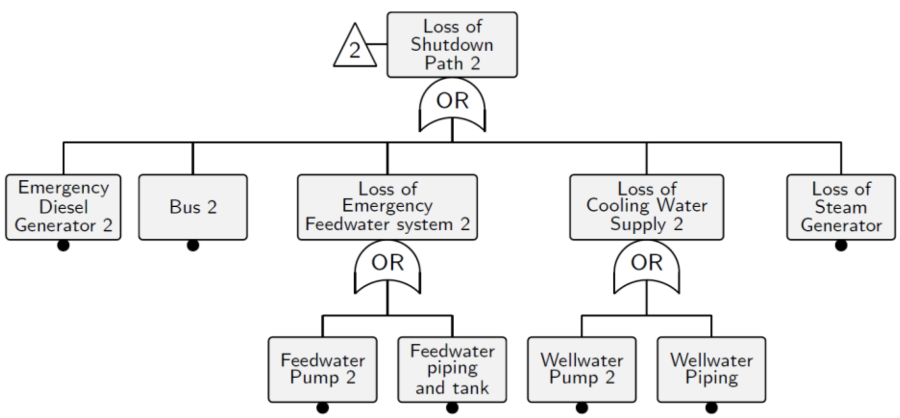


Figure 5. Fault Tree for the Loss of Shutdown Path 2

Basic events related to equipment failures numbered 1 for path number 1 and 2 for path number 2 (EDGs, buses and pumps) correspond to different equipment for the two paths, but which are of the same type. These pairs of equipment provide redundancy to the system, but can be subject to Common Cause Failures (CCF). The other basic events which are the Loss of FeedWater piping and tank, the Loss of Wellwater piping, and the Loss of the Steam Generator are unique for the whole system, therefore they are shared basic events between the two fault trees of Path 1 and 2 (same basic event).

This fault tree has been used as an academic case study in the METIS research project, Droszcz (2023) as well as by Gerontati *et al.* (2024). The tree used here has been slightly modified, particularly in terms of the probabilities of basic events.

Seismic Fragilities Of The Components

Log-normal seismic fragilities for component failures are used, the values are considered realistic, based on feedback and expert opinions.

Table 1: Seismic fragilities for the components, median capacity (PGA), randomness and uncertainty parameters

Basic Events	**Median Capacity A_m [g]**	**Randomness parameter β_R**	**Uncertainty parameter β_U**
Emergency diesel generators 1 and 2	1.72	0.25	0.31
Buses 1 and 2	1.04	0.25	0.31
Feed water pumps 1 and 2	1.30	0.18	0.33
Feed piping and tank	1.39	0.18	0.33
Well water pumps 1 and 2	1.42	0.24	0.38
Well water piping	1.40	0.22	0.36
Steam generator	2.00	0.24	0.38

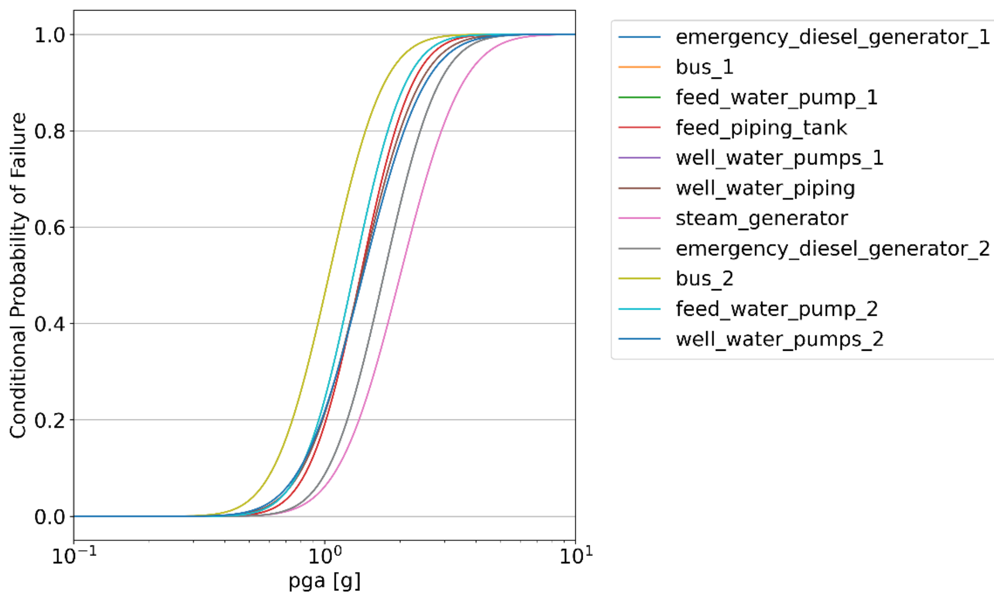


Figure 6. Seismic fragilities for the components of the considered fault trees

Common Cause Failures (CCF)

Quantification is performed with and without taking into account Common Cause Failure dependencies for the Well water pump, Feedwater pumps and for the Emergency Diesel Generators. CCF parameter model retained is the alpha-factor model. The numerical parameters of the alpha-factor model for the three CCG groups of two components are taken from document *CCF Parameters Estimation*, NRC (2022), and are provided in Tables 2 to 4 hereafter.

Table 2: Alpha factors for a group of $N = 2$ Emergency Diesel Generator

Apha factor	**N=2**
α_1	9.92e-1
α_2	8.28e-3

Table 3: Alpha factors for a group of $N = 2$ Feedwater Pumps

Apha factor	**N=2**
α_1	9.63e-1
α_2	3.65e-2

Table 4: Alpha factors for a group of $N = 2$ Well water Pumps

Apha factor	**N=2**
α_1	9.90e-1
α_2	9.57e-3

PROBABILITY CALCULATIONS

SCRAM PSA Tool

In this study, we propose using the PSA tool SCRAM, which was initialized by Rakhimov (2015-2018), and was recently updated within the framework of the Horizon 2020 European Project METIS – *Methods and tools innovations for seismic risk assessment*. Droszcz (2023) provides all necessary guidelines for installation and use of SCRAM.

SCRAM is a command-line risk analysis tool that facilitates event tree analysis, static fault tree analysis, analysis with common cause failure models, probability calculations with significance analysis, and uncertainty analysis through Monte Carlo simulations. SCRAM is open-source and supports the Open-PSA model exchange format (OPSAMEF). OPSAMEF is a format promoted by the Open PSA Initiative, Epstein (2009), it is an XML format, Bray *et al*. (1998), which allows to define a clear and open representation of the PSA models.

Exact Probability Calculation: BDD

The exact failure probability is calculated with Binary Decision Diagram (BDD) based algorithms that are implemented in SCRAM.

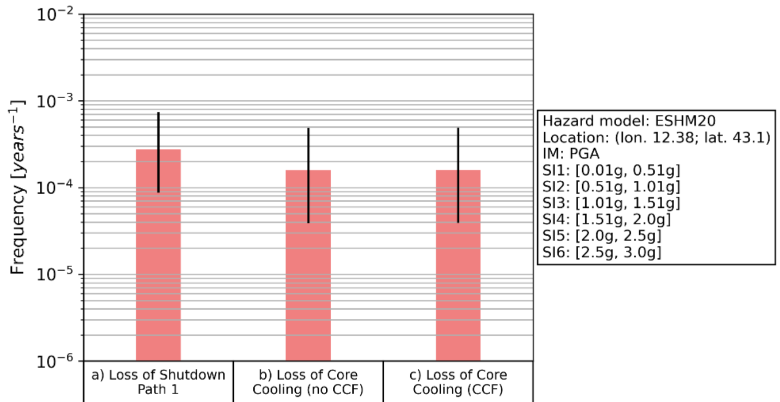
Studied Configurations

The risk quantification is performed for three model configurations: a) for Path 1 only (quantification of the Loss of Shutdown Path 1 top gate), i.e. without taking into account the redundancy provided by paralleling the two paths, b) for the complete Loss of Core Cooling model with both Paths, i.e. with redundancy (quantification of the Loss of Core Cooling top gate) but without taking into account the CCF dependencies, and c) for this same complete model with redundancy and also with consideration of the CCF dependencies. Calculations are carried out for the three percentiles of the hazard curves, 16%, 50% and 84%. Finally, the calculations are carried out for an increasing number of bins ranging from 4 to 20 with a step of 2.

For each bin, the boolean calculations associated with the fault trees are carried out with the failure probabilities of the Basics Events associated with each bin, thus ensuring the preservation of the physics of the system described by the fault trees, and the dependencies between each equipment involved in the safety missions. This implies that the quantification step is performed as many times as there are bins, with basic event failure probabilities and seismic initiator frequencies updated for each bin, corresponding to the IM value of the considered bin.

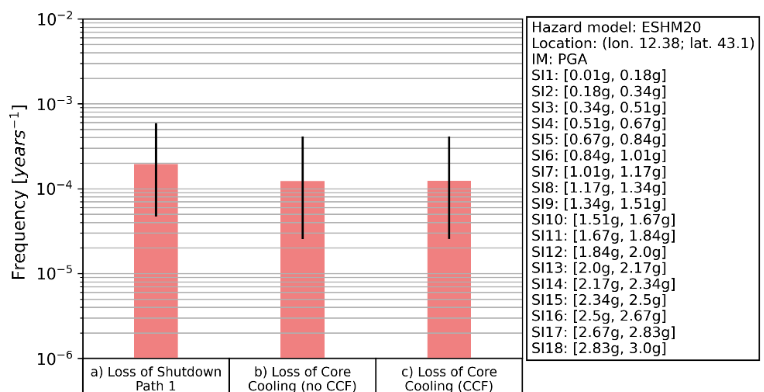
RESULTS

For the three studied model configurations and the three hazard percentiles, annual failure frequencies are given in Figure 5 using 6 bins, and in Figure 6 using 18 bins.



	a) Loss of Shutdown Path 1	b) Loss of Core Cooling (no CCF)	c) Loss of Core Cooling (CCF)
risk (fract.84%)	7.402e-04	4.868e-04	4.893e-04
risk (fract.50%)	2.748e-04	1.578e-04	1.590e-04
risk (fract.16%)	8.692e-05	3.889e-05	3.933e-05

Figure 5. Annual Failure Frequency for model a) Loss of Shutdown Path 1 only, model b) Loss of Core cooling Path 1 and Path 2 without CCFs and c) with CCFs, for the 16%, 50% and 84% percentiles of the seismic hazard, for 6 seismic bins.



	a) Loss of Shutdown Path 1	b) Loss of Core Cooling (no CCF)	c) Loss of Core Cooling (CCF)
risk (fract.84%)	5.897e-04	4.130e-04	4.147e-04
risk (fract.50%)	1.937e-04	1.228e-04	1.235e-04
risk (fract.16%)	4.696e-05	2.534e-05	2.558e-05

Figure 6. Annual Failure Frequency for model a) Loss of Shutdown Path 1 only, model b) Loss of Core cooling Path 1 and Path 2 without CCFs and c) with CCFs, for the 16%, 50% and 84% percentiles of the seismic hazard, for 18 seismic bins.

In both cases, taking into account redundancy by considering the paralleling of the two paths (quantification of model a) Loss of Shutdown Path 1 versus model b) Loss of Core Cooling no CCFs) leads to a significant reduction in risk. This decrease is from 1.94e-4 yrs^{-1} to 1.22e-4 yrs^{-1} considering the median percentile and 18 bins. The effect of taking CCFs into account (passing from model b) to model c)) is to increase the annual frequency, but to a much lesser extent compared to the effect of redundancy. In the case of 18 bins, taking into account the CCFs increases the frequency from 1.228e-5 to 1.235e-5 yrs^{-1} (for the median percentile). The variability introduced by taking into account the 16% and 84% percentiles of the hazard curves is much more significant than that introduced by considering redundancy, and even more so compared to that introduced by considering the CCFs.

For the three model configurations, for the median hazard curves, frequencies obtained using a number of bins between 4 and 20 are plotted in Figure 7.

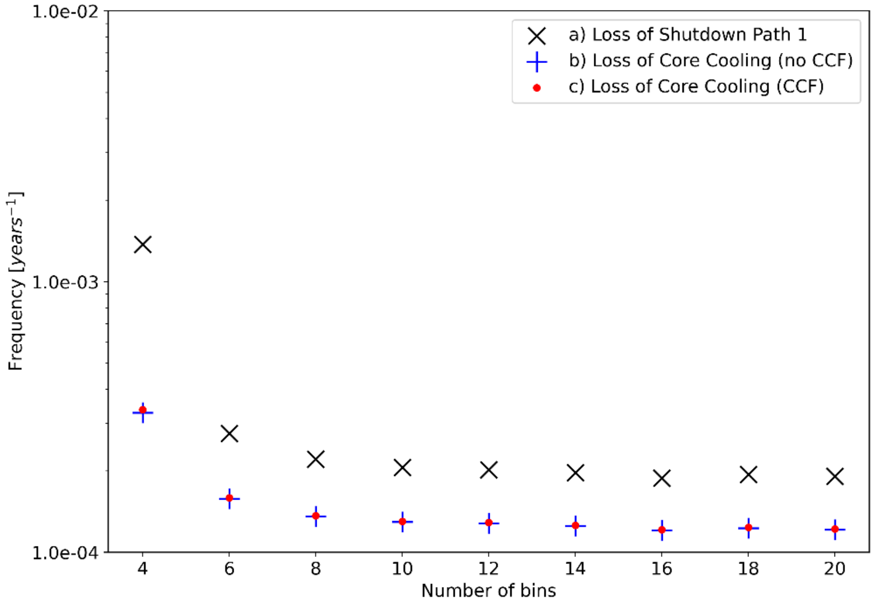


Figure 7. Frequency for model a) Loss of Shutdown Path 1 only, model b) Loss of Core Cooling Path 1 and Path 2 without CCFs and c) with CCFs, for the median hazard curve, for a number of seismic bins between 4 and 20.

The same conclusions regarding the effect of accounting for redundancy and CCFs can be observed regardless of the number of bins considered. The annual failure frequency exhibits a marked decrease as the number of bins increases from 4 to 6, and tends to stabilize from 10 bins onwards.

CONCLUSION

This study investigates the sensitivity of seismic risk quantification for a facility using a fault tree analysis framework, with particular emphasis on the influence of the number of seismic intensity bins. The analysis is conducted on a representative model of a nuclear system, under various configurations accounting for, or neglecting, system redundancy introduced through parallel arrangements, as well as the presence or absence of common cause failure (CCF) dependencies. The results indicate that using an insufficient number of bins can lead to an inaccurate prediction of seismic risk. Moreover, we cannot generally prove that the error committed when using a limited number of bins is on the safe side. So, it should always be recommended to increase the number of seismic bins until the calculation of risk is stabilized.

This study is part of the development of a computational toolchain aimed at assessing the seismic risk of a facility using fault tree analysis, based on seismic hazard curves and the seismic fragility of the facility's components. This tool enables sensitivity analyses on the various parameters and assumptions inherent to the seismic risk assessment methodology, including seismic hazard characterization, equipment fragility models, the fault tree structure, and the algorithms used to compute the probability of the undesired event.

ACKNOWLEDGEMENTS

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REFERENCES

Bray, T., Paoli, J., Sperberg-McQueen, M., Maler, E., Yergeau, F. (1998). Extensible markup language (xml). World Wide Web Consortium Recommendation.

Danciu L., Nandan S., Reyes C., Basili R., Weatherill G., Beauval C., Rovida A., Vilanova S., Sesetyan K., Bard P-Y., Cotton F., Wiemer S., Giardini D. (2021). *The 2020 update of the European Seismic Hazard Model: Model Overview, https://doi.org/10.12686/a15, EFEHR Technical Report 001.*

Droszcz C. (2023). *Seismic PSA Tool for the risk quantification – SCRAM – Andromeda*. Horizon 2020 project METIS – Seismic Risk Assessment for Nuclear Safety, Deliverable D7.3.

Epstein, S., Rauzy, A., Reinhart, FM. (2009). *The Open PSA initiative for next generation probabilistic safety assessment*. *Kerntechnik.*

Gerontati A., Karaferis N., Šipčić N., Vamvatsikos D., Bazzurro P., Droszcz C., (2024). *A minimalistic computational testbed for evaluating fragility assessment, record selection, and intensity measure optimality for nuclear powerplants*.

Rakhimov O (2015-2018). *SCRAM - Command-line Risk Analysis Multi-tool*. https://github.com/SCRAM-NG/scram, cloned from https://github.com/rakhimov/scram (accessed Oct. 19, 2024).

NRC (2022). *CCF Parameter Estimations, 2020 Update, Revision 1*. https://nrcoe.inl.gov/publicdocs/CCF/ccfparamest2020rev1.pdf, August 2022.