Research & Innovation Action

NFRP-2019-2020

Benchmark of PSA models

Version N°1

Authors:

Gumenyuk Dmytro

Ponochovnyi Oleg

Oleksandr Sevbo

Sylvain Boulley

Disclaimer

Document Information

Grant agreement	945121
Project title	Methods and Tools Innovations for Seismic Risk Assessment
Project acronym	METIS
Project coordinator	Dr. Irmela Zentner, EDF
Project duration	1st September 2020 – 31st May 2025
Related work package	WP 7
Related task(s)	Tasks 7.4.1 and 7.4.2
Lead organisation	SSTC NRS (7.4.1), IRSN (7.4.2)
Contributing partner(s)	SSTC NRS, Energorisk
Due date	
Submission date	
Dissemination level	Public

History

Version	Submitted by	Reviewed by	Date	Comments
N°1	O.Ponochovnyi	Charles Droszcz (GDS)	18.12.2024	

Table of Contents

Introduction 7

1. Benchmark scenarios 9

  1.1. Considered design 9

  1.2. Seismic inputs 10

    1.2.1. Scenario 1 (without GRID) 10

    1.2.2. Second scenario (with GRID) 12

2. PSA modelling 15

  2.1. METIS tool model 15

    2.1.1. Event tree 15

    2.1.2. Fault trees 15

  2.2. SAPHIRE model 17

    2.2.1. Event tree 17

    2.2.2. Fault trees 17

  2.3. RiskSpectrum PSA model 21

    2.3.1. Event tree 21

    2.3.2. Fault trees 21

3. Results 23

4. Conclusions 25

5. References 27

Abbreviations and Acronyms

Acronym	Description
CDF	Core Damage Frequency
DG	Diesel Generator
EFWS	Emergency FeedWater System
HCLPF	High Confidence of Low Probability of Failure
MFW	Main Feed Water
NPP	Nuclear Power Plant
PGA	Peak Ground Acceleration
PSA	Probabilistic Safety Analysis
SG	Steam Generator
SSC	System Structure and Components
WP	Work Package
WWP	Well Water Pump

Summary

One of the goals of the METIS project is to further develop and improve tools and methodologies employed in seismic safety assessments of nuclear reactors. METIS particularly aims at providing a new calculation framework for seismic PSA, based on SCRAM code for Boolean computations, on ANDROMEDA software for fault trees and event trees definition and User interface, and on a tool developed in the frame of METIS project for managing and generating seismic data (METIS Seismic database from WP 7.2).

A test case of a NPP seismic PSA was defined in WP3 and is to be performed in the framework of WP7 in order to demonstrate the interest in the improved PSA tools and methodologies developed in the METIS project.

This document presents the results of the representative benchmark of models related to Seismic PSA level 1 and results of benchmark calculations using the METIS tool, SAPHIRE and Risk Spectrum codes.

The results of the benchmark calculations will be a basis for further development of the METIS tool improvement and modelling.

Keywords

Codes, methodologies, software, PSA, benchmark

Introduction

One of the goals of the METIS project is to further develop and improve tools and methodologies employed in seismic safety assessments of nuclear reactors. METIS particularly aims at providing a new calculation framework for seismic PSA, based on SCRAM code for Boolean computations, on ANDROMEDA software for fault trees and event trees definition and User interface, and on a tool developed in the frame of METIS project for managing and generating seismic data (METIS Seismic database from WP 7.2).

A test case of a NPP seismic PSA was defined in WP3 and is to be performed in the framework of WP7 in order to demonstrate the interest in the improved PSA tools and methodologies developed in the METIS project.

The goal of METIS Tasks 7.4.1 and 7.4.2 is to perform representative benchmark calculations for the METIS tool developed in frame of Task 7.3.1, using proven PSA commercial codes. The scope of activity includes:

- Selection of representative hazard scenario(s);
- Model testing and benchmark calculations using the METIS tool vs commercial PSA tools.
- Development of recommendations for improvement of the METIS tool, based on benchmark results and test calculations.

Under Subtask 7.4.1 and 7.4.2 the SAPHIRE and RiskSpectrum PSA benchmark calculations for ANDROMEDA software were conducted. The benchmark calculations were conducted for the example taken from the 25 February 2022 METIS workshop and presented by P. Renault from Swissnuclear [1].

This study has been performed using the following codes and software:

- SAPHIRE version 8.1.8, ;
- RiskSpectrum PSA version 1.4.0;
- Coupled Andromeda-SCRAM tool version 2.8 (further METIS tool);
- METIS Seismic database from Work Package 7.2, which enables:
  - introduction, for all SSCs, of the seismic data/parameters used as inputs to the computation of SSCs failure probability, and their tracking;
  - automatic computation of SSC seismic failure probabilities from such inputs.

Section 1 provides review of the benchmark scenarios (presents a simplified system that has been modelled, the seismic data used as inputs, and SSC failure probability).

Section 2 presents PSA modelling using the SAPHIRE and RiskSpectrum PSA tools.

Sections 3 and 4 contain the results of the test cases, recommendations, conclusions and acknowledgments.

Section 5 includes a list of references.

1. Benchmark scenarios

The benchmark calculations were conducted for two scenarios based on the example from the 25 February 2022 METIS workshop presented by P. Renault from Swissnuclear [1].

The main differences of these scenarios (benchmark cases) are in different seismic input data and component fragility data. As additional difference of the scenarios is the consideration of national grid power. First scenario is based on seismic data and fragilities from [1] and does not take into account the national grid supply (see 1.2.1). Second scenario is based on different seismic data and fragilities, which are realistic but correspond neither to real hazard nor to real building and equipment, and takes into account the power supply from the national grid (see 1.2.2).

Selection of these scenarios was made in order to investigate the impact of the different seismic input data used on the benchmark results and to obtain validation results for a wider range of seismic impacts.

1.1. Considered design

The considered design is a building which contains a steam generator emergency feedwater system (EFWS) with its electrical equipment, see Figure 1~~Figure 1~~.

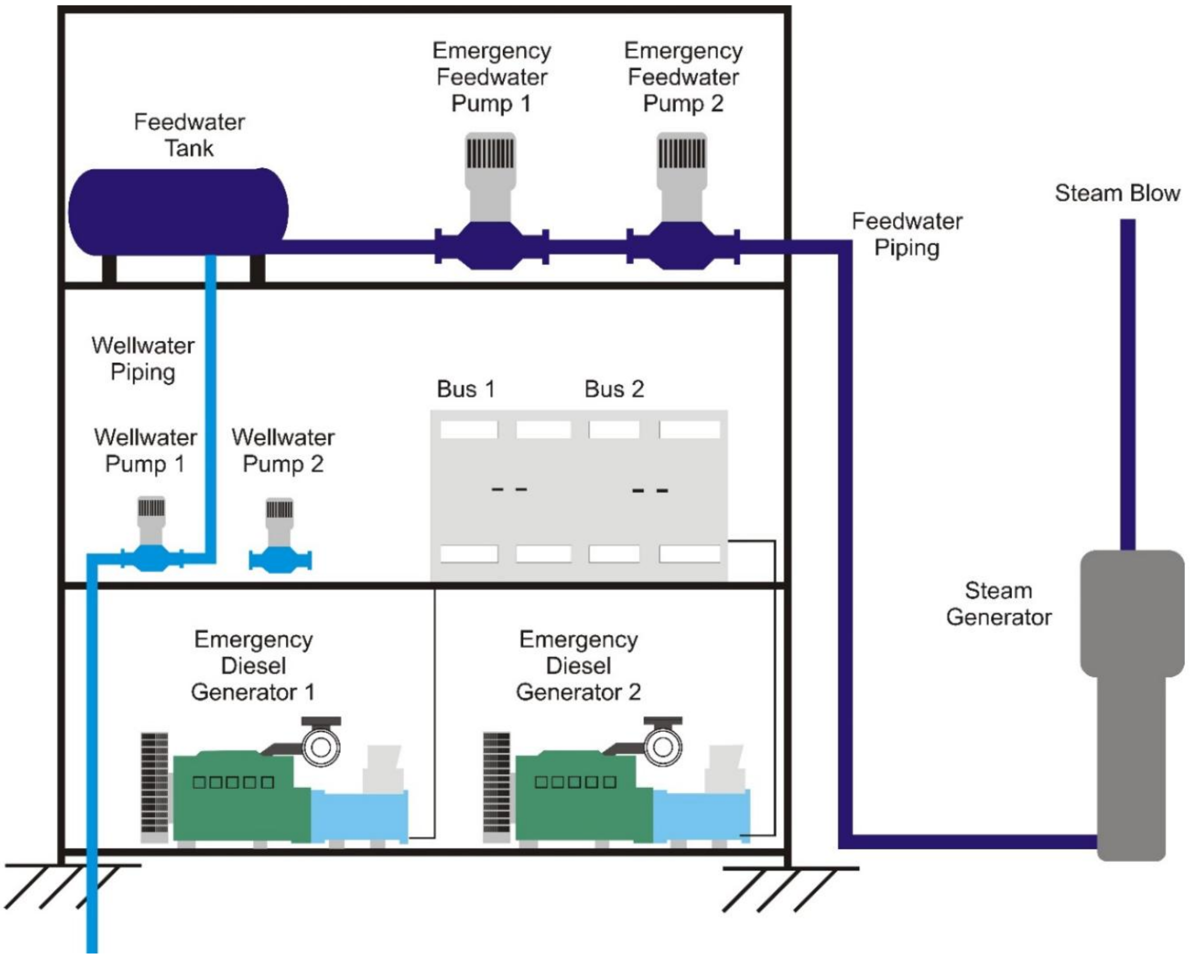


Figure 1 Supposeddesign for benchmark study

The steam generator can be fed by 2 x 100% redundant trains P1 and P2. Core cooling is lost if both trains fail. Each train contains an emergency feedwater pump (named EFWP1 respectively EFWP2) powered through a busbar (named B1 respectively B2) by an emergency diesel generator (named DG1 respectively DG2) or by the national grid (GRID). Water is fed to each feedwater pump by a wellwater pump (named WWP1 respectively WWP2) through a feedwater tank.

Seismically induced failures of the feedwater tank, the piping and the building itself are considered negligible compared to the failure of the other components and are not taken into account in this short study. The components that are considered in the study are:

- Emergency feedwater pumps;
- Wellwater pumps;
- Busbars;
- Emergency diesel generators;
- Steam generator;
- The national grid (this component was considered only in scenario 2).

In order to have a simple example, it is supposed that any earthquake induces a reactor scram and the start-up of the SG emergency feedwater pumps with a probability of 1, though this is not realistic for low Peak Ground Acceleration(PGA) earthquakes (see 2.1.1).

1.2. Seismic inputs

1.2.1. Scenario 1 (without GRID)

1.2.1.1. Hazard curve

The following hazard curve is assumed in our example:

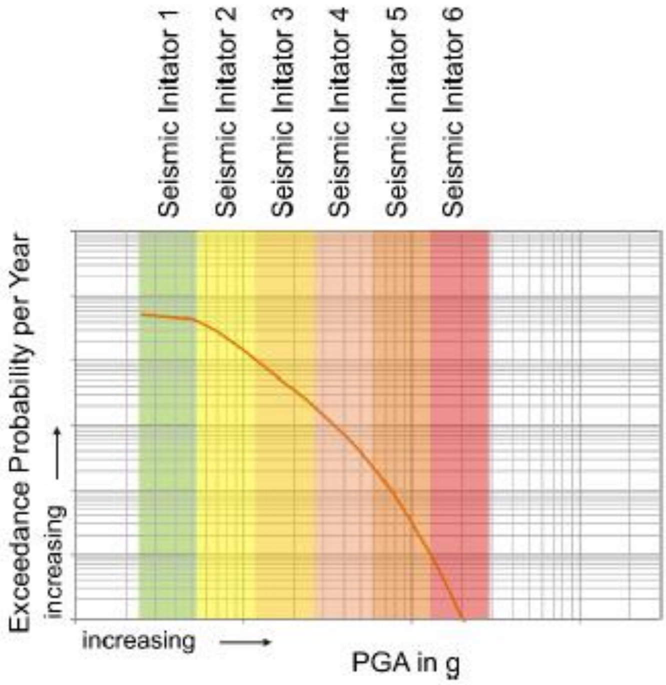


Figure 2 Hazard curve

Table 1 Definition of hazard curve

Row	Seismic Initiating Event	1	2	3	4	5	6
1	Probability	8.11E-03	1.45E-03	3.40E-04	7.86E-05	1.55E-05	3.55E-06
2	PGA in g	0.03-0.1	0.1-0.2	0.2-0.35	0.35-0.55	0.55-0.75	0.75-0.9

1.2.1.2. Components' fragility curves

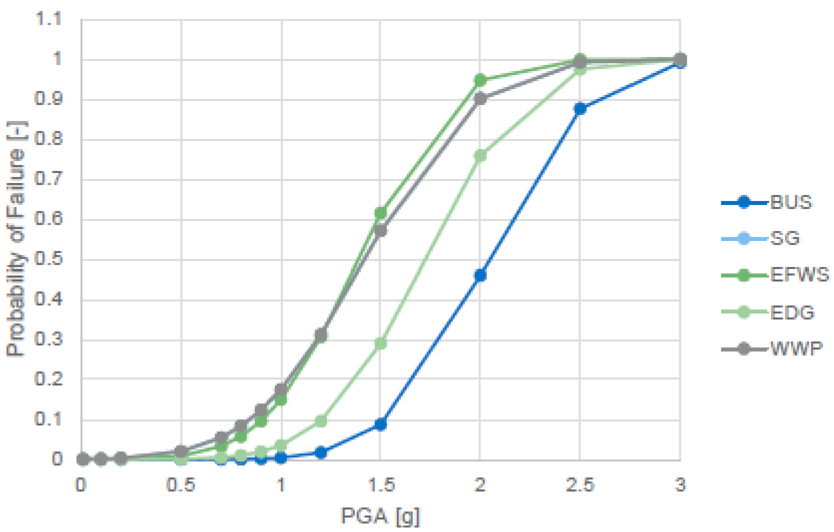


Figure 3 Component fragilities

Table 2 Definition of fragility curve parameters

Row	Components	PGA Median Capacity Am [g]	Randomness Parameter, β_R	Uncertainty Parameter, β_U	PGA HCLPF [g]
1	Bus	2.04	0.25	0.31	0.81
2	Steam Generator	1.42	0.24	0.38	0.51
3	Emergency Feed Water	1.39	0.18	0.33	0.6
4	Emergency Diesel Generator	1.72	0.25	0.31	0.68
5	Well water Pumps	1.42	0.24	0.38	0.51

1.2.1.3. SSCs failure probability computation

For the presented test case, a median probability of seismic failure for each of the SSCs described in 1.1 has been computed for each PGA interval of the hazard curve described in 1.2.1.1, using a value of 0.5 for the confidence interval Q. The results are gathered in Table 3.

Table 3 Failure probability

Row	Components	1	2	3	4	5	6
A	Bus	0	0	0	0	3.3E-3	3.3E-2
B	Steam Generator	0	0	0	0	0	7.4E-3
C	Emergency Feed Water	0	0	0	0	1.7E-2	7.7E-2
D	Emergency Diesel Generator	0	0	0	1.5E-3	3.8E-2	1.1E-1
E	Well water Pumps	0	0	0	1.5E-3	3.8E-2	1.1E-1

1.2.2. Second scenario (with GRID)

1.2.2.1. Hazard curve

The following hazard curve is assumed in our example:

Table 4 Definition of hazard curve

PGA (g)	0	0,16	0,27	0,4	0,5	0,67	0,83	1,03	1,44	2

Exceedance frequency (/year)	1	1.00E-04	1.00E-05	5.30E-06	3.22E-06	1.84E-06	9.85E-07	4.83E-07	2.16E-07	1.23E-07

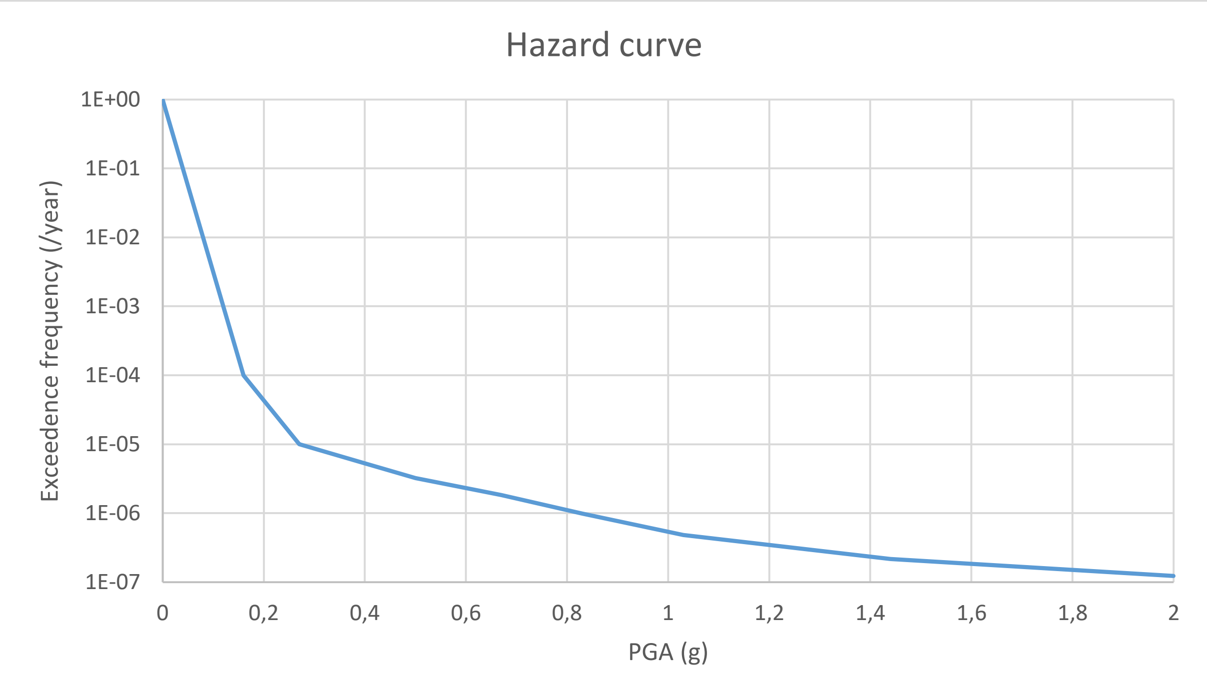


Figure 4 Hazard curve

1.2.2.2. Components' fragility curves

The probability of seismic failure of a component subject to ground motion a' is defined [3] as

$$P'_f(a') = \Phi\left(\frac{\ln(a'/A_m) + \beta_U \Phi^{-1}(Q)}{\beta_R}\right),$$

with Phi the standard Gaussian cumulative distribution function, Am the SSC median capacity and Q a confidence level.

Table 5 Definition of fragility curve parameters

Row	Components	PGA Median Capacity Am [g]	Randomness Parameter, β_R	Uncertainty Parameter, β_U	PGA HCLPF [g]
1	Busbars	0.53	0.17	0.44	-
2	Steam Generator	0.46	0.24	0.26	0.2

3	Emergency Feed Water pumps	0.55	0.17	0.44	
4	Emergency Diesel Generators	0.68	0.24	0.32	0.27
5	Well water Pumps	0.69	0.17	0.44	-
6	Grid	0.23	0.24	0.26	0.1

HCLPF is needed only when the component fragility is assessed based on the simplified fragility method described in [2]. It is not defined for the components whose fragility is defined based on the EPRI approach for tested components described in [2].

1.2.2.3. SSCs failure probability computation

To compute the probability of seismic failure, for all the SSCs described in 1.1, using the equation of 1.2.2.2, the METIS Seismic database delivered by IRSN in the framework of WP7.2 has been used, see [4].

For the presented test case, a median probability of seismic failure for each of the SSCs described in 1.1 has been computed for each PGA interval of the hazard curve described in 1.2.2.1, using a value of 0.5 for the confidence interval Q. The results are gathered in Table 6.

Table 6 Median probability of seismic failure depending on PGA

PGA	Busbar	Diesel Gen.	EFWP	GRID	WWP	SG
0,16	3.55E-12	8.19E-10	8.47E-13	6.95E-02	5.55E-17	6.29E-06
0,27	5.56E-05	5.91E-05	2.39E-05	7.58E-01	4.60E-08	1.44E-02
0,40	5.29E-02	1.35E-02	3.44E-02	9.90E-01	9.84E-04	2.91E-01
0,50	3.66E-01	9.98E-02	2.93E-01	9.99E-01	3.44E-02	6.48E-01
0,67	9.08E-01	4.75E-01	8.71E-01	1.00E+00	4.42E-01	9.45E-01
0,83	9.95E-01	7.96E-01	9.91E-01	1.00E+00	8.59E-01	9.94E-01
1,03	1.00E+00	9.58E-01	1.00E+00	1.00E+00	9.90E-01	1.00E+00
1,44	1.00E+00	9.99E-01	1.00E+00	1.00E+00	1.00E+00	1.00E+00
2,00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

The METIS Seismic database may also be used to perform Monte-Carlo sampling of the ground acceleration (PGA) inside those PGA intervals and of the confidence interval value Q. This feature has not been used in the present study.

2. PSA modelling

2.1. METIS tool model

2.1.1. Event tree

The probability of core damage after a seismic event due to a failure of the core cooling by the emergency feedwater has been modelled using Andromeda as the following event tree (Figure 5~~Figure 5~~).

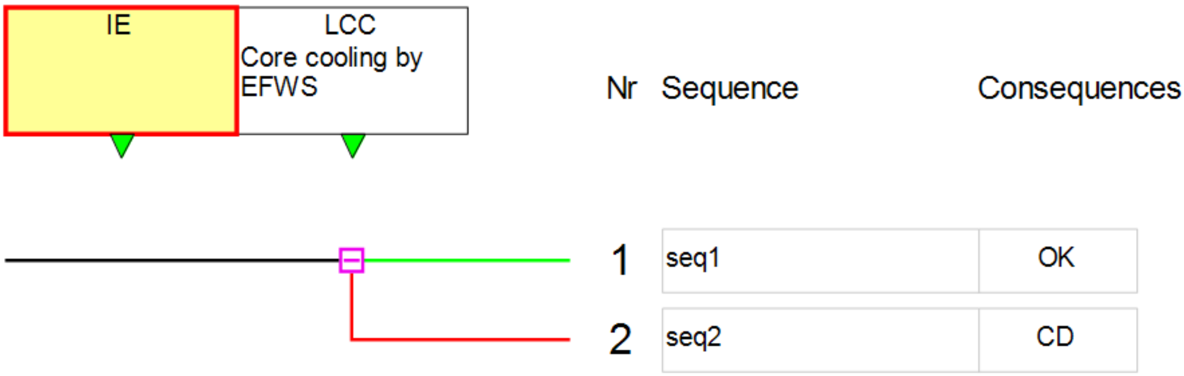


Figure 5 Event tree at Andromeda

In this very simple event tree, it is supposed that the seismic event, whatever its PGA, induces a reactor trip and a switch from the main feedwater to the emergency feedwater with a probability of one. Such a modelling is of course a conservative simplification since low-PGA seismic events would not trigger any reactor trip or loss of the MFW and would therefore not require the successful operation of the EFW for preventing core damage. In a more realistic seismic PSA study, one would have to introduce a probability for each level of PGA of the seismic event to trigger a reactor trip and a switch from the MFW to the EFW.

2.1.2. Fault trees

Loss of cooling has been modelled in Andromeda as presented Figure 6~~Figure 6~~. Basic event's failure probabilities are indicted for PGA 0,27g.

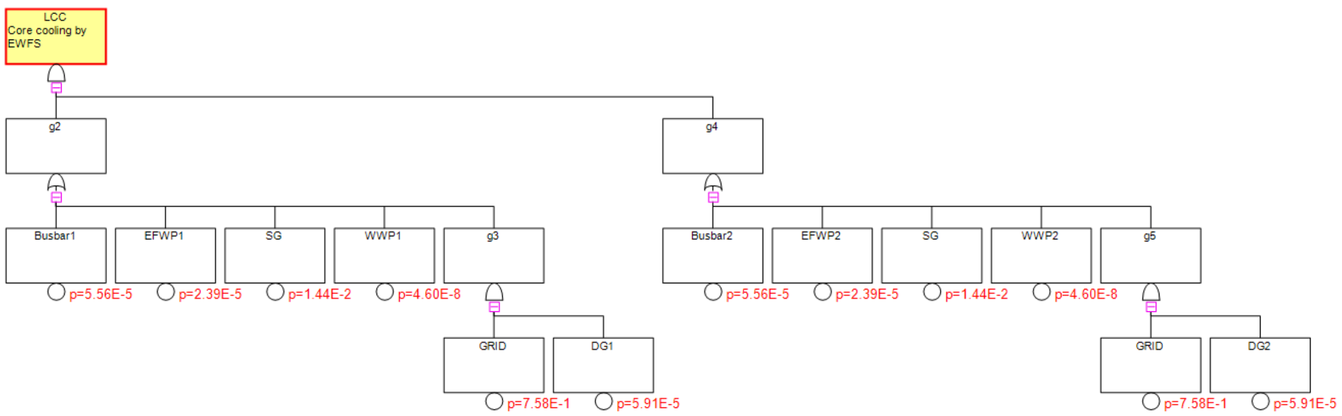


Figure 6 Master tree at Andromeda

The minimal cutsets are:

SG + WWP1*WWP2 + EFWP1*WWP2 + EFWP2*WWP1 + EFWP1 * EFWP2 + B2*WWP1 + B1*WWP2 + EFWP1 * B2 + B1 * EFWP2 + B1 * B2 + DG2*WWP1*GRID + DG1*WWP2*GRID + EFWP1 * DG2 * GRID + DG1 * EFWP2 * GRID + DG1 * DG2 * GRID + B1 * DG2 * GRID + DG1 * B2 * GRID

With SG=steam generator; WWP=Wellwater pump; EFWP=Emergency feedwater pump; B=busbar; DG=Diesel generator

The minimal cutsets of test case are illustrated in table below (for the first interval of PGA) and in Figure 7~~Figure 7~~ (for PGA 0,27g).

Table 7 Minimal cutsets for PGA 0,16 gNo	P	Contribution (%)	Event 1	Event 2	Event 3	Event 4
1	1.21E-03	74,4	SG	SE		
2	1.33E-04	8,2	WWP1	WWP2	SE	
3	9.32E-05	5,7	EFWP1	WWP2	SE	
4	9.32E-05	5,7	EFWP2	WWP1	SE	
5	6.52E-05	4	EFWP1	EFWP2	SE	
6	8.95E-06	0,6	B1	WWP2	SE	
7	8.95E-06	0,6	B2	WWP1	SE	
8	6.27E-06	0,4	B1	EFWP2	SE	
9	6.27E-06	0,4	B2	EFWP1	SE	
10	6.024E-07	0	B1	B2	SE	
11	3.993E-07	0	DG1	WWP2	GRID	SE
12	3.993E-07	0	DG2	WWP1	GRID	SE
13	2.795E-07	0	DG1	EFWP2	GRID	SE
14	2.795E-07	0	DG2	EFWP1	GRID	SE
15	1.198E-07	0	DG1	DG2	GRID	SE
16	2.686E-08	0	DG1	B2	GRID	SE
17	2.686E-08	0	DG2	B1	GRID	SE

PSA Result
Cutsets
Cutsets(17) | Importance Factors(11) | Overview

Rank	P	Contribution (%)	Order	Event 1	Event 2	Event 3	Event 4
1	1.440e-07	100.0	2	IE	SG		
2	3.091e-14	0.0	3	IE	Busbar1	Busbar2	
3	2.648e-14	0.0	4	IE	DG1	DG2	GRID
4	2.491e-14	0.0	4	IE	Busbar2	DG1	GRID
5	2.491e-14	0.0	4	IE	Busbar1	DG2	GRID
6	1.329e-14	0.0	3	IE	Busbar1	EFWP2	
7	1.329e-14	0.0	3	IE	Busbar2	EFWP1	
8	1.071e-14	0.0	4	IE	DG1	EFWP2	GRID
9	1.071e-14	0.0	4	IE	DG2	EFWP1	GRID
10	5.712e-15	0.0	3	IE	EFWP1	EFWP2	
11	2.558e-17	0.0	3	IE	Busbar1	WWP2	
12	2.558e-17	0.0	3	IE	Busbar2	WWP1	
13	2.061e-17	0.0	4	IE	DG1	GRID	WWP2
14	2.061e-17	0.0	4	IE	DG2	GRID	WWP1
15	1.099e-17	0.0	3	IE	EFWP1	WWP2	
16	1.099e-17	0.0	3	IE	EFWP2	WWP1	
17	2.116e-20	0.0	3	IE	WWP1	WWP2	

Figure 7 MCS representation at Andromeda format

2.2. SAPHIRE model

2.2.1. Event tree

The probability of core damage after a seismic event due to a failure of the core cooling by the emergency feedwater has been modelled using SAPHIRE as the following event tree (for both scenarios).

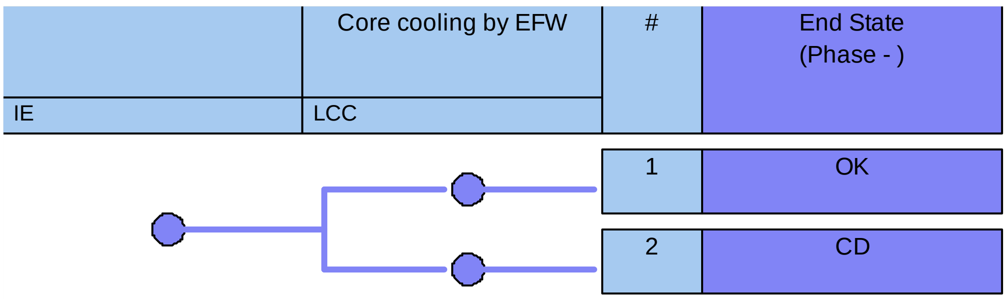


Figure 8 Event tree at SAPHIRE

2.2.2. Fault trees

Loss of cooling has been modelled in SAPHIRE as the following fault trees.

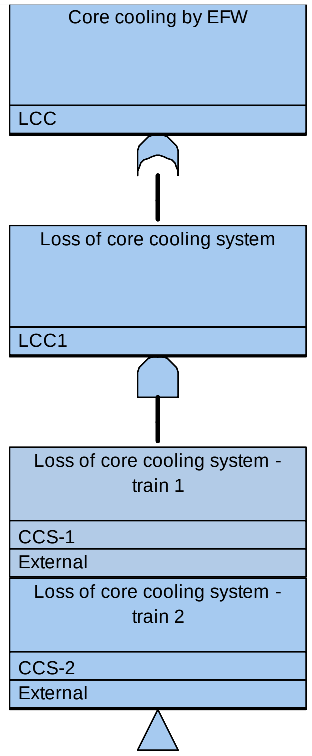


Figure 9 Loss of core cooling system

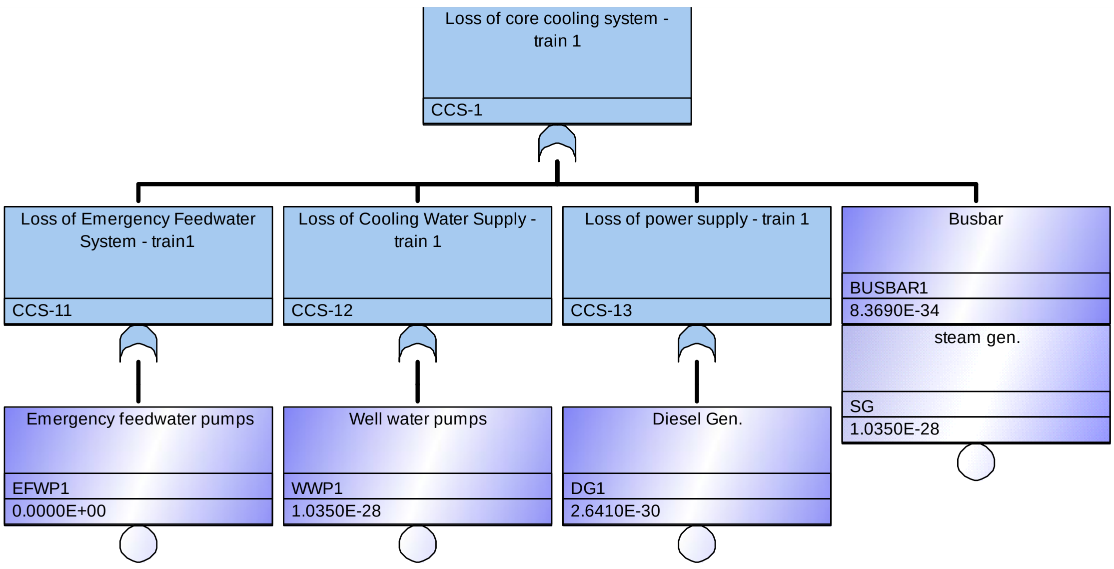


Figure 10 Loss of train 1 for scenario 1 (without GRID)

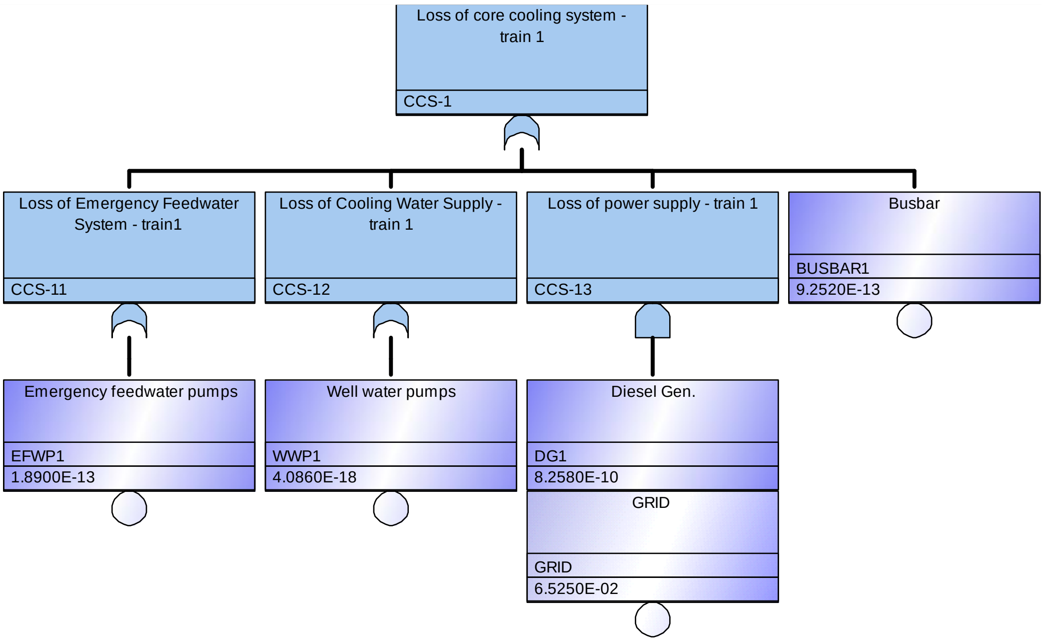
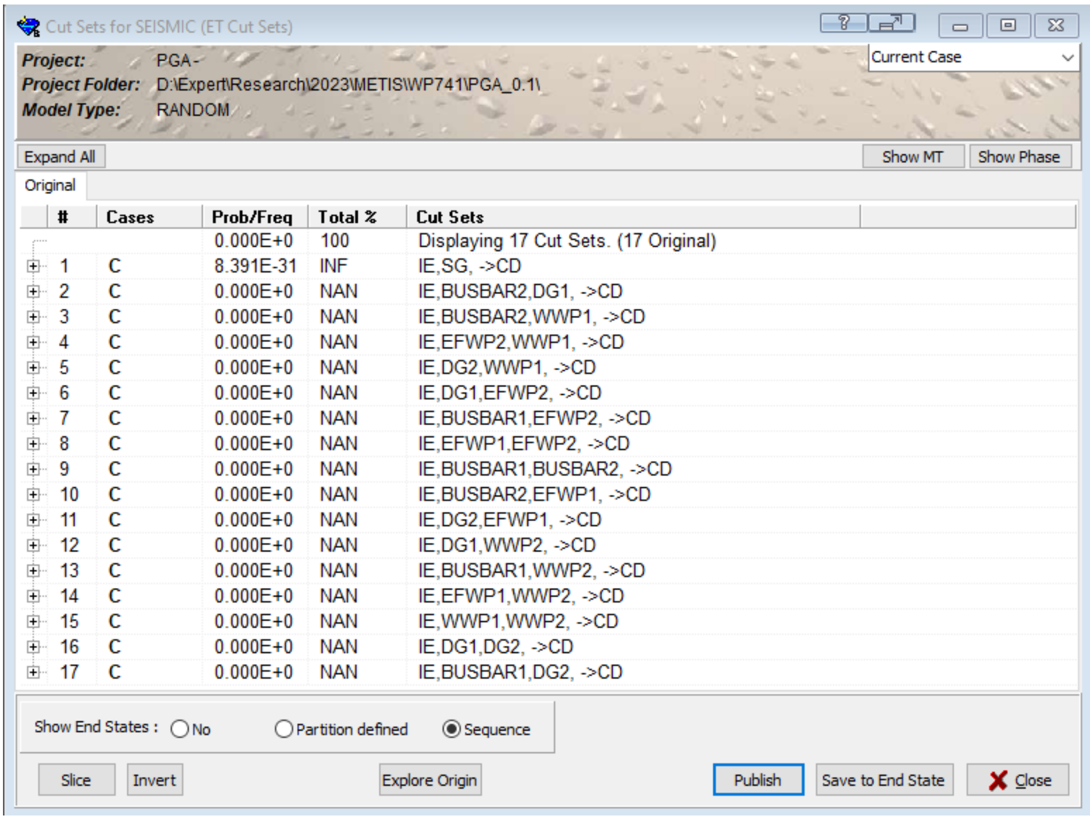
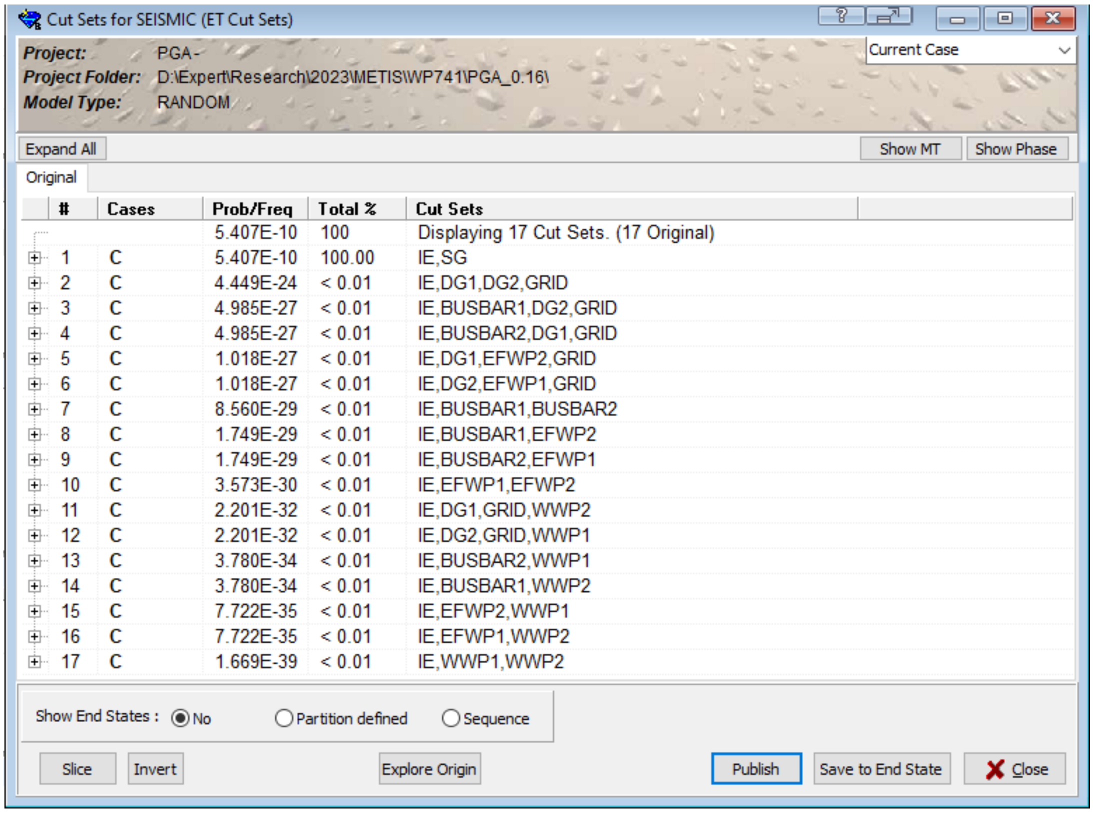


Figure 11 Loss of train 1 for scenario 2 (with GRID)

The figures below contain information on the cutsets obtained with the SAPHIRE PSA tool for different PGAs.



#	Cases	Prob/Freq	Total %	Cut Sets
		0.000E+0	100	Displaying 17 Cut Sets. (17 Original)
1	C	8.391E-31	INF	IE,SG, ->CD
2	C	0.000E+0	NAN	IE,BUSBAR2,DG1, ->CD
3	C	0.000E+0	NAN	IE,BUSBAR2,WWP1, ->CD
4	C	0.000E+0	NAN	IE,EFWP2,WWP1, ->CD
5	C	0.000E+0	NAN	IE,DG2,WWP1, ->CD
6	C	0.000E+0	NAN	IE,DG1,EFWP2, ->CD
7	C	0.000E+0	NAN	IE,BUSBAR1,EFWP2, ->CD
8	C	0.000E+0	NAN	IE,EFWP1,EFWP2, ->CD
9	C	0.000E+0	NAN	IE,BUSBAR1,BUSBAR2, ->CD
10	C	0.000E+0	NAN	IE,BUSBAR2,EFWP1, ->CD
11	C	0.000E+0	NAN	IE,DG2,EFWP1, ->CD
12	C	0.000E+0	NAN	IE,DG1,WWP2, ->CD
13	C	0.000E+0	NAN	IE,BUSBAR1,WWP2, ->CD
14	C	0.000E+0	NAN	IE,EFWP1,WWP2, ->CD
15	C	0.000E+0	NAN	IE,WWP1,WWP2, ->CD
16	C	0.000E+0	NAN	IE,DG1,DG2, ->CD
17	C	0.000E+0	NAN	IE,BUSBAR1,DG2, ->CD


Cut Sets for SEISMIC (ET Cut Sets)

Project: PGA-
Project Folder: D:\Expert\Research\2023\METIS\WP741\PGA_0.16\
Model Type: RANDOM

Current Case

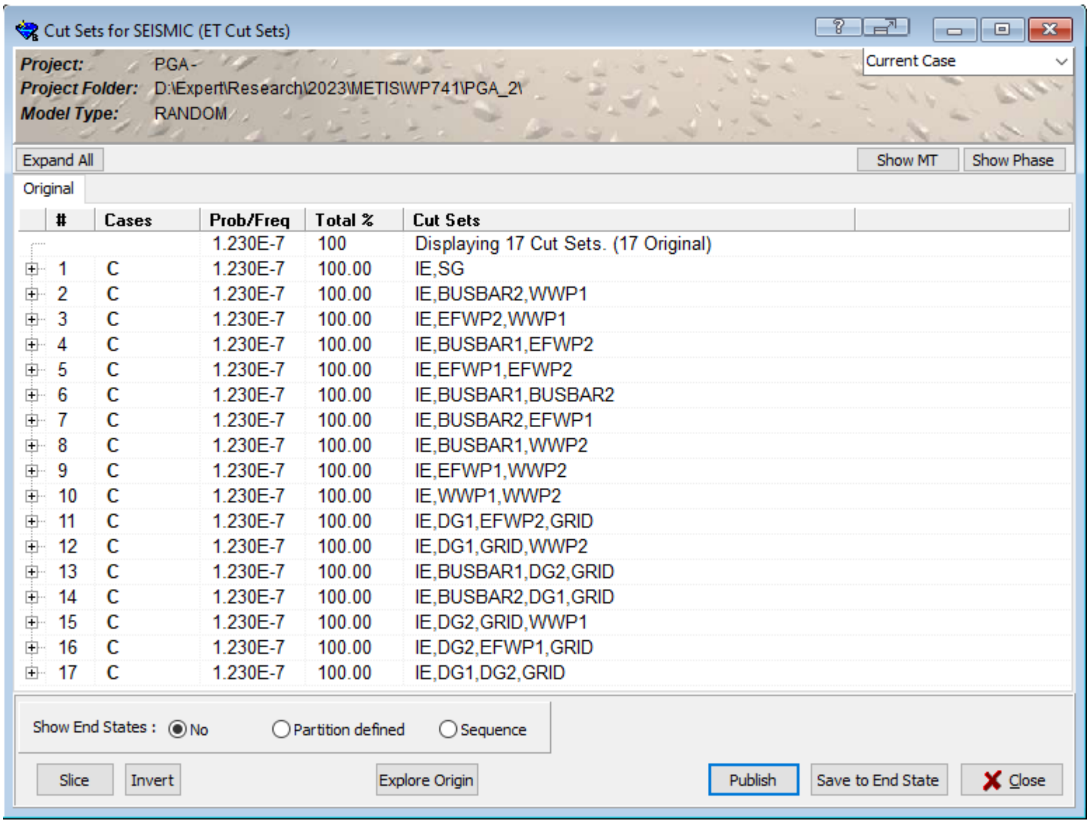
Expand All | Show MT | Show Phase

Original

#	Cases	Prob/Freq	Total %	Cut Sets
		5.407E-10	100	Displaying 17 Cut Sets. (17 Original)
1	C	5.407E-10	100.00	IE,SG
2	C	4.449E-24	< 0.01	IE,DG1,DG2,GRID
3	C	4.985E-27	< 0.01	IE,BUSBAR1,DG2,GRID
4	C	4.985E-27	< 0.01	IE,BUSBAR2,DG1,GRID
5	C	1.018E-27	< 0.01	IE,DG1,EFWP2,GRID
6	C	1.018E-27	< 0.01	IE,DG2,EFWP1,GRID
7	C	8.560E-29	< 0.01	IE,BUSBAR1,BUSBAR2
8	C	1.749E-29	< 0.01	IE,BUSBAR1,EFWP2
9	C	1.749E-29	< 0.01	IE,BUSBAR2,EFWP1
10	C	3.573E-30	< 0.01	IE,EFWP1,EFWP2
11	C	2.201E-32	< 0.01	IE,DG1,GRID,WWP2
12	C	2.201E-32	< 0.01	IE,DG2,GRID,WWP1
13	C	3.780E-34	< 0.01	IE,BUSBAR2,WWP1
14	C	3.780E-34	< 0.01	IE,BUSBAR1,WWP2
15	C	7.722E-35	< 0.01	IE,EFWP2,WWP1
16	C	7.722E-35	< 0.01	IE,EFWP1,WWP2
17	C	1.669E-39	< 0.01	IE,WWP1,WWP2

Show End States : No | Partition defined | Sequence

Slice | Invert | Explore Origin | Publish | Save to End State | Close


Cut Sets for SEISMIC (ET Cut Sets)

Project: PGA-
Project Folder: D:\Expert\Research\2023\METIS\WP741\PGA_2\
Model Type: RANDOM

Current Case

Expand All | Show MT | Show Phase

Original

#	Cases	Prob/Freq	Total %	Cut Sets
		1.230E-7	100	Displaying 17 Cut Sets. (17 Original)
1	C	1.230E-7	100.00	IE,SG
2	C	1.230E-7	100.00	IE,BUSBAR2,WWP1
3	C	1.230E-7	100.00	IE,EFWP2,WWP1
4	C	1.230E-7	100.00	IE,BUSBAR1,EFWP2
5	C	1.230E-7	100.00	IE,EFWP1,EFWP2
6	C	1.230E-7	100.00	IE,BUSBAR1,BUSBAR2
7	C	1.230E-7	100.00	IE,BUSBAR2,EFWP1
8	C	1.230E-7	100.00	IE,BUSBAR1,WWP2
9	C	1.230E-7	100.00	IE,EFWP1,WWP2
10	C	1.230E-7	100.00	IE,WWP1,WWP2
11	C	1.230E-7	100.00	IE,DG1,EFWP2,GRID
12	C	1.230E-7	100.00	IE,DG1,GRID,WWP2
13	C	1.230E-7	100.00	IE,BUSBAR1,DG2,GRID
14	C	1.230E-7	100.00	IE,BUSBAR2,DG1,GRID
15	C	1.230E-7	100.00	IE,DG2,GRID,WWP1
16	C	1.230E-7	100.00	IE,DG2,EFWP1,GRID
17	C	1.230E-7	100.00	IE,DG1,DG2,GRID

Show End States : No | Partition defined | Sequence

Slice | Invert | Explore Origin | Publish | Save to End State | Close

2.3. RiskSpectrum PSA model

2.3.1. Event tree

The probability of core damage after a seismic event due to a failure of the core cooling by the emergency feedwater has been modelled using RiskSpectrum PSA as the following event tree (for both scenarios).

Seismic event	Core cooling by EFW				
SEISMIC	LCC	No.	Freq.	Conseq.	Code
		1		CA	
		2		CD	LCC

Figure 12 Event tree at RiskSpectrum

2.3.2. Fault trees

Loss of cooling has been modelled in RiskSpectrum PSA as the following fault tree.

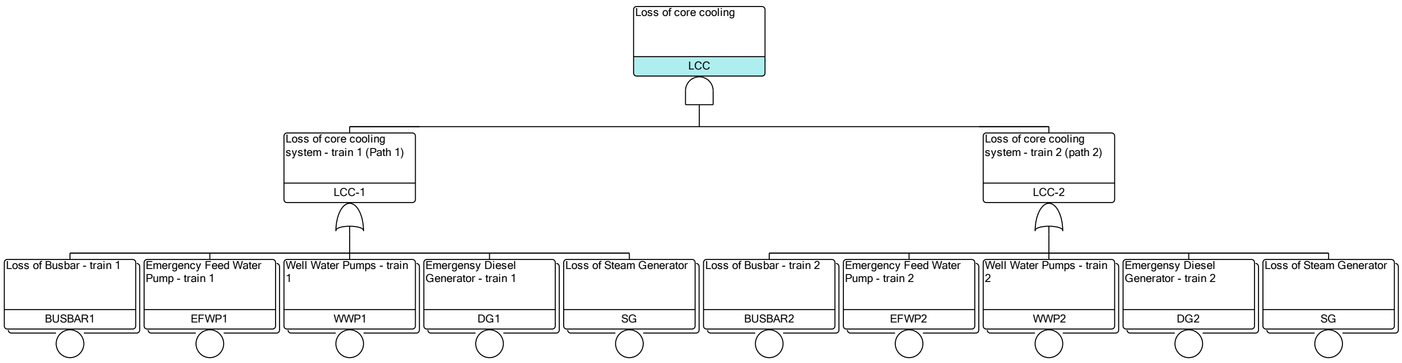


Figure 13 Fault tree at RiskSpectrum for Loss of core cooling system for the first scenario (without GRID)

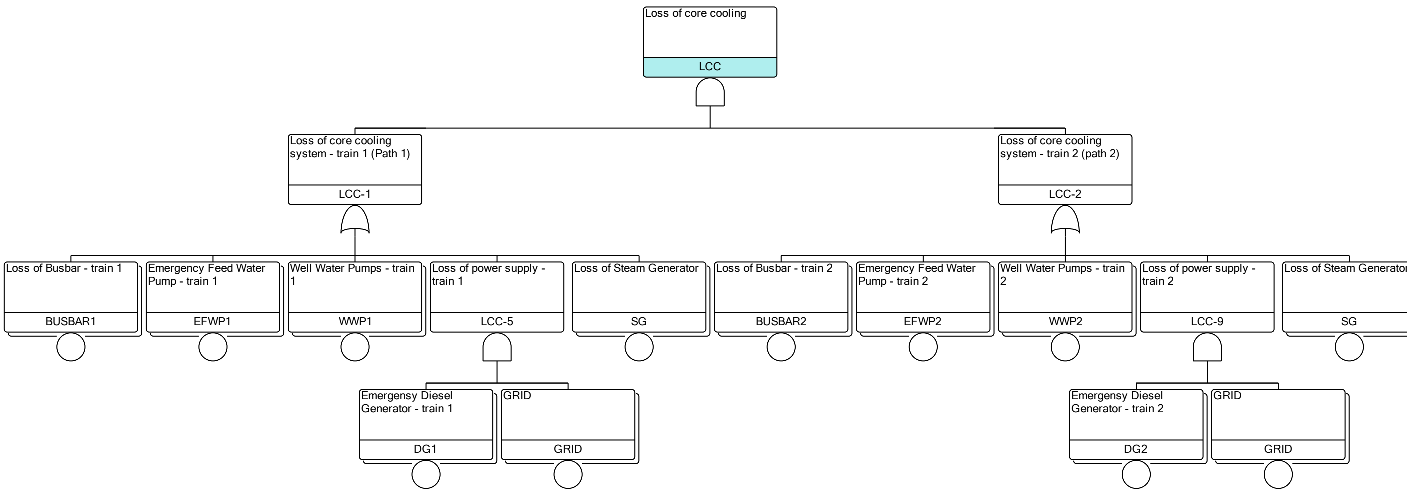
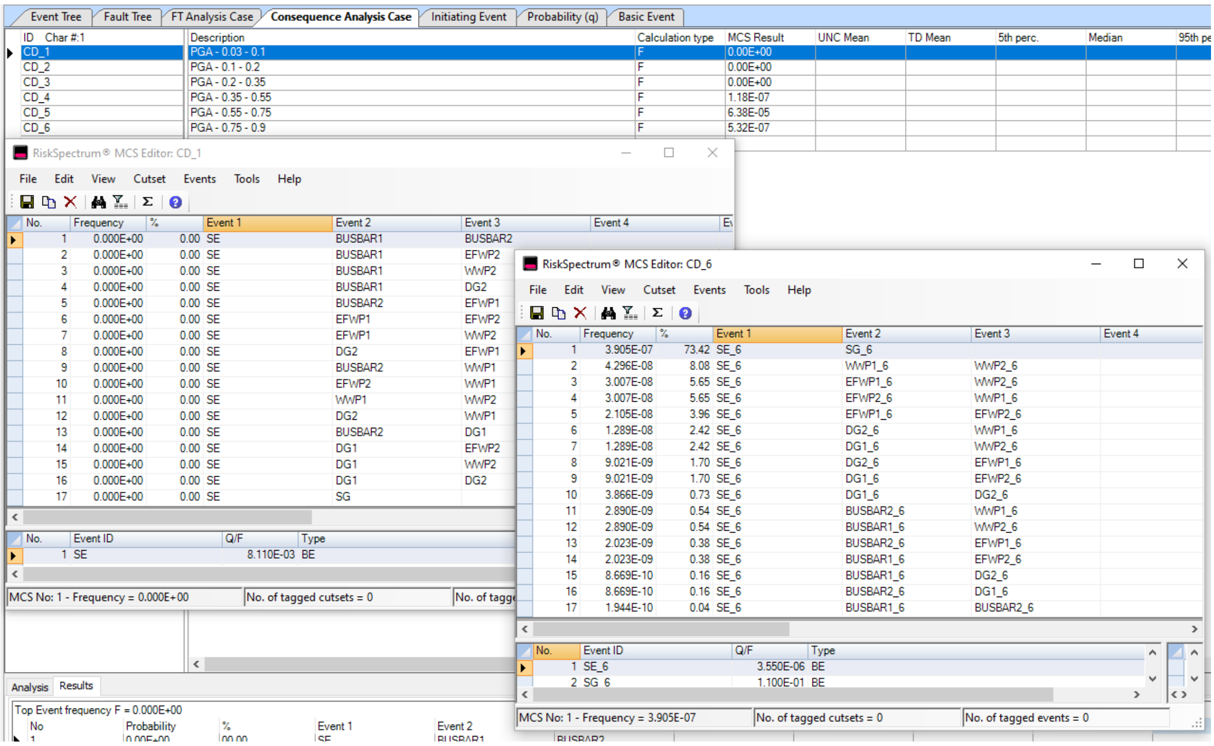
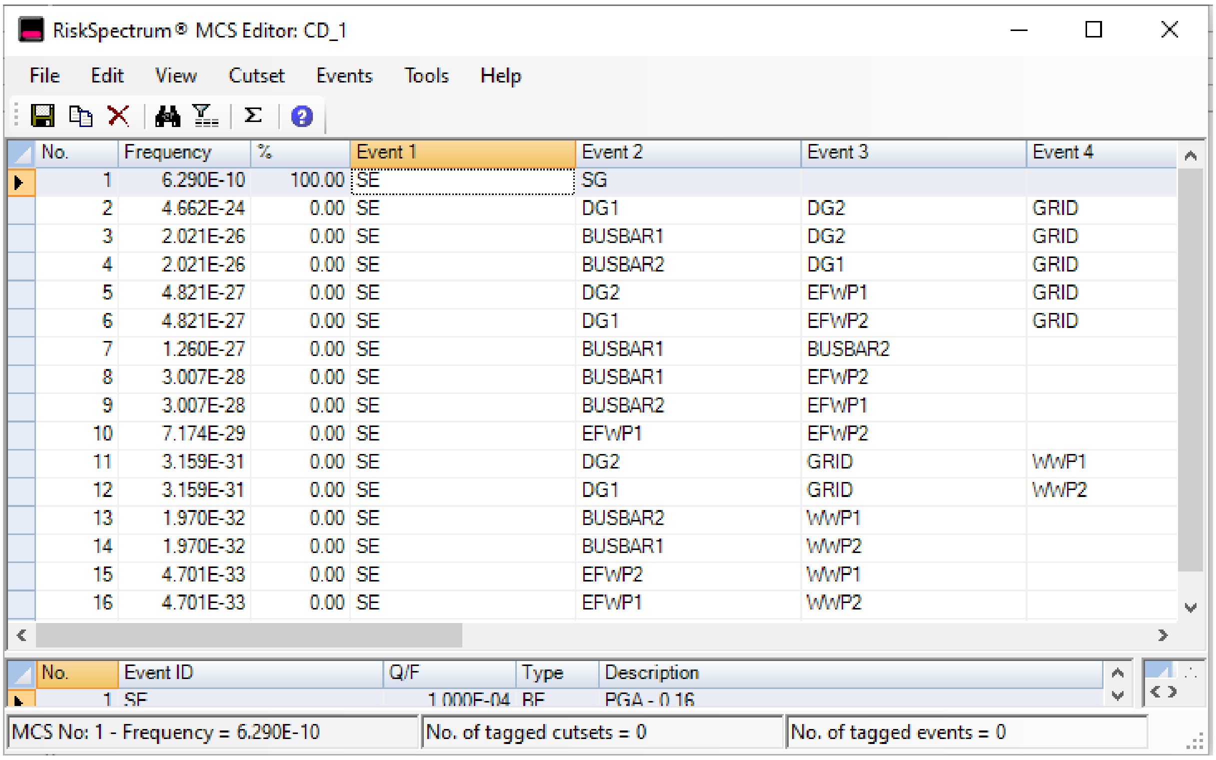


Figure 14 Fault tree at RiskSpectrum for Loss of core cooling system for the second scenario (with GRID)

The figures below contain information on the cutsets obtained with the RiskSpectrum PSA tool for different PGAs.

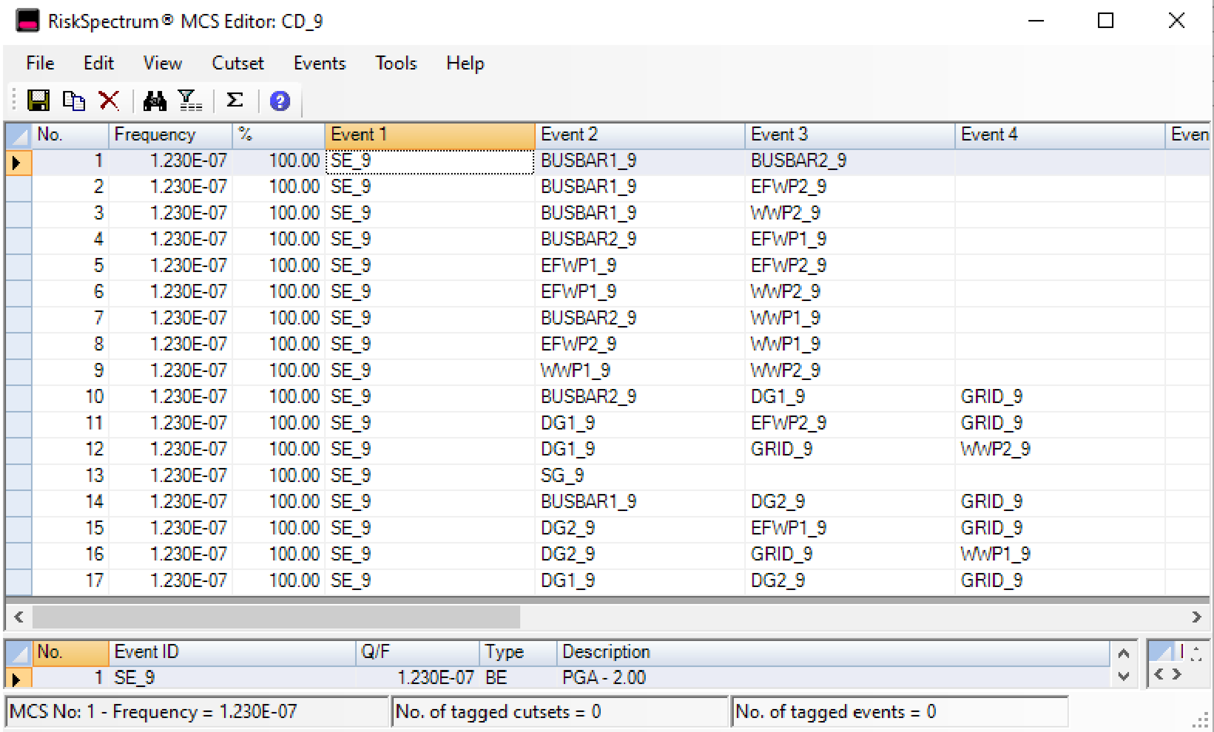




No.	Frequency	%	Event 1	Event 2	Event 3	Event 4
1	6.290E-10	100.00	SE	SG		
2	4.662E-24	0.00	SE	DG1	DG2	GRID
3	2.021E-26	0.00	SE	BUSBAR1	DG2	GRID
4	2.021E-26	0.00	SE	BUSBAR2	DG1	GRID
5	4.821E-27	0.00	SE	DG2	EFWP1	GRID
6	4.821E-27	0.00	SE	DG1	EFWP2	GRID
7	1.260E-27	0.00	SE	BUSBAR1	BUSBAR2	
8	3.007E-28	0.00	SE	BUSBAR1	EFWP2	
9	3.007E-28	0.00	SE	BUSBAR2	EFWP1	
10	7.174E-29	0.00	SE	EFWP1	EFWP2	
11	3.159E-31	0.00	SE	DG2	GRID	WWP1
12	3.159E-31	0.00	SE	DG1	GRID	WWP2
13	1.970E-32	0.00	SE	BUSBAR2	WWP1	
14	1.970E-32	0.00	SE	BUSBAR1	WWP2	
15	4.701E-33	0.00	SE	EFWP2	WWP1	
16	4.701E-33	0.00	SE	EFWP1	WWP2	

No.	Event ID	Q/F	Type	Description
1	SE	1.000E-04	BE	PGA - 0.16

MCS No: 1 - Frequency = 6.290E-10 | No. of tagged cutsets = 0 | No. of tagged events = 0


RiskSpectrum® MCS Editor: CD_9

File Edit View Cutset Events Tools Help

No.	Frequency	%	Event 1	Event 2	Event 3	Event 4	Even
1	1.230E-07	100.00	SE_9	BUSBAR1_9	BUSBAR2_9		
2	1.230E-07	100.00	SE_9	BUSBAR1_9	EFWP2_9		
3	1.230E-07	100.00	SE_9	BUSBAR1_9	WWP2_9		
4	1.230E-07	100.00	SE_9	BUSBAR2_9	EFWP1_9		
5	1.230E-07	100.00	SE_9	EFWP1_9	EFWP2_9		
6	1.230E-07	100.00	SE_9	EFWP1_9	WWP2_9		
7	1.230E-07	100.00	SE_9	BUSBAR2_9	WWP1_9		
8	1.230E-07	100.00	SE_9	EFWP2_9	WWP1_9		
9	1.230E-07	100.00	SE_9	WWP1_9	WWP2_9		
10	1.230E-07	100.00	SE_9	BUSBAR2_9	DG1_9	GRID_9	
11	1.230E-07	100.00	SE_9	DG1_9	EFWP2_9	GRID_9	
12	1.230E-07	100.00	SE_9	DG1_9	GRID_9	WWP2_9	
13	1.230E-07	100.00	SE_9	SG_9			
14	1.230E-07	100.00	SE_9	BUSBAR1_9	DG2_9	GRID_9	
15	1.230E-07	100.00	SE_9	DG2_9	EFWP1_9	GRID_9	
16	1.230E-07	100.00	SE_9	DG2_9	GRID_9	WWP1_9	
17	1.230E-07	100.00	SE_9	DG1_9	DG2_9	GRID_9	

No.	Event ID	Q/F	Type	Description
1	SE_9	1.230E-07	BE	PGA - 2.00

MCS No: 1 - Frequency = 1.230E-07 | No. of tagged cutsets = 0 | No. of tagged events = 0

3. Results

The seismic core damage frequency for each scenario has been computed using:

- the frequencies of a seismic initiating event,
- the probabilities of seismic failure of SSCs,
- the event trees and fault trees.

The results are provided in the following tables. In these results, the core damage frequency for low values of PGA is overestimated due to the conservative assumption that a reactor trip and the loss of the main feedwater are postulated regardless of PGA.

Scenario 1 (without GRID)

Table 8 Frequency of seismic core damage depending on PGA for the first scenario (without GRID)

Seismic Initiating Event	**1**	**2**	**3**	**4**	**5**	**6**
PGA in g	0.03-0.1	0.1-0.2	0.2-0.35	0.35-0.55	0.55-0.75	0.75-0.9
Initiating event frequency (/year)	8.11E-03	1.45E-03	3.40E-04	7.86E-05	1.55E-05	3.55E-06
METIS tool CDF (/year)	0.00E+00	0.00E+00	0.00E+00	7.07E-10	1.35E-07	3.15E-07

Seismic Initiating Event	1	2	3	4	5	6
SAPHIRE CDF Seismic parameters (/year)	0.00E+00	1.610E-19	9.126E-13	3.045E-09	6.095E-08	1.080E-07
SAPHIRE CDF Point Value (/year)	0.00E+00	0.00E+00	0.00E+00	7.063E-10	1.349E-07	3.288E-07
RiskSpectrum CDF (/year)	0.00E+00	0.00E+00	0.00E+00	7.063E-10	1.349E-07	3.288E-07

Calculations with the SAPHIRE code were performed for two different input data: first using seismic parameters for calculations of the probabilities of equipment failures (Table 2 and Table 5), second case with probabilities of the equipment failure from Table 3 and Table 6.

Scenario 2 (with GRID)

Table 9 Frequency of seismic core damage depending on PGA for the second scenario (with GRID)

PGA (g)	0,16	0,27	0,4	0,5	0,67	0,83	1,03	1,44	2
Initiating event frequency (/year)	1.00E-04	1.00E-05	5.30E-06	3.22E-06	1.84E-06	9.85E-07	4.83E-07	2.16E-07	1.23E-07
METIS tool CDF (/year)	6,29E-10	1,44E-07	1,58E-06	2,63E-06	1,84E-06	9,85E-07	4,83E-07	2,16E-07	1,23E-07
SAPHIRE CDF Seismic parameters (/year)	5.407E-10	1.321E-07	1.518E-06	2.602E-06	1.840E-06	9.850E-07	4.830E-07	2.160E-07	1.230E-07
SAPHIRE CDF Point Value (/year)	6.290E-10	1.440E-07	1.581E-06	2.633E-06	1.840E-06	9.850E-07	4.830E-07	2.160E-07	1.230E-07
RiskSpectrum CDF (/year)	6.29E-10	1.44E-07	1.58E-06	2.63E-06	1.84E-06	9.85E-07	4.83E-07	2.16E-07	1.23E-07

4. Conclusions

The main aim of this report is benchmark calculations METIS tool v.s. PSA wide used tools SAPHIRE and RiskSpectrum. The results of these benchmarks would be good basis for preliminary validation of the METIS tool for seismic PSA analyses.

This study was conducted to compare the calculation results for the test scenarios obtained using the METIS, SAPHIRE and RiskSpectrum PSA tools. The results for the METIS tool, SAPHIRE and RiskSpectrum PSA computer codes generally are in good agreement, as evidenced by the calculations (see Table 7 and Table 8). However, it should be noted that the SAPHIRE code sets the failure probability for components using seismic parameters (Am, βu and βr), making it easier to determine the failure probabilities for components and generally produce more accurate calculation results.

There were two scenarios selected for the benchmark. The main differences of these scenarios (benchmark cases) were in different seismic input data and SSCs fragility data.

Selection of these scenarios was made in order to investigate the impact of the different seismic input and fragility data used on the benchmark results and to obtain validation results for a wider range of seismic impacts.

The benchmark results showed good agreement between METIS tool, SAPHIRE and RiskSpectrum, that could conclude, that using of the similar input data and similar approaches for modelling could establish evidenced results of the METIS tool.

For analysis of the differences between SAPHIRE/RiskSpectrum and METIS tool calculations, the additional study was performed. Results of this study showed, if the seismic parameters (Am, βR, βU) given in Table 5 were used, the values of the probability of equipment failure were obtained that differ from those given in Table 6. These differences are result of the sensitivity of the formula to the rounding of the value of the Am parameter in Table 5. The values of the probability of equipment failure obtained in the SAPHIRE code are presented in Table 10.

Table 10 Comparison of probability of seismic failure (second scenario)

Components	0.16	0.27	0.4	0.5	0.67	0.83	1.03	1.44
Busbar	9.25E-13	3.63E-05	4.89E-02	3.66E-01	9.16E-01	9.96E-01	1.00E+00	1.00E+00
(SAPHIRE/ Table 6)	3.55E-12	5.56E-05	5.29E-02	3.66E-01	9.08E-01	9.95E-01	1.00E+00	1.00E+00
Diesel Gen.	8.26E-10	5.94E-05	1.35E-02	1.00E-01	4.75E-01	7.97E-01	9.58E-01	9.99E-01
(SAPHIRE/ Table 6)	8.19E-10	5.91E-05	1.35E-02	9.98E-02	4.75E-01	7.96E-01	9.58E-01	9.99E-01
EFWP	1.89E-13	1.42E-05	3.05E-02	2.88E-01	8.77E-01	9.92E-01	1.00E+00	1.00E+00
(SAPHIRE/ Table 6)	8.47E-13	2.39E-05	3.44E-02	2.93E-01	8.71E-01	9.91E-01	1.00E+00	1.00E+00
GRID	6.53E-02	7.48E-01	9.89E-01	9.99E-01	1.00E+00	1.00E+00	1.00E+00	1.00E+00

(SAPHIRE/ Table 6)	6.95E-02	7.58E-01	9.90E-01	9.99E-01	1.00E+00	1.00E+00	1.00E+00	1.00E+00
WWP	4.09E-18	1.70E-08	6.70E-04	2.91E-02	4.31E-01	8.61E-01	9.91E-01	1.00E+00
(SAPHIRE/ Table 6)	5.55E-17	4.60E-08	9.84E-04	3.44E-02	4.42E-01	8.59E-01	9.90E-01	1.00E+00
SG	5.41E-06	1.32E-02	2.80E-01	6.36E-01	9.41E-01	9.93E-01	1.00E+00	1.00E+00
(SAPHIRE/ Table 6)	6.29E-06	1.44E-02	2.91E-01	6.48E-01	9.45E-01	9.94E-01	1.00E+00	1.00E+00

5. References

[1] Educational example of a seismic PSA for a critical facility, Andromeda-Scram & Seismic-PSA theory WS 25.02.2022, Philippe Renault, Swissnuclear.

[2] EPRI report – Methodology for Developing Seismic Fragilities, EPRI, Palo Alto, CA: 1994, TR 1003959.

[3] Numerical computation of fragility curves for NPP equipment, I. Zentner, Nuclear Engineering and Design 240, 2010.

[4] Nicolas DUFLOT, “ Development of seismic database management tool”, Horizon 2020 project METIS, Deliverable D7.2, 2023