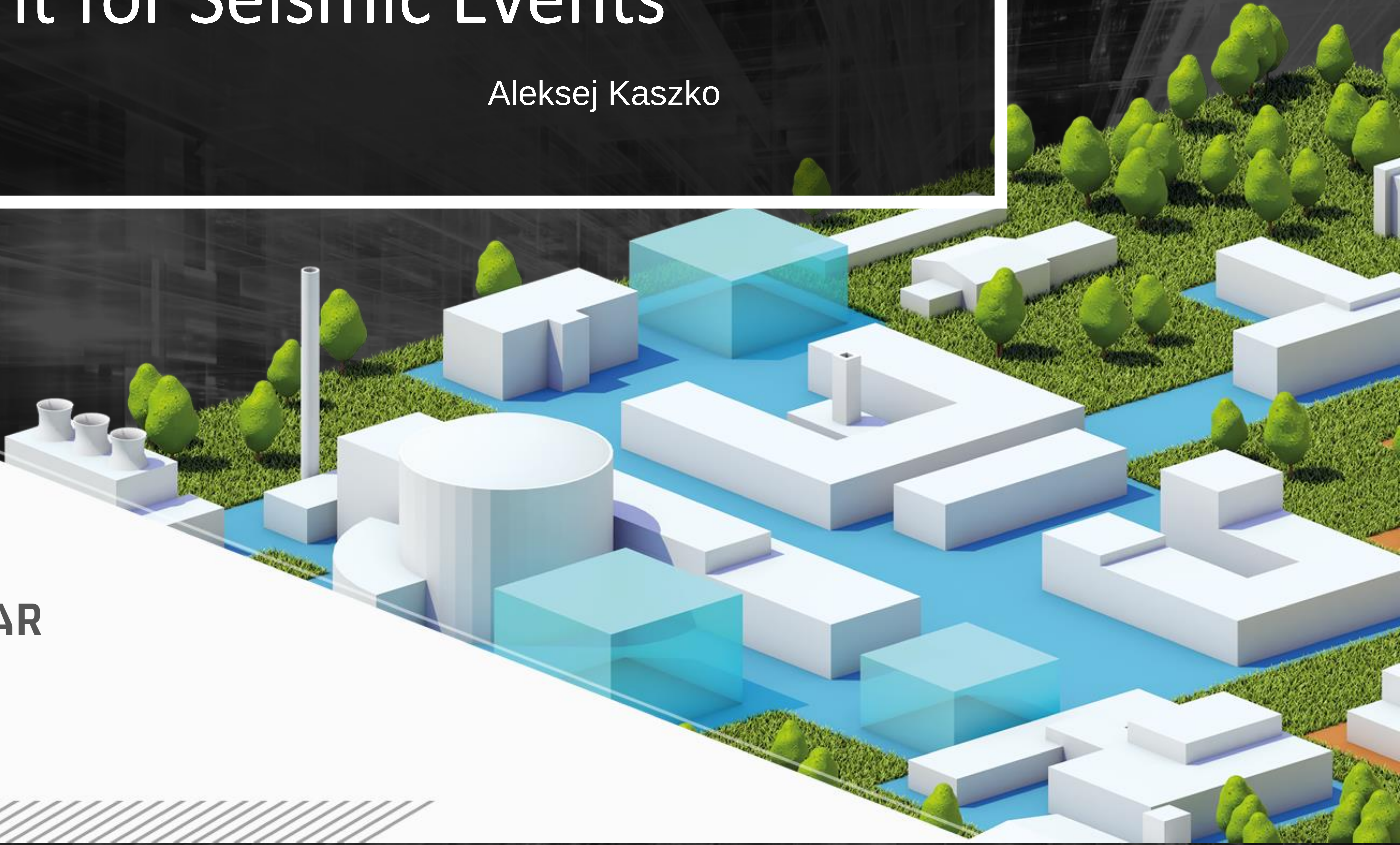
Example of Probabilistic Safety Assessment for Seismic Events

Aleksej Kaszko



NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

1. Introduction
2. Influence of earthquakes on components
3. Component fragility curves
4. Example of hazard histogram usage based on NARSIS Project
5. Example of defined seismic g-level model based on DONES installation
6. Conclusions

Introduction

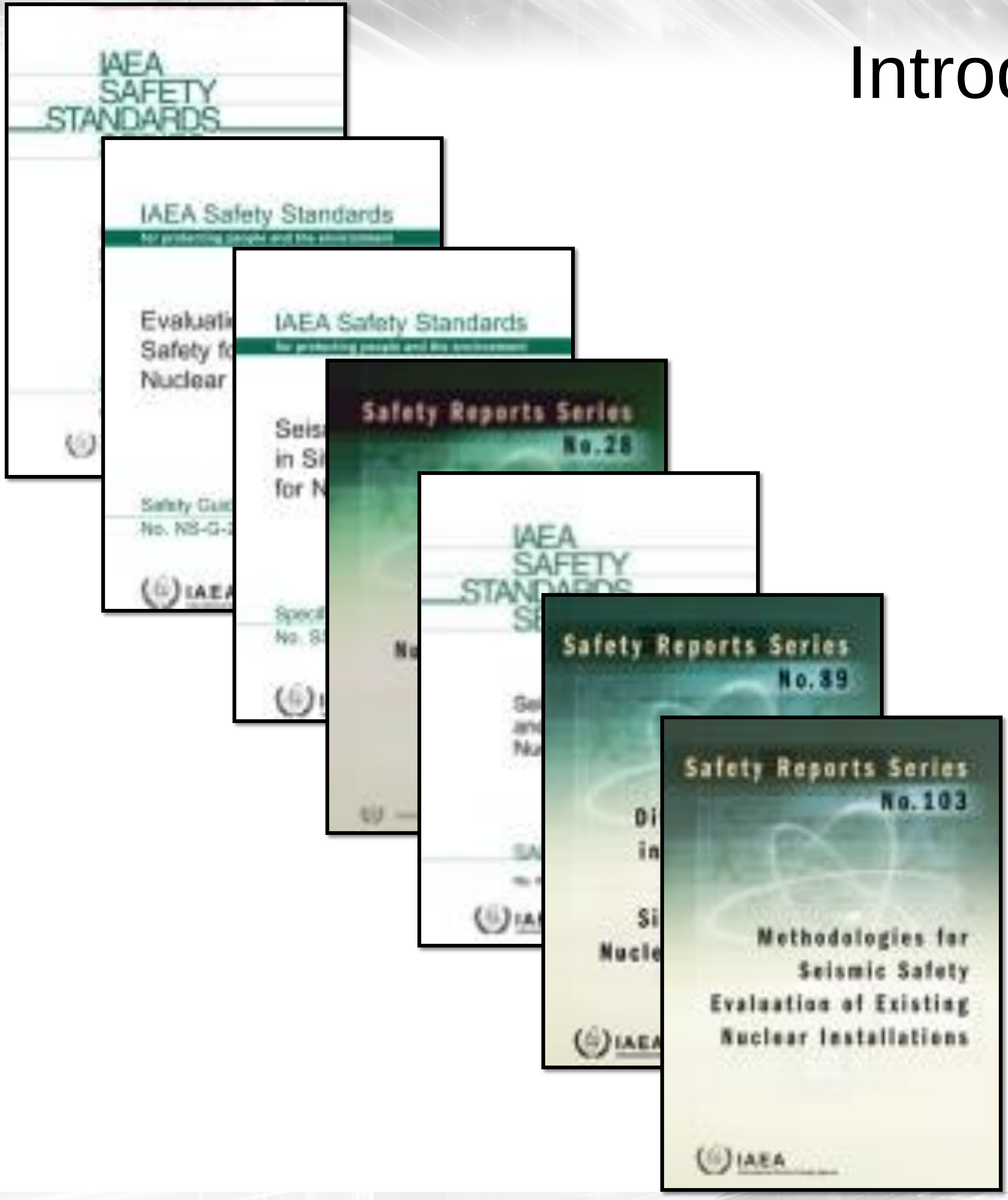
It is estimated that 20% of nuclear reactors are operating in areas of significant seismic activity. Earthquake external events are one of the most important events affecting NPP safety.

In 1993 International Atomic Energy Agency (IAEA) published Technical Document called Probabilistic Safety Assessment for seismic events as a response for Member States interest.

According to IAEA seismic PSA may be conducted for following reasons:

- responce to regulatory requirement for licensing a new plant;
- resolution of existing seismic issues;
- resolution of new seismic issues;
- development of risk management program;
- plant life extension
- other

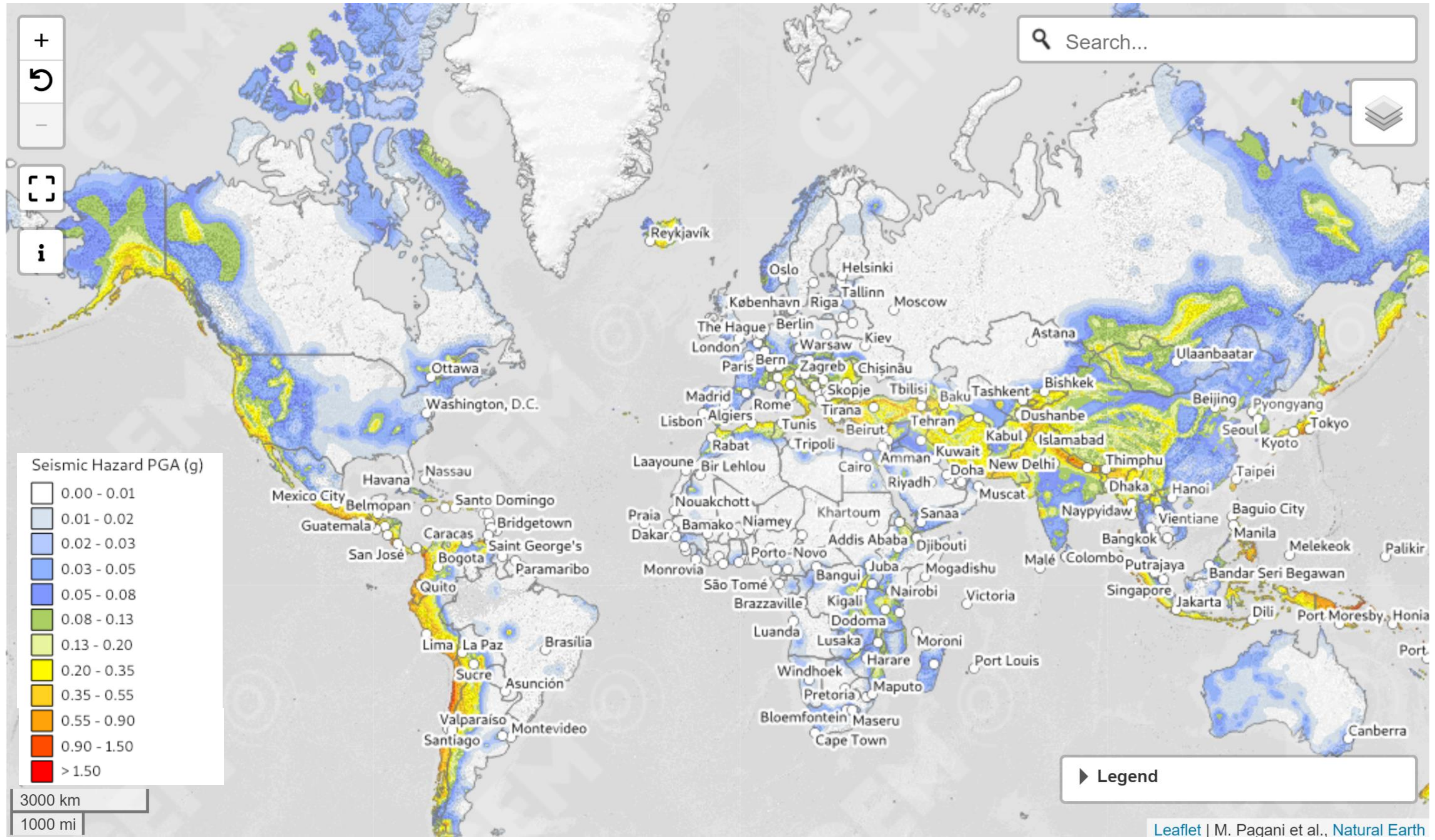
Introduction



Because of the huge interest IAEA published multiple Technical Documents, Safety Guides and Safety Reports such as:

- Diffuse Seismicity in Seismic Hazard Assessment for Site Evaluation of Nuclear Installations
- Seismic Evaluation of Existing Nuclear Facilities
- Probabilistic Safety Assesssment for Seismic Events
- Seismic Evaluation of Existing Nuclear Power Plants
- Seismic Design and Qualification for Nuclear Power Plants
- Evaluation of Seismic Safety for Existing Nuclear Installations
- Evaluation of Seismic Hazards for Nuclear Power Plants
- Methodologies for Seismic Safety Evaluation of Existing Nuclear Installations
- And many more

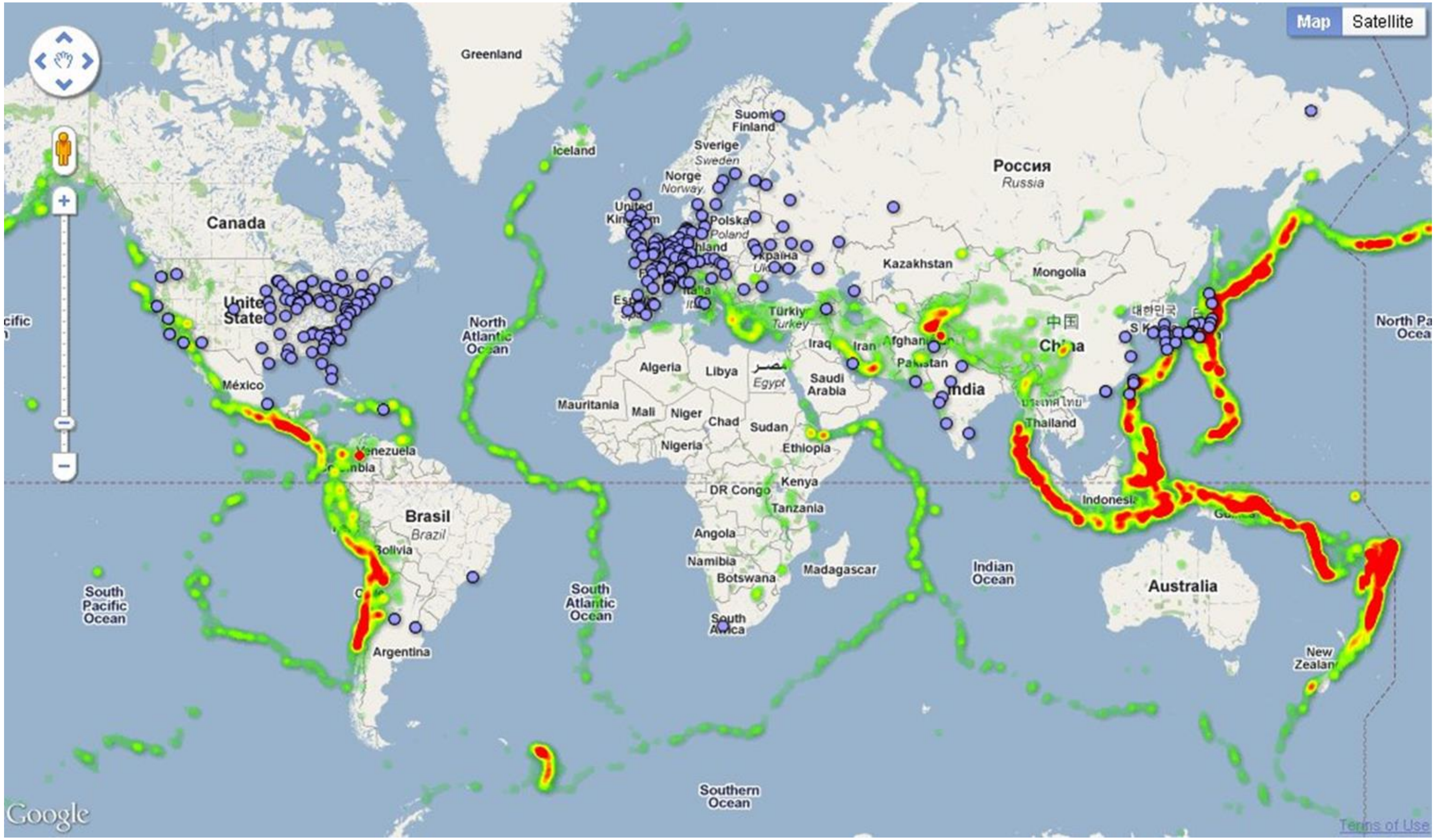
Introduction



Design basis earthquake ground motions for different instalations world wide:
Korean APR-1400 – 300 Gal (0.3g)
China's CAP1400 – 300 Gal (0.3g)
Fukushima – 600 Gal (0.61g)
Sendai – 620 Gal (0.63g)
San Onofre plant – 657 Gal (0.67g)
Takahama – 700 Gal (0.71g)
Diablo Canyon plant – 735 Gal (0.75g)
Tokai – 900 Gal (0.91g)
Hokuriku, Shika ABWR– 1000 Gal (1.02g)
Kashiwazaki kariwa 5-7 – 1209 Gal (1.23g)
Kashiwazaki-Kariwa 1-4 – 2300 Gal (2.34g)

1 Gal = 1 cm/s^2 1g = 9,81m/s^2 1g = 981 Gal

Introduction



Worldwide map of nuclear power stations and earthquake zones

Influence of earthquakes on components

Influence of earthquakes on NPP components

One of the main problem during Seismic PSA is to identify seismic response of structures, systems, components and to obtain reliable data on seismic fragilities.

Seismic fragilities of the components is usually obtained through experiments or from the field data.

Currently there are various data sources regarding seismic fragilities for structure, systems and components. One of the most complete datasets for the Nuclear Power Plants is shown in EPRI's Seismic Probabilistic Risk Assessment Implementation Guide.

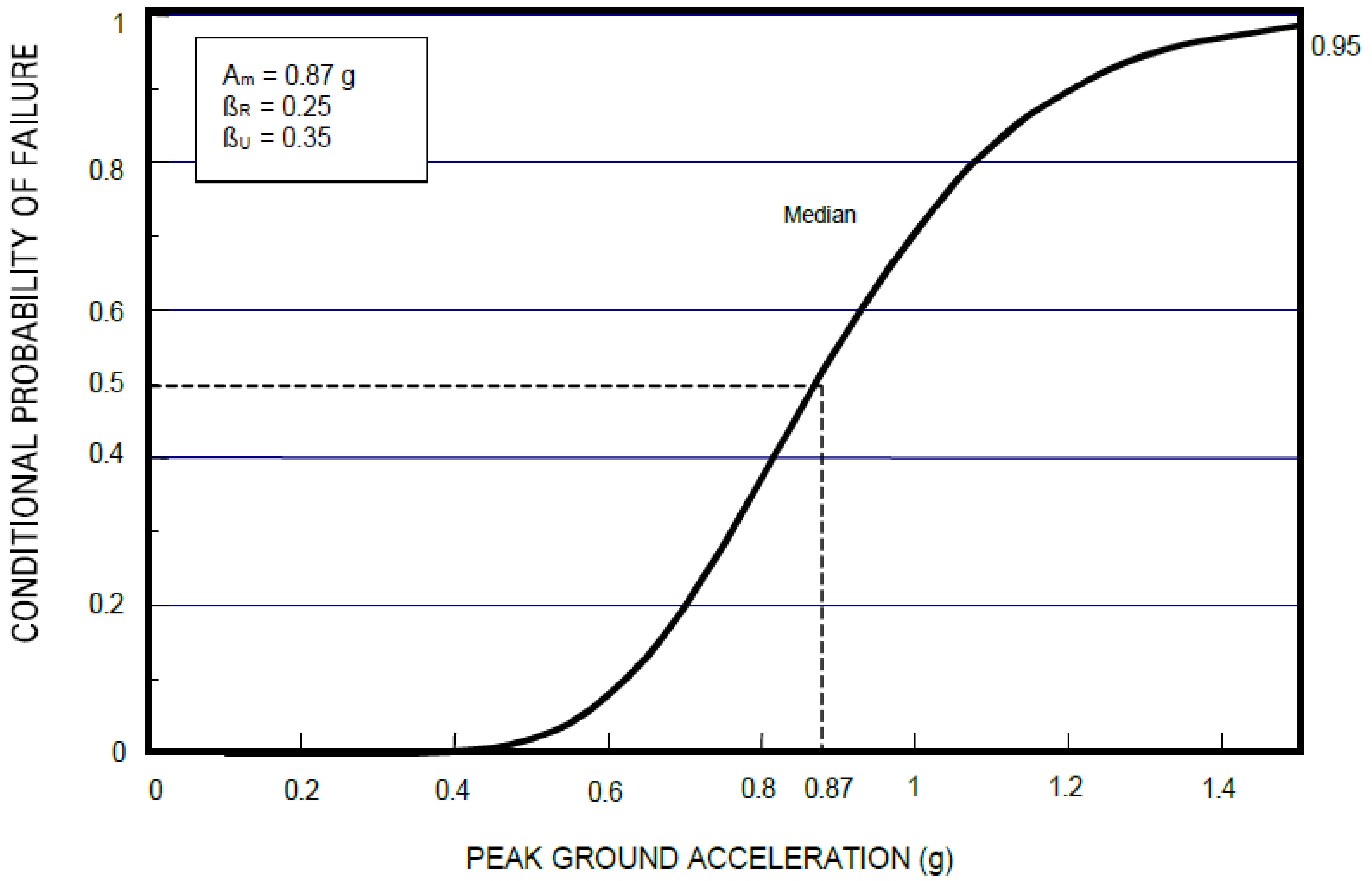
SSC	1983 BWR Mark II SPRA[3]				NUREG/CR-4832 & -4550[4]				2010 EPRI Surry SPRA[5]			
	A_m	βr	βu	Notes	A_m	βr	βu	Notes	A_m	βr	βu	Notes
Electrical Supply / Distribution Equipment												
Offsite power	0.20	0.20	0.25	Ceramic insulators	0.21	0.3	0.37	Generic (insulators)	0.30	0.27	0.40	Generic (functional)
480VAC Motor Control Center (MCC) / Switchgear / Bus	1.45	0.38	0.44	440V Bus (breaker trip)	3.23	0.21	0.60	Generic (MCCs)	0.69 0.97	0.23 0.24	0.36 0.31	Various MCCs in Aux and Srvc bldgs Srvc Bldg emergency bus
4kV+ AC Bus / Switchgear	1.46	0.38	0.44	Breaker Trip	1.55	0.16	0.33	4kV SWGR Aux Bldg El. 710' & 731' (anchorage)	1.17	0.24	0.25	Srvc Bldg emergency bus
DC Motor Control Center (MCC) / Switchgear / Bus	1.49	0.36	0.43	125 / 250V Bus (function)	3.23	0.21	0.60	Generic (MCCs)	-	-	-	Screened
Panel (Electric or Instrument)	-	-	-	-	2.21 3.32 5.42 6.14	0.16 0.19 0.48 0.08	0.35 0.28 0.74 0.27	Rx Lvl/Press panel RPS logic board Generic (Panel) Remote Shtdwn Pnl	1.21 to 2.17	0.23	0.25 to 0.50	Various RPS, safeguards, relay panels in Srvc Bldg
Electromechanical Relay Chatter Failure (During Seismic Event)	2.07	-	-	Electrical and control equipment chatter	1.3	0.15	0.21	SWGR/MCCs chatter	1.37-1.93	0.21	0.46	Various relay chatters
Electromechanical Relay Chatter Failure (After Seismic Event)	7.97	-	-	Electrical and control equipment trip (structural failure is significantly higher)	-	-	-	-	2.84-2.97	0.21	0.45	Various relay chatters
Emergency Diesel Generator (EDG)	2.00	0.28	0.27	Skid Bolts	1.52	0.19	0.39	Jacket water pipe bolts	1.07 1.08	0.30 0.24	0.30 0.45	Safety DGs DG Day Tanks
Batteries	2.56	0.40	0.37	Battery case	1.85	0.21	0.78	Batteries	1.02	0.20	0.42	

SSC	2010 BWR Mark I SPRA[6]				NUREG/CR-4334[7]				Recommended Range of Representative Fragilities[8]				
	A_m	βr	βu	Notes	A_m	βr	βu	Notes	A_m	βr	βu	Failure Mode[9]	Comment
Electrical Supply / Distribution Equipment													
Offsite power	0.24	0.40	0.38	Generic (functional)	0.20 0.25 0.25 0.26 0.30 0.40	0.20 0.20 0.20 0.20 0.25 0.25	0.25 0.25 0.25 0.25 0.50 0.54	Offsite AC (insulators) Offsite AC (insulators) Offsite AC (insulators) Offsite AC (insulators) Offsite AC (insulators) Switchyard	0.30	0.30	0.45	Functional	The generic functional value of 0.30g is representative of later vintage SPRAs.
480VAC Motor Control Center (MCC) / Switchgear / Bus	0.40 1.10 1.81 2.00	0.25 0.25 0.20 0.40	0.37 0.37 0.35 0.6	380V BOP SWGR unanchored Safety Bldg (SG) ground Elev. bus Safety Bldg (SG) -11m Elev. bus Safety Bldg (SG) ground Elev. bus	0.9 1.8 1.8 2.2 2.3 2.9	0.28 0.36 0.36 0.28 0.32 0.24	0.22 0.47 0.47 0.58 0.76 0.52	480V cabinet structure 480V switchgear 480V MCC 480V MCC 480V MCC structure 480V MCC	0.7-2.0 0.4	0.30 0.30	0.35 0.35	Loss of function (Anchored) Loss of function (Unanchored)	The various bus/MCC categories are considered as whole and the same fragility estimates provided for each. Unanchored bus/MCC based on reasonable judgment and review of the few data points for unanchored cabinets.
4kV+ AC Bus / Switchgear	0.23	0.30	0.40	6kv BOP buses, unanchored	1.5 1.7 1.8 3.1 3.2	0.32 0.39 0.36 0.28 -	0.48 0.46 0.47 0.81 -	4kV SWGR trip 4kV SWGR trip 4kV SWGR 4kV SWGR trip 4kV SWGR non-recoverable failure	0.7-2.0 0.4	0.30 0.30	0.35 0.35	Loss of function (Anchored) Loss of function (Unanchored)	The various bus/MCC categories are considered as whole and the same fragility estimates provided for each. Unanchored bus/MCC based on reasonable judgment and review of the few data points for unanchored cabinets.
DC Motor Control Center (MCC) / Switchgear / Bus	1.81	0.20	0.35	Functional	>2.0	0.4	0.5	Various non-recoverable DC MCC failures in the 2-3g range	0.7-2.0 0.4	0.30 0.30	0.35 0.35	Loss of function (Anchored) Loss of function (Unanchored)	The various bus/MCC categories are considered as whole and the same fragility estimates provided for each. Unanchored bus/MCC based on reasonable judgment and review of the few data points for unanchored cabinets.
Panel (Electric or Instrument)	0.69 1.81	0.24 0.2	0.46 0.35	Unanchored (uplift) Anchored panel (function)	>2.0	0.4	0.5	Various non-recoverable panel failures in the 2-5g range	0.7-2.0 0.4	0.30 0.30	0.35 0.35	Loss of function (Anchored) Loss of function (Unanchored)	The various bus/MCC categories are considered as whole and the same fragility estimates provided for each. Unanchored bus/MCC based on reasonable judgment and review of the few data points for unanchored cabinets.
Electromechanical Relay Chatter Failure (During Seismic Event)	-	-	-	Screened based on system analysis	0.9 - 3.1	0.35	0.47	Various relay chatters; study does not specify during or after	1.0-2.0	0.30	0.35	Relay chatter	• This failure mode indicates chatter during the event but the relay remains functional after event (although equipment may require re-setting). • Solid state relays may be assessed as more rugged. Refer to Note (11).
Electromechanical Relay Chatter Failure (After Seismic Event)	-	-	-	Screened based on system analysis; to be investigated further in future	0.9 - 3.1	0.35	0.47	Various relay chatters; study does not specify during or after	1.0-3.0	0.30	0.35	Loss of function	• This failure mode indicates the relay is not functional after the event. • Solid state relays may be assessed as more rugged. Refer to Note (11).
Emergency Diesel Generator (EDG)	0.43 1.52- 2.16 2.00	0.15 0.22 0.28	0.47 0.39 0.42	BOP DG (anchor) DG Day Tanks (support) Safety DGs	0.91 1.06 1.3 1.51 1.6 2.5	0.24 0.35 0.27 0.36 0.24 0.28	0.43 0.37 0.25 0.35 0.52 0.27	L.O. cooler attchmnt DG system DG system DG anchorage DG system DG skid bolts	1.0-2.0	0.30	0.35	Loss of function	
Batteries	1.09 2.79	0.20 0.20	0.33 0.33	125V batteries (functional) New upgraded batteries (functional)	0.9 1.2 1.6 1.7 2.8 2.9	0.33 0.28 0.32 0.29 0.40 0.33	0.34 0.63 0.30 0.31 0.37 0.47	Battery Battery Battery Battery Battery Battery	1.0-2.0	0.30	0.35	Loss of function	

System, structure, and component seismic fragilities from EPRI report

Influence of earthquakes on NPP components

The response of system, structure, and component to earthquake is expressed as fragility curve. Fragility curve depicts the conditional probability of failure of the component for any given ground motion level.



Example of Seismic fragility curve

Influence of earthquakes on NPP components

Seismic failure probability

The most common form of a seismic fragility function is the lognormal cumulative distribution function:

$$f(a) = \Phi\left(\frac{ln\left(\frac{a}{A_m}\right)}{\beta}\right)$$

Where:

Φ: standard Gausian cumulative distribution function

β: logarithmic standard deviation

a: seismic acceleration (typically expressed in peak ground acceleration)

A_m: Median ground acceleration capacity

G	P = Φ[ln(gspecified/a)/Br].	The basic event is to be treated as a seismic event. The probability value for screening will be calculated using the "screening G-level" (ground acceleration) and median failure acceleration (fragility) specified by the user. Strictly for use only in seismic analyses.
H	P = Φ[ln(ghazard/a)/Br].	The basic event is to be treated as a seismic event. The probability value for screening will be calculated using the highest G-level (ground acceleration) from the project's "seismic hazard curve" and median failure acceleration (fragility) specified by the user. Strictly for use only in seismic analyses.

Notes: Φ = standard normal cumulative distribution function

a = median failure acceleration (the approximate ground acceleration sufficient to cause the component to fail)

B_r = amount the failure acceleration "a" can vary

g = ground acceleration for screening

Seismic failure probability

If we use following relation

$$\beta \equiv \beta_c = \sqrt{\beta_r^2 + \beta_u^2}$$

we will obtain conditional probability of failure with seismic log normal uncertainty distribution:

$$f(a) = \Phi\left(\frac{ln\left(\frac{a}{A_m}\right) + \beta_u \Phi^{-1}(Q)}{\beta_r}\right)$$

Where:

β_r: variability due to inherent randomness in factors involved in the derivation of the seismic capacity, such as earthquake time histories and structural material properties;

β_u : variability due to sources of uncertainty in the derivation of the seismic capacity, such as the lack of complete structural knowledge

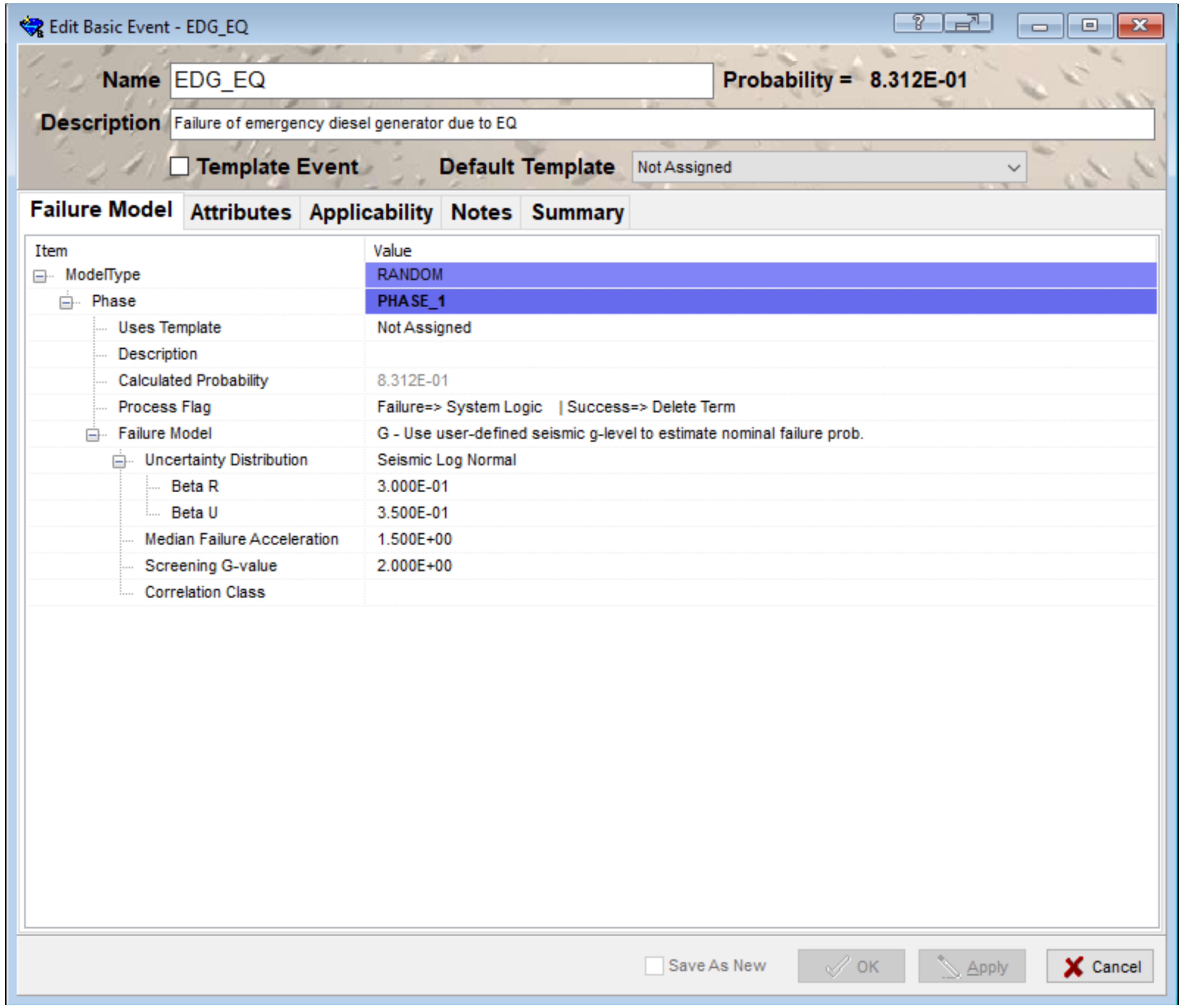
a: seismic acceleration (typically expressed in peak ground acceleration)

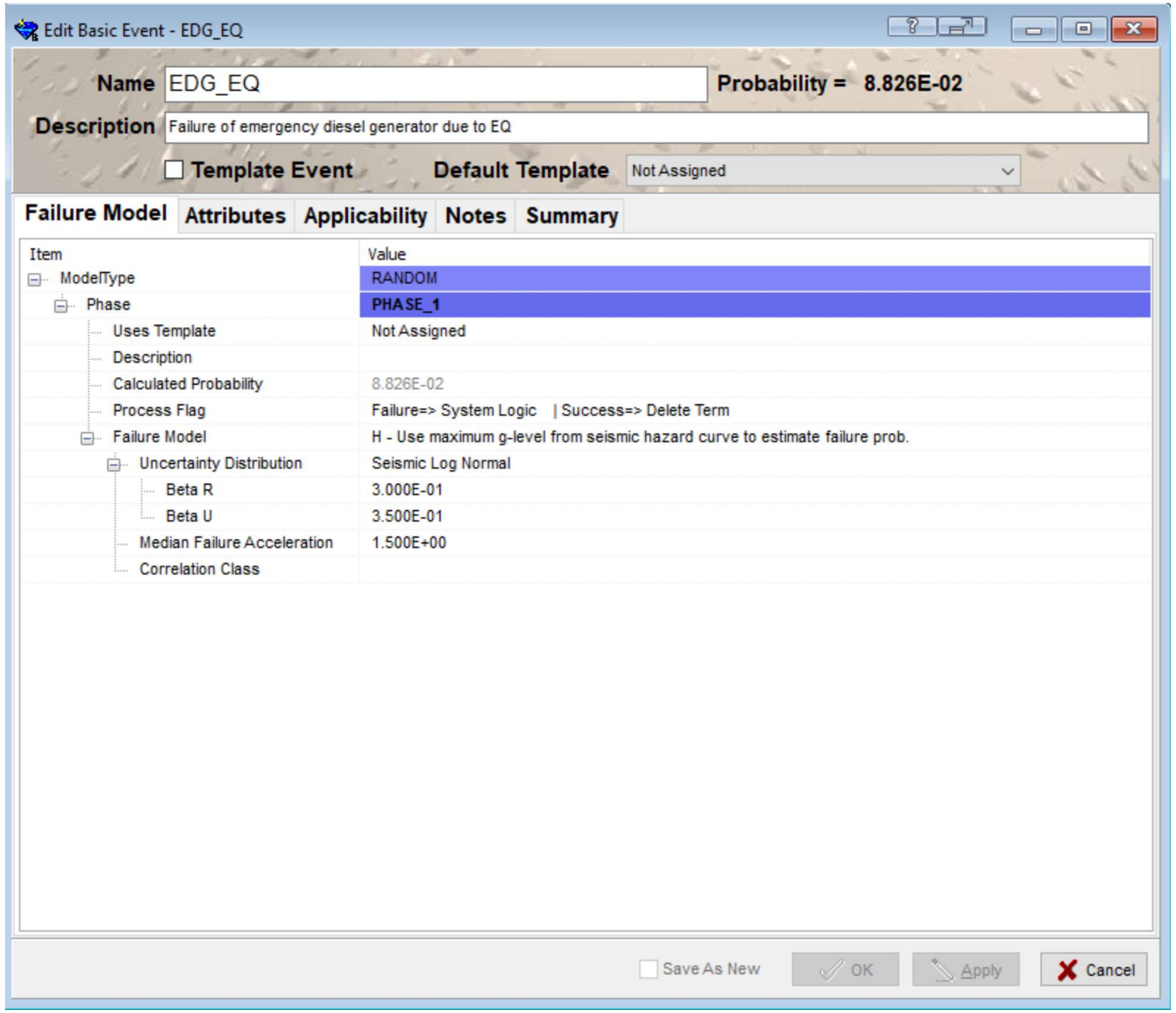
A_m: Median ground acceleration capacity

Q: subjective probability (confidence) that the conditional probability of failure is less than f for peak ground acceleration a

SAPHIRE seismic basic event

Multiple seismic basic events need to be created within the project for calculation

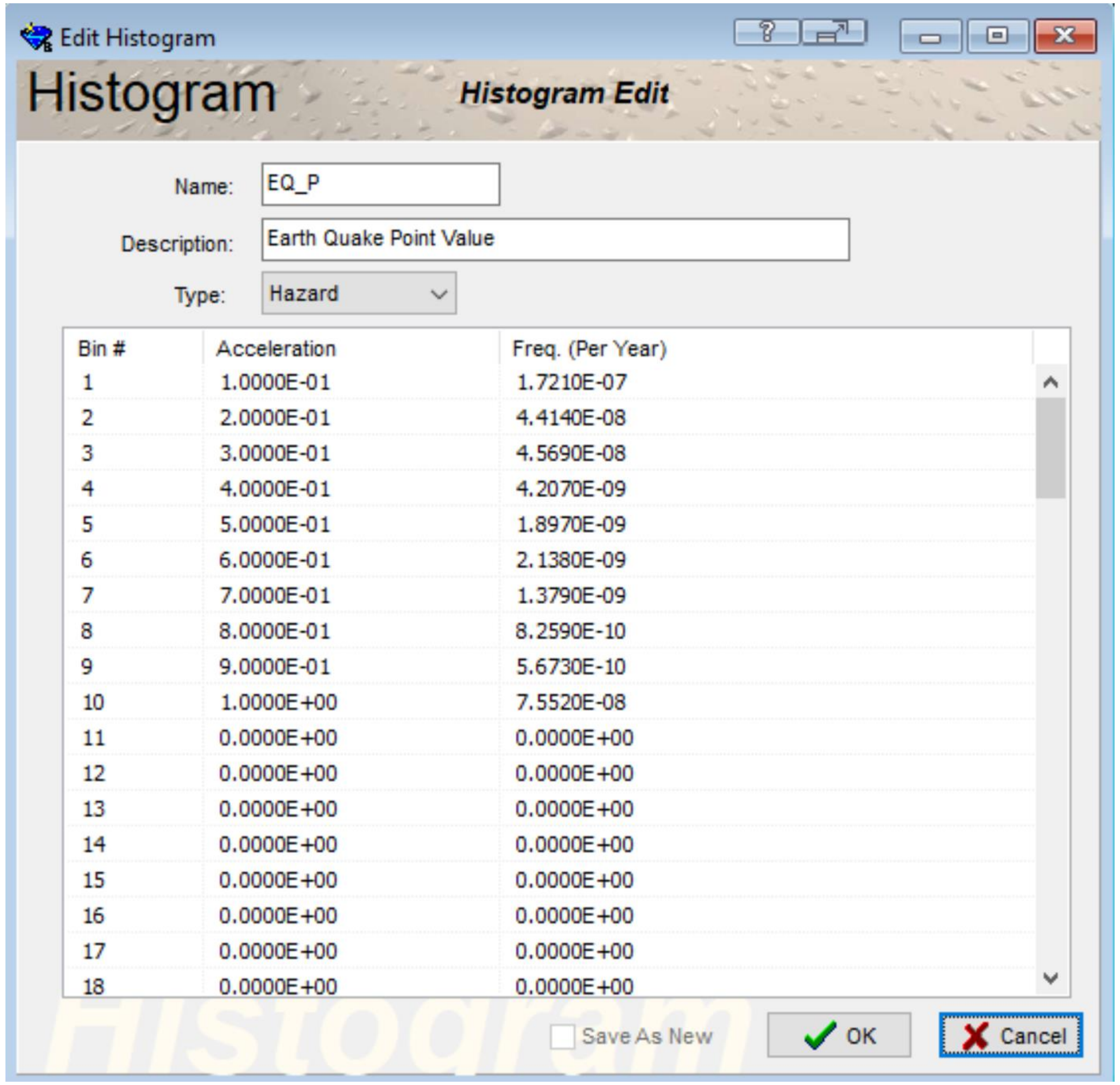




Histogram of ground motions

In case when basic event model type is used as „H", failure acceleration is used from Histogram, that should be first created. In SAPHIRE histograms can have up to 100 bins.

In case of user specified ground motion the probbability of exceedance of this ground motion is needed.

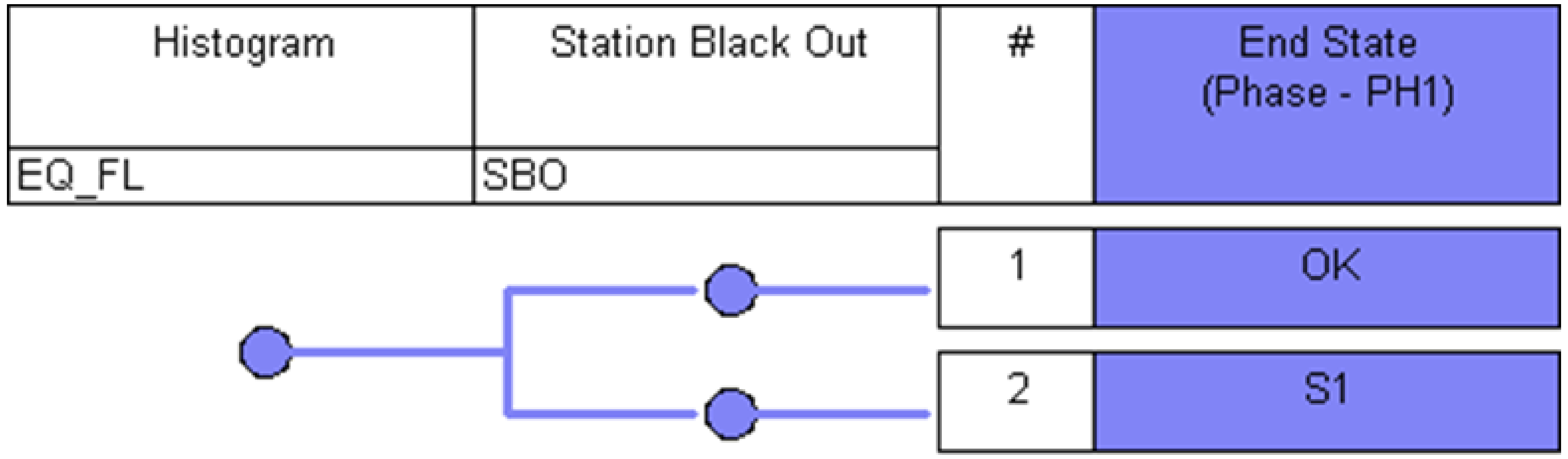


Narsis Example Histogram of Ground Motions

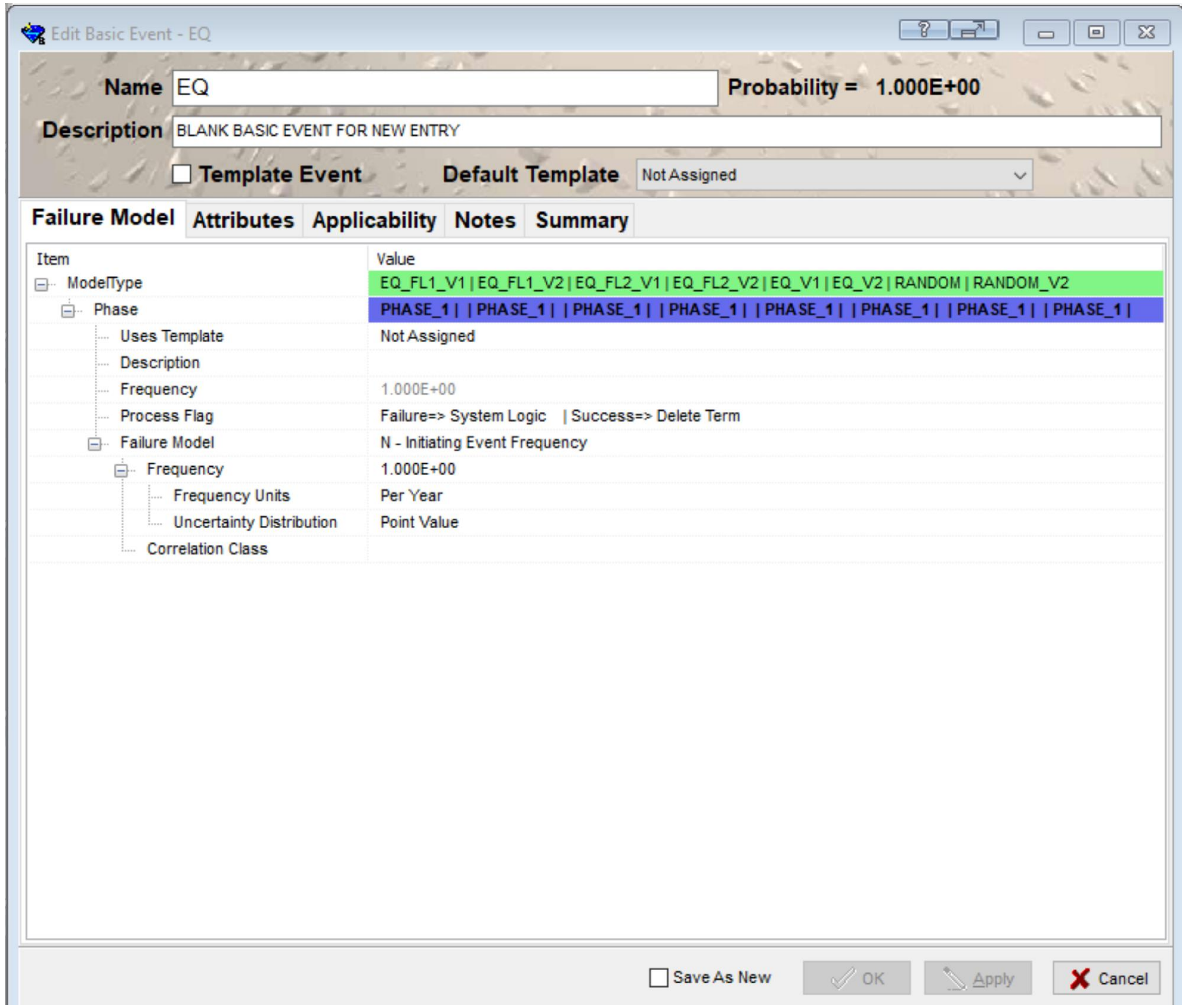
Event Tree

For calculation purproses in case of histogram usage, simple event tree is needed, where Initiating Event has probability of 1.

In case of user specified ground motion, event tree is created with Initiating Event probability equals to probability of exceedance of specified ground motion



Event Tree



Initiating Event

Example 1 from NARSIS project

Station Black Out fault tree with 9 EQ basic events **Orange Color** and 35 Basic events including Common Cause Failure **Blue Color**

The equipment used during SBO is 4 Emergency Diesel Generators, their busbases and Instrumentation and Control that actuates Diesel Generators.

Example 1 from NARSIS project

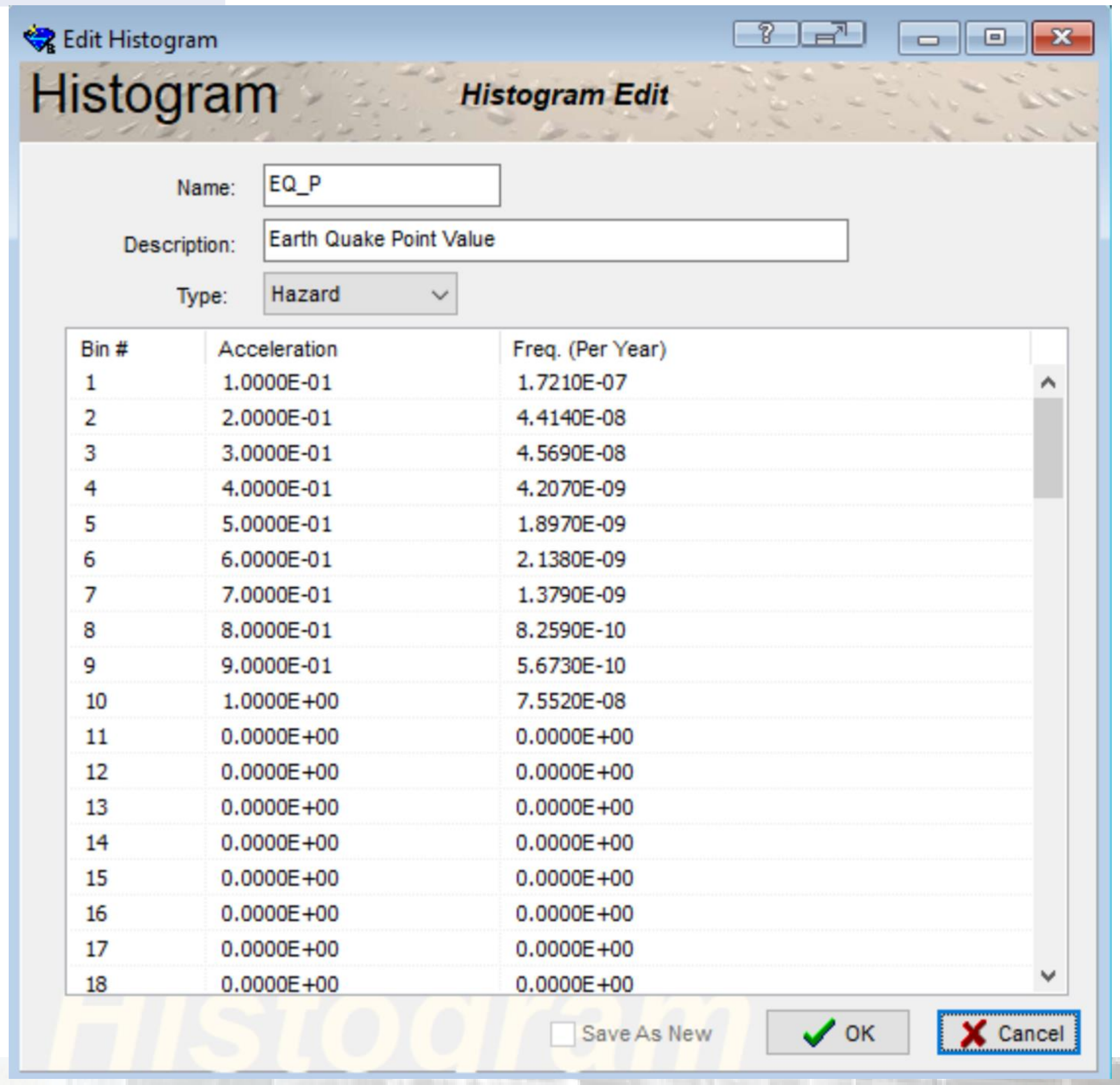
For the NARSIS project example purposes EPRI recommended System, Structure, and Component seismic fragilities were taken for:

- Instrumentation and Control
- Emergency Diesel Generator
- Busbar

Name	Am	Br	Bu	Note
480 VAC Motor Control Center (MCC) / 4 kV+ AC Bus / DC Motor Control Center (MCC) / Panel (Electric or Instrument) / Switchgear / Bus	2.0	0.30	0.35	Used in example
	0.5	0.30	0.35	
Local instruments / transmitters	3.0	0.35	0.50	Used as I&C failure
Emergency Diesel Generator (EDG)	1.5	0.30	0.35	Loss of function

EPRI recommended seismic fragilities

Additionally histogram of ground motion with 10 bins was created



Example 1 from NARSIS project

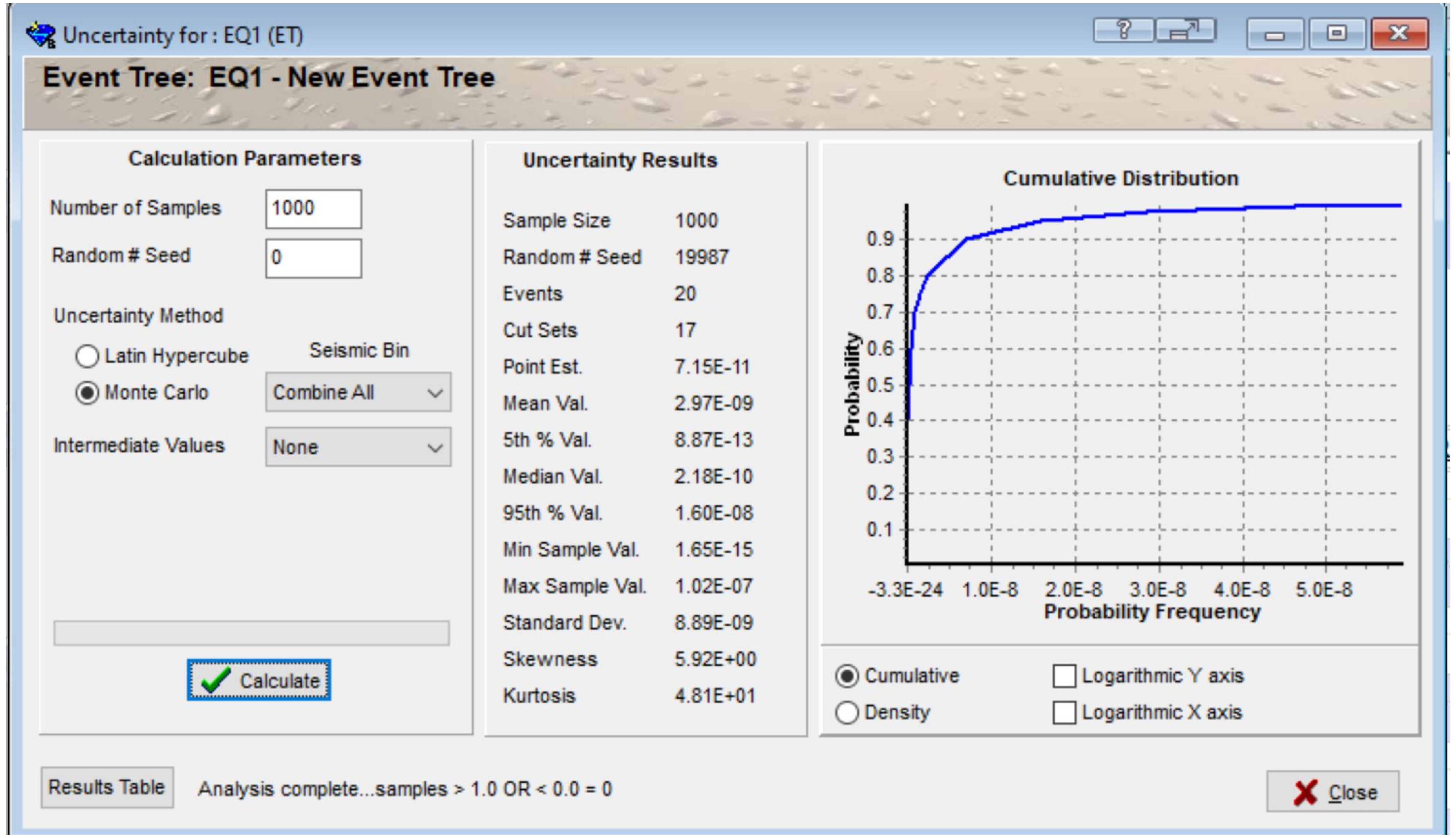
Failure of SBO without EQ is 2.74E-4

Failure of the SBO due to EQ only with PGA of 1g is calculated as 9.43E-4 (without EQ frequency)

Mean EQ Failure probability based on histogram: 2.97E-9

Overall probability of SBO failure is sum of failure without EQ and failure due to EQ. That gives us 2.74E-4+2.97E-9

In this case uncertainty of separate histogram bins can be measured



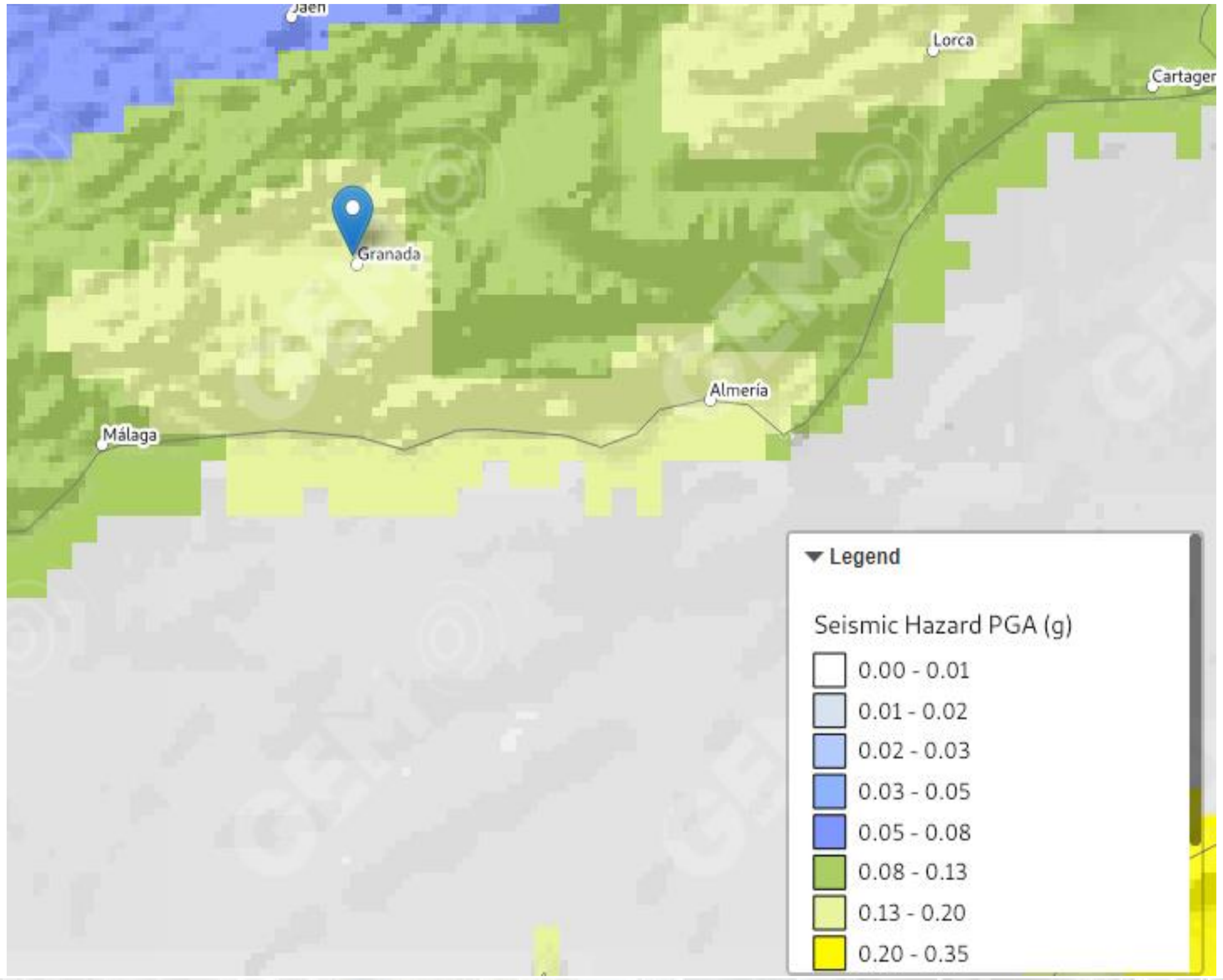
Example 2 from DONES project

This example is more complex due to complexity of Test Cell isolation and Lithium Loop Cell Isolation.

Because of lack of precise information on EQ in the location of the facility user defined seismic g-level was used.

Maximum PGA and probability of Exceedance were taken from Global Earthquake Model Foundation

The International Fusion Materials Irradiation Facility - Demo Oriented NEutron Source (IFMIF-DONES) is a single-sited novel Research Infrastructure for testing, validation and qualification of the materials to be used in a fusion reactor. It is based on a unique neutron source with energy spectrum and flux tuned to those expected for the first wall containing future fusion reactors.



Example 2 from DONES project

Information regarding EQ fragility was taken from various sources and consists of 9 fragilities

The project has:
3 Main Fault Trees
10 Sub Trees
131 Basic Event
109 Gates
and
11 Model Types

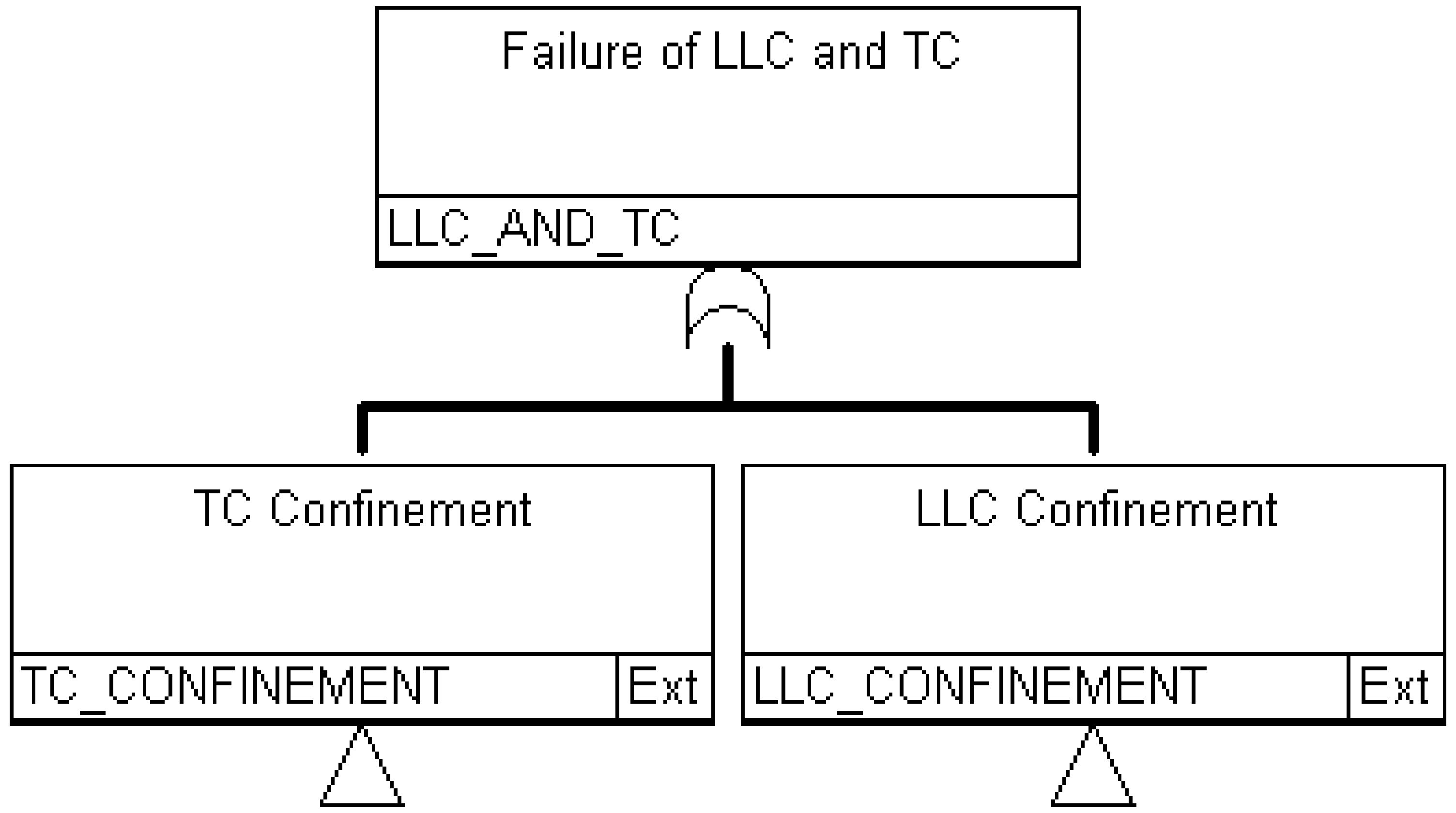
Statistics	TC Confinement for Eurofussion
11.12.2020 16:08:43	

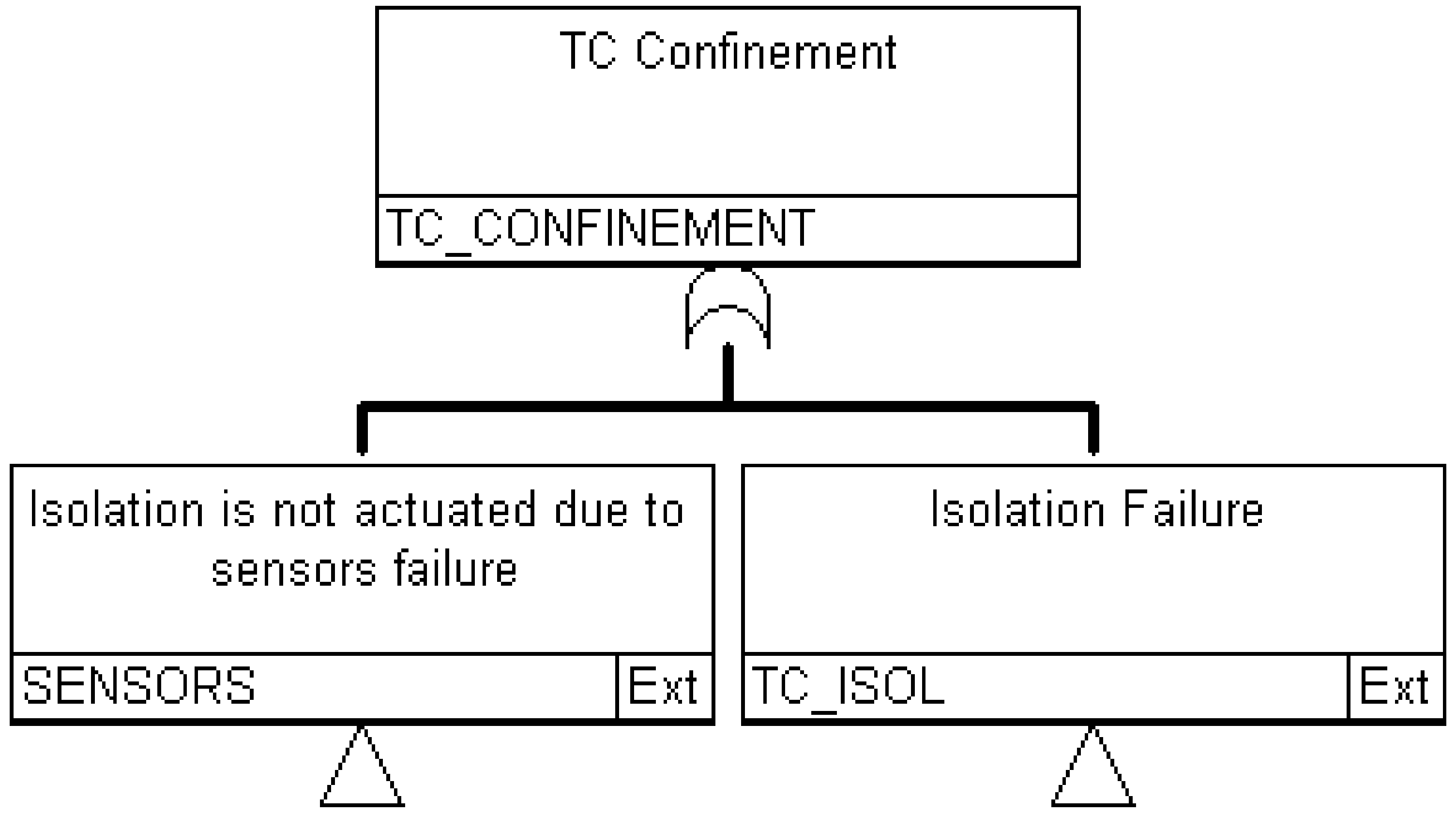
Data Type	Number of Records
Fault Trees (Tops)	3
Fault Trees (All)	13
Event Trees (Tops)	0
Event Trees (All)	0
Basic Events	131
Gates	109
Sequences	0
End States	2
Change Sets	0
Flag Sets	0
Histograms	1
Model Types	11
Phases	1

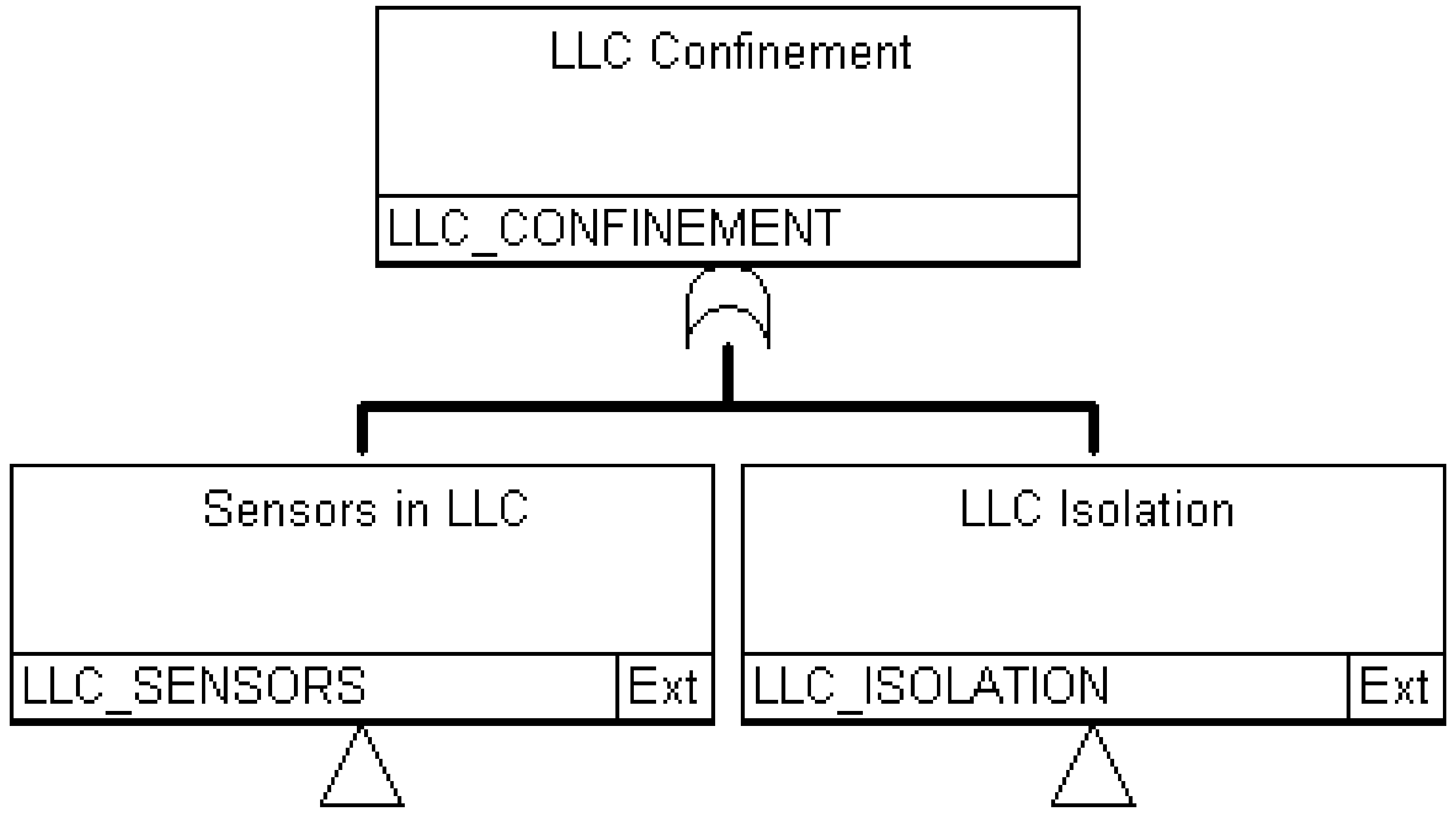
Name	Am	B	Br	Bu
Failure of hatch (tearing)	3		0.18	0.2
Failure of sealing gasket	0.5		0.3	0.25
Failure of flange	4.665	0.413	0.2	0.361
Failure of change position of Solenoid Valve	12.34		0.37	0.39
Leakage/Repture of Solenoid Valve	2.5		0.3	0.5
Failure of Pipe	8.24	0.144	0.104	0.1
Failure of weld	4.933		0.2	0.33
Failure of window (plastic)	1		0.18	0.33
Failure of Liner (steel plate)	2		0.3	0.35

Example 2 from DONES project

It was assumed that sensors can't be damaged by EQ







Example 2 from DONES project

Example 2 from DONES project

Example 2 from DONES project

Fault Tree Name	Failure Probability	Description
TC_HATCH	3.38E-03	Test Cell Hatches Isolation
TC_ISOL_TSA	0.000E+0	Failure of TSA Automatic Isolation Valves
PENETRATIONS	8.216E-15	Penetrations Isolation
TC_LINER_WELDINGS	8.216E-15	Failure of Liner or Liner Welding's
TC_ISOL	3.38E-03	Isolation Failure
LLC_VALVE_PENETRATIONS	8.216E-15	Failure of Isolation Valves and Penetration Isolation
LLC_LINER_WELDINGS	8.216E-15	Failure of Liner or Liner Welding's
LLC_ISOLATION	1.643E-14	Isolation Failure
LLC_AND_TC	3.38E-03	Fail of LLC isolation or TC isolation

Seismic Fault Tree results for 0.2g

Sub Failure Tree Name	Failure Probability	Description
TC_HATCH	1.271E-01	Test Cell Hatches Isolation
TC_ISOL_TSA	2.365E-12	Failure of TSA Automatic Isolation Valves
PENETRATIONS	1.517E-10	Penetrations Isolation
TC_LINER_WELDINGS	1.277E-10	Failure of Liner or Liner Welding's
TC_ISOL	1.271E-01	Isolation Failure
LLC_VALVE_PENETRATIONS	1.510E-10	Failure of Isolation Valves and Penetration Isolation
LLC_LINER_WELDINGS	1.277E-10	Failure of Liner or Liner Welding's
LLC_ISOLATION	2.786E-10	Isolation Failure
LLC_AND_TC	1.271E-01	Fail of LLC isolation or TC isolation

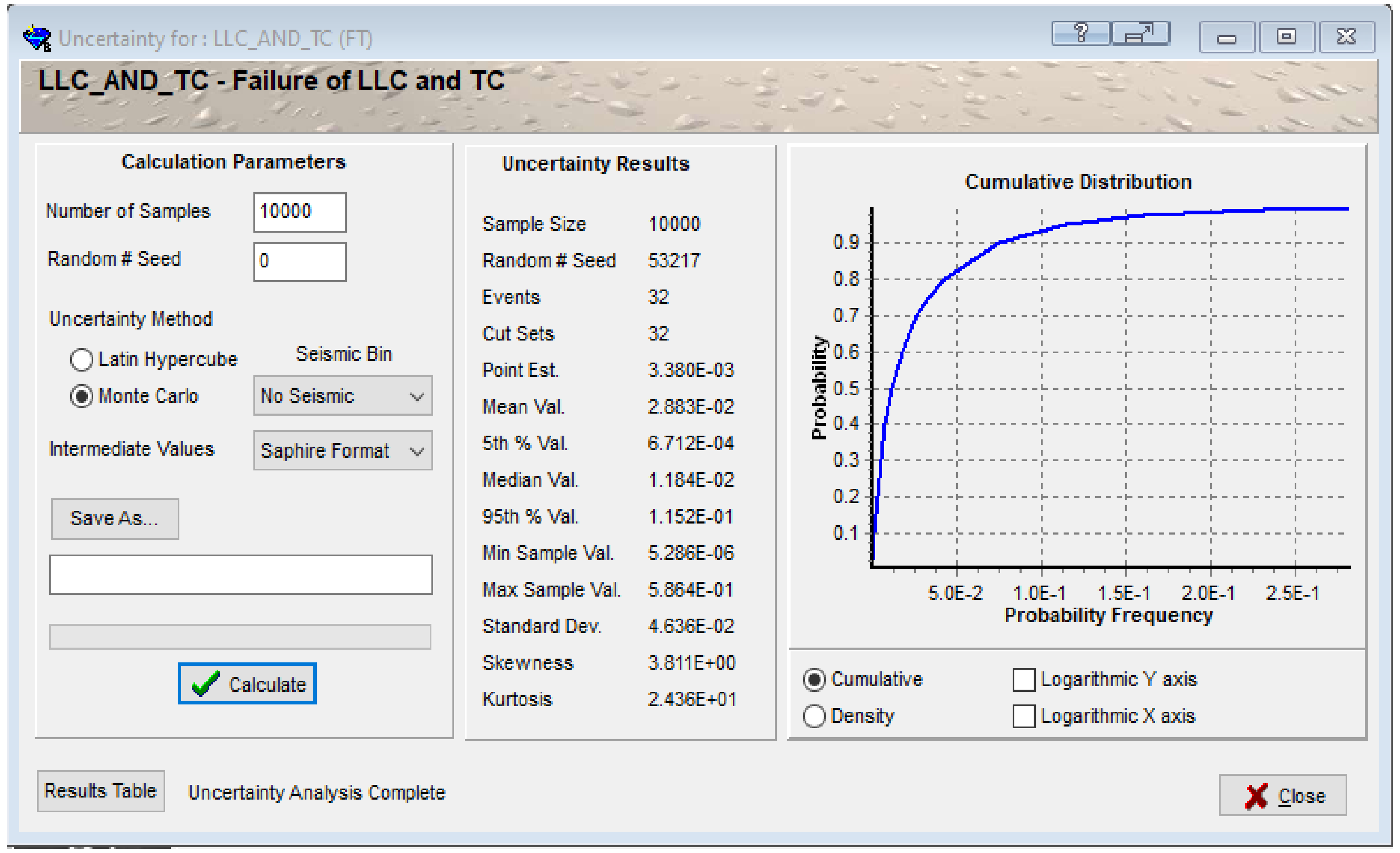
Seismic Fault Tree results for 0.3g

Conditional Probability assuming that EQ has occured

Example 2 from DONES project

#	Prob/Freq	Total %	Cut Set
Total	3.380E-3	100	Displaying 32 Cut Sets. (32 Original)
1	1.128E-3	33.37	TCCP_SG
2	1.128E-3	33.37	TLIC_HATCH_B_SG
3	1.128E-3	33.37	TLIC_HATCH_A_SG
4	8.253E-15	< 0.01	LLC_LINER
5	8.253E-15	< 0.01	TC_LINER
6	8.253E-15	< 0.01	TLIC_CONFINEMENT
7	1.897E-17	< 0.01	BD_A_VALVE_L
8	1.897E-17	< 0.01	BD_B_VALVE_L
9	1.897E-17	< 0.01	GPS_VALVE_L
10	1.897E-17	< 0.01	MPHCS_VALVE_L
11	1.897E-17	< 0.01	LPHCS_VALVE_L
12	1.897E-17	< 0.01	LLC_VALVE_SGS_L
13	1.923E-19	< 0.01	TLIC_WINDOW_A_L
14	1.923E-19	< 0.01	TLIC_WINDOW_B_L
15	1.323E-22	< 0.01	LLC_LINER_WELD
16	3.948E-29	< 0.01	BD_A_VLAVE_FTCP
17	3.948E-29	< 0.01	BD_B_VALVE_FTCP
18	3.948E-29	< 0.01	GPS_VALVE_FTCP
19	3.948E-29	< 0.01	MPHCS_VALVE_FTCP
20	3.948E-29	< 0.01	LPHCS_VALVE_FTCP
21	3.948E-29	< 0.01	LLC_VALVE_SGS_FTCP
22	4.523E-42	< 0.01	TCCP1

Seismic Cut Sets for 0.2g



Uncertainty Results for 0.2 g without EQ frequency

Example 2 from DONES project

Sub Fault Tree Name	Failure Probability	Description
TC_Confinement	9.697E-3	Failure of TC Confinement
LLC_Confinement	4.504E-3	Failure of LLC Confinement
LLC_AND_TC	1.263E-2	Failure of LLC and/or TC

Results of the DONES Test Cell and Lithium Loop Cell Confinement Failure without EQ

#	Prob/Freq	Total %	Cut Set
Total	1.263E-2	100	Displaying 36 Cut Sets. (36 Original)
1	1.000E-3	7.92	HUMAN_D
2	1.000E-3	7.92	BD_A_VLAVE_FTCP
3	1.000E-3	7.92	BD_B_VALVE_FTCP
4	1.000E-3	7.92	GPS_VALVE_FTCP
5	1.000E-3	7.92	MPHCS_VALVE_FTCP
6	1.000E-3	7.92	LPHCS_VALVE_FTCP
7	1.000E-3	7.92	LLC_VALVE_SGS_FTCP
8	8.756E-4	6.93	TLIC_WELD
9	8.756E-4	6.93	TC_LINER_WELD
10	8.756E-4	6.93	LLC_LINER_WELD
11	8.157E-4	6.46	TC_RAD_ND
12	6.190E-4	4.90	BD_A_FLANGE
13	6.190E-4	4.90	BD_B_FLANGE
14	2.928E-4	2.32	TLIC_WINDOW_A_L
15	2.928E-4	2.32	TLIC_WINDOW_B_L
16	8.760E-5	0.69	LLC_LINER
17	8.760E-5	0.69	TC_LINER
18	8.760E-5	0.69	TLIC_CONFINEMENT

Example 2 from DONES project

According to GEM foundation their Open Quake map shows 10% probability of exceedance in 50 years.

Therefore probability of exceedance of 0.13-0.2g Earthquake for Escuzar province of Granada will be 2E-3

With this information we can calculate probability of Failure due to EQ as multiplication of conditional probability and probability of exceedance of PGA and it will give us probability 6,76E-6

The overall failure probability will be sum of Probability of failure withought EQ and Probability of failure due to EQ. The sum of this probabilities will give us: 1.263E-2. Since the probability of failure due to EQ is 4 order of size lower.

Conclusions

To perform Seismic Probabilistic Risk Assessment there is need for:

a) Seismic hazard analysis – for developing frequencies of occurence of different levels of earthquake ground motion (PGA) at the site

b) Seismic fragility evaluation – estimates the conditional probabilities of failure of important structures and equipment

c) Systems analysis – used to model the combinations of structural and eqipment failures that could initiate and propagate seismic failure sequence (for NPP seismic core damage sequence)

The SAPHIRE program is well known tool that is used in U.S. NRC, NASA. It has implemented seismic system analysis tools, shown during presentation.

With apropriate modification of fault trees and histograms there is option to model multiple hazards such as combination of EQ and Flooding etc.

References

[1] IAEA-TECDOC-724 „*Probabilistic safety assessment for seismic events*”

[2] Nuclear Power Plans and Earthquakes (www.world-nuclear.org)

[3] Saphire 8 Advance manual

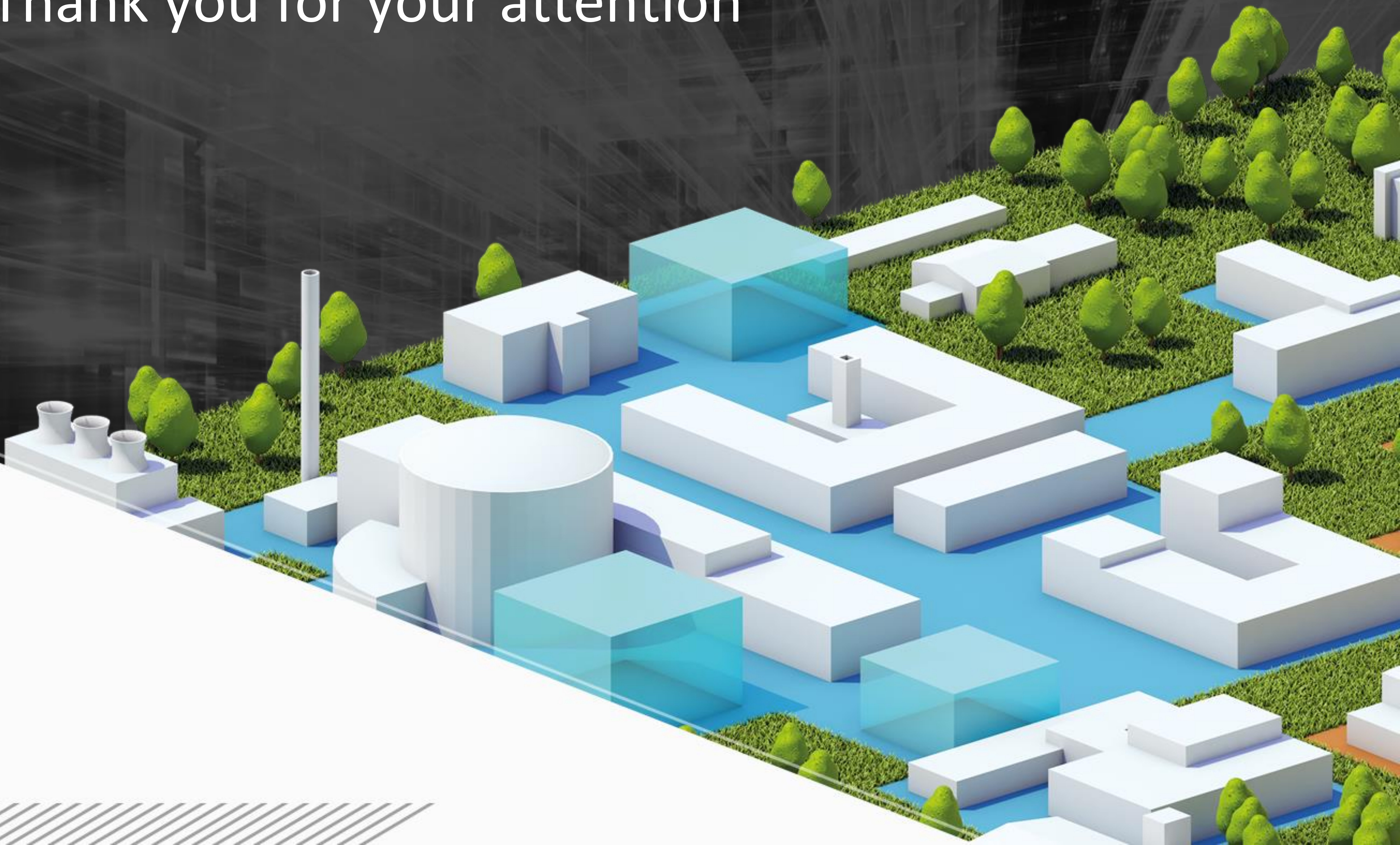
[4] Saphire 8 Basic manual

[5] I. Zentner et all. *Numerical Calculation Of Fragility Curves For Probabilistic Seismic Risk Assessment.* The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China

[6] EPRI *Seismic Probabilistic Risk Assessment Implementation Guide*

[7] Global Earthquake Model Foundation (https://www.globalquakemodel.org)

Thank you for your attention



NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

www.ncbj.gov.pl

Multiple hazard

SBO with 4-5.62m flooding.
Histogram consist of probability of EQs with Flooding 4m-5.62m