



Advanced Safety Assessment
Methodologies: extended PSA



"NUCLEAR FISSION"
Safety of Existing Nuclear Installations

Contract 605001

**Report 1: Guidance document on practices to model and implement
SEISMIC hazards in extended PSA**

- *This version of the report will be submitted to a peer review*
- *The conclusions of the review will be discussed during the ASAMPSA_E workshop with PSA End-Users (12-14th Sept. 2016)*
- *The report will then be improved before the end of the project (31st Dec. 2016)*

Reference ASAMPSA_E
Technical report ASAMPSA_E/ WP22/ D22.2-1 2016-19
Reference IRSN PSN/RES/SAG/2016-0233

J. Prochaska (VUJE), P. Halada (VUJE), M. Pellissetti (Areva),
M. Kumar (LRC)

Period covered: from 01/07/2013 to 31/12/2016		Actual submission date: 29/06/2016
Start date of ASAMPSA_E: 01/07/2013		Duration: 42 months
WP No: 22	Lead topical coordinator : Jan Prochaska	His organization name : VUJE

Project co-funded by the European Commission Within the Seventh Framework Programme (2013-2016)		
Dissemination Level		
PU	Public	No
RE	Restricted to a group specified by the partners of the ASAMPSA_E project	Yes
CO	Confidential, only for partners of the ASAMPSA_E project	No

	<p>Advanced Safety Assessment Methodologies: extended PSA</p>	
--	---	--

ASAMPSA_E Quality Assurance page

Partners responsible of the document : VUJE, LRC, IRSN	
Nature of document	Technical report
Reference(s)	Technical report ASAMPSA_E/ WP22/ D22.2-1 2016-19 Reference IRSN PSN/RES/SAG/2016-0233
Title	Summary report of already existing guidance on the implementation of External Hazards in extended Level 1 PSA
Author(s)	J. Prochaska (VUJE), P. Halada (VUJE), M. Pellissetti (Areva), M. Kumar (LRC)
Delivery date	29 June 2016
Topical area	Probabilistic safety assessment, external hazards, seismic
For Journal & Conf. papers	No
<p><u>Summary :</u></p> <p>The objective of this report is to provide guidance for the implementation of external hazards in extended L1 PSA. This report is a deliverable of the work package 22 (WP22) - 'How to introduce hazards in L1 PSA and all possibilities of events combinations' - which aims to promote exchanges and to identify some good practices on the implementation of external events in L1 PSA, having as a perspective the development of extended PSA from an existing (internal events) L1 PSA (event trees).</p> <p>The following topics are addressed :</p> <ol style="list-style-type: none"> 1) Impact on the SSCs modelled in L1 PSA event trees 2) Impact on Human Reliability Assessment modelling in L1 PSA 3) Site impact modelling in L1 PSA event trees 4) Link between external initiating events of PSA and NPP design basis conditions. 	

Visa grid			
	Main author(s) :	Verification	Approval (Coordinator)
Name (s)	J. Prochaska (VUJE)	M. Kumar (LRC)	E. Raimond (IRSN)
Date	23.6.2016	28.06.2016	29.06.2016
Signature			

MODIFICATIONS OF THE DOCUMENT

Version	Date	Authors	Pages or paragraphs modified	Description or comments
a030	11.03.2016	J. Prochaska (VUJE)	All	Draft for review
a035	23.06.2016	J. Prochaska (VUJE)	All	Incorporated review comments from LRC, AREVA, JANSI, INRNE, IRSN.
V1	29.09.2016	E. Raimond (IRSN)	All	Few editorial modifications. The report could be completed with practical examples during the review phase.

LIST OF DIFFUSION

European Commission (Scientific Officer)

Name	First name	Organization
Passalacqua	Roberto	EC

ASAMPSA_E Project management group (PMG)

Name	First name	Organization	
Raimond	Emmanuel	IRSN	Project coordinator
Guigueno	Yves	IRSN	WP10 coordinator
Decker	Kurt	UNIVIE	WP21 coordinator
Klug	Joakim	LRC	WP22 coordinator until 2015-10-31
Kumar	Manorma	LRC	WP22 coordinator from 2015-11-01
Wielenberg	Andreas	GRS	WP30 coordinator until 2016-03-31
Löffler	Horst	GRS	WP40 coordinator WP30 coordinator from 2016-04-01

REPRESENTATIVES OF ASAMPSA_E PARTNERS

Name	First name	Organization
Grindon	Liz	AMEC NNC
Mustoe	Julian	AMEC NNC
Cordoliani	Vincent	AREVA
Dirksen	Gerben	AREVA
Godefroy	Florian	AREVA
Kollasko	Heiko	AREVA
Michaud	Laurent	AREVA
Hasnaoui	Chiheb	AREXIS

Name	First name	Organization
Hurel	François	AREXIS
Schirrer	Raphael	AREXIS
De Gelder	Pieter	Bel V
Gryffroy	Dries	Bel V
Jacques	Véronique	Bel V
Van Rompuy	Thibaut	Bel V
Cazzoli	Errico	CCA
Vitázková	Jirina	CCA

Name	First name	Organization
Passalacqua	Roberto	EC
Banchieri	Yvonnick	EDF
Benzoni	Stéphane	EDF
Bernadara	Pietro	EDF
Bonnevialle	Anne-Marie	EDF
Brac	Pascal	EDF
Coulon	Vincent	EDF
Gallois	Marie	EDF
Henssien	Benjamin	EDF
Hibti	Mohamed	EDF
Jan	Philippe	EDF
Lopez	Julien	EDF
Nonclercq	Philippe	EDF
Panato	Eddy	EDF
Parey	Sylvie	EDF
Romanet	François	EDF
Rychkov	Valentin	EDF
Vasseur	Dominique	EDF
Burgazzi	Luciano	ENEA
Hultqvist	Göran	FKA
Karlsson	Anders	FKA
Ljungbjörk	Julia	FKA
Pihl	Joel	FKA
Loeffler	Horst	GRS
Mildenberger	Oliver	GRS
Sperbeck	Silvio	GRS
Tuerschmann	Michael	GRS
Wielenberg	Andreas	GRS
Benitez	Francisco Jose	IEC
Del Barrio	Miguel A.	IEC
Serrano	Cesar	IEC
Apostol	Minodora	ICN
Nitoi	Mirela	ICN
Groudev	Pavlin	INRNE
Stefanova	Antoaneta	INRNE
Andreeva	Marina	INRNE
Petya	Petrova	INRNE
Armingaud	François	IRSN
Bardet	Lise	IRSN
Baumont	David	IRSN
Bonnet	Jean-Michel	IRSN
Bonneville	Hervé	IRSN
Clement	Christophe	IRSN
Corenwinder	François	IRSN
Denis	Jean	IRSN
Duflot	Nicolas	IRSN
Duluc	Claire-Marie	IRSN
Dupuy	Patricia	IRSN
Durin	Thomas	IRSN
Georgescu	Gabriel	IRSN
Guigueno	Yves	IRSN
Guimier	Laurent	IRSN
Lanore	Jeanne-Marie	IRSN
Laurent	Bruno	IRSN
Pichereau	Frederique	IRSN
Rahni	Nadia	IRSN
Raimond	Emmanuel	IRSN
Rebour	Vincent	IRSN
Sotti	Oona	IRSN
Volkanovski	Andrija	JSI
Prošek	Andrej	JSI
Alzbutas	Robertas	LEI
Matuzas	Vaidas	LEI
Rimkevicius	Sigitas	LEI
Häggström	Anna	LRC
Klug	Joakim	LRC
Kumar	Manorma	LRC
Olsson	Anders	LRC
Borysiewicz	Mieczyslaw	NCBJ
Kowal	Karol	NCBJ

Name	First name	Organization
Potemski	Slawomir	NCBJ
La Rovere	Stephano	NIER
Vestrucci	Paolo	NIER
Brinkman	Hans (Johannes L.)	NRG
Kahia	Sinda	NRG
Bareith	Attila	NUBIKI
Lajtha	Gabor	NUBIKI
Siklossy	Tamas	NUBIKI
Morandi	Sonia	RSE
Caracciolo	Eduardo	RSE
Dybach	Oleksiy	SSTC
Gorpinchenko	Oleg	SSTC
Claus	Etienne	TRACTEBEL
Dejardin	Philippe	TRACTEBEL
Grondal	Corentin	TRACTEBEL
Mitaille	Stanislas	TRACTEBEL
Oury	Laurence	TRACTEBEL
Zeynab	Umidova	TRACTEBEL
Yu	Shizhen	TRACTEBEL
Bogdanov	Dimitar	TUS
Ivanov	Ivan	TUS
	Kaleychev	TUS
Holy	Jaroslav	UJV
Hustak	Stanislav	UJV
Jaros	Milan	UJV
Kolar	Ladislav	UJV
Kubicek	Jan	UJV
Decker	Kurt	UNIVIE
Halada	Peter	VUJE
Prochaska	Jan	VUJE
Stojka	Tibor	VUJE

REPRESENTATIVE OF ASSOCIATED PARTNERS (External Experts Advisory Board (EEAB))

Name	First name	Company
Hirata	Kazuta	JANSI
Hashimoto	Kazunori	JANSI
Inagaki	Masakatsu	JANSI
Yamanana	Yasunori	TEPCO
Coyne	Kevin	US-NRC
González	Michelle M.	US-NRC

EXECUTIVE SUMMARY

/The executive summary will be improved in the final version - The report may be merged with ASAMPSA_E deliverable D21.3-1 [4] -SEISMIC hazards modelling in extended PSA /

The report provides guidance on practices to model and implement seismic hazards in extended PSA. It includes the following sections:

- Section 2 “Objectives/Scope of seismic PSA” and section 3 “Structure of seismic PSA” provide link between standard PSA methodology and enhanced methodology to incorporate requirements from the ASAMPSA_E extended PSA framework.
- Section 4 “Development of extended seismic PSA” discusses detail regarding implementation of extended seismic PSA.
- Section 5 “Post-seismic PSA” introduces outline of methodology to evaluate situation beyond mission time considered in PSA including the emergency response.
- Section 6 discusses conclusions, recommendations and open issues in development of extended seismic PSA.

As it was recommended by ASAMPSA_E end users (WP 10 report [38]), this guidance includes considerations for the extension of seismic PSA, including the methods to model the combinations/correlations/dependencies of hazards, possible secondary effects, multi-unit response, mitigating and aggravating factors. This report contains approaches to model mobile equipment but despite this fact, input data related to this (reliability and related human actions, assessment of time for its running) remains a source of significant uncertainty. Approaches for building hazards curves and fragility curves are described in the guidance and presented useful references, as well as approaches for site response analysis (SSCs failure modes, buildings resistance, etc.). The question of how to perform post-seismic analyses is also considered by the report.

The scope of the guidance is quite wide thus the report presents some specific focus on the open issues in the existing guidance and current practices. The report aims to provide brief discussion regarding seismic PSA from ASAMPSA_E point of view and considering post- Fukushima lessons learned on PSA.

ASAMPSA_E PARTNERS

The following table provides the list of the ASAMPSA_E partners involved in the development of this report.

1	Institute for Radiological Protection and Nuclear Safety	IRSN	France
5	Lloyd's Register Consulting	LRC	Sweden
16	AREVA NP SAS France	AREVA NP SAS	France
19	VUJE	VUJE	Slovakia
25	Institute of nuclear research and nuclear energy - Bulgarian Academia of science	INRNE	Bulgaria
31	Japan Nuclear Safety Institute	JANSI	Japan

CONTENT

MODIFICATIONS OF THE DOCUMENT	3
LIST OF DIFFUSION	3
EXECUTIVE SUMMARY	6
ASAMPSA_E Partners	7
CONTENT	8
ABBREVIATIONS	10
DEFINITIONS	11
1 INTRODUCTION	12
2 OBJECTIVES/SCOPE OF SEISMIC PSA	13
2.1 General consideration regarding Objectives and scope of seismic PSA	13
3 STRUCTURE OF SEISMIC PSA	16
4 DEVELOPMENT OF EXTENDED SEISMIC PSA	23
4.1 Review plant safety and modify available event analyses	24
4.1.1 (Internal) Seismic initiating events	24
4.1.2 (Internal) seismically induced initiating events	24
4.1.2.1 Internal fires and explosions.....	25
4.1.2.2 Internal floods.....	26
4.1.3 Induced external events.....	27
4.1.4 Summary of step 1 - Review Plant Safety.....	33
4.2 Developing seismic PSA SSC List	36
4.3 Seismic Hazard Analysis	37
4.4 Walkdowns.....	38
4.5 Screening	39
4.5.1 Initiating events screening	39
4.5.2 SSC screening	40
4.5.2.1 Surrogating approach	41
4.5.2.2 Screening based on seismic capacity	42
4.6 Fragility analysis	42
4.6.1 Basic internal items ensuring fulfillment of fundamental safety functions including (internal) seismic events (category BI and TI)	42
4.6.2 Flood internal items which failure can lead to internal floods (category FI)	44
4.6.3 Fire internal items acting as potential ignition sources (category II)	44
4.6.4 External items capable evoking induced events (category EI).....	45
4.6.4.1 Assessment of probability of occurrence of seismic event (Ps)	45

4.6.4.2 Assessment of probability of releasing source of potential damage (Pm)	45
4.6.4.3 Assessment of conditional probability of affecting plant safety (Pa)	46
4.6.5 Special internal items that involve in-site effects (category SI)	47
4.6.6 Concluding notes to the fragility analysis	47
4.6.7 Hazard and fragility analysis PSA tool	48
4.7 Developing seismic fault and event trees	53
4.7.1 Event trees.....	53
4.7.2 Fault trees.....	56
4.7.3 Human error probabilities (HEP).....	59
4.8 Seismic risk quantification	60
4.9 Reporting.....	60
4.10 Specific aspects of extended PSA	61
4.10.1 Interface PSA Level 1 and PSA level 2	61
4.10.1.1 Definition of Plant Damage States (PDS) for seismic initiating events	61
4.10.2 Level 2 PSA	62
4.10.3 Seismic hazard analysis	63
4.10.4 Spent fuel Pool and other nuclear facilities (multi-unit effects).....	63
4.10.5 Correlation of seismic failures	63
5 POST-SEISMIC PSA.....	64
5.1 Discussion regarding post-seismic PSA	64
5.2 Outline of methodology for post-seismic analysis.....	65
6 CONCLUSION, RECOMMENDATIONS AND OPEN ISSUES	67
7 LIST OF REFERENCES	68
8 LIST OF TABLES	70
9 LIST OF FIGURES.....	70

ABBREVIATIONS

/This table will be updated in the final version of the report/

BWR	Boiling Water Reactor
CCF	Common Cause Failure
CCDF	Conditional Core Damage Frequency
CDF	Core Damage Frequency
CWS	Cooling Water System
DB	Data Base
DPD	Discrete Probability Distributions
EOP	Emergency Operating Procedure
EPRI	Electric Power Research Institute
ESWS	Essential Service Water System
ET	Event Tree
HEP	Human Error Probability
HRA	Human Reliability Analysis
HVAC	Heating, Ventilation, Air Conditioning
I&C	Instrumentation and Control
IAEA	The International Atomic Energy Agency
IRS	Incident Reporting System
LERF	Large Early Release Frequency
LRF	Large Release Frequency
LOCA	Loss of Coolant Accidents
LOOP	Loss of Off-Site Power
NPP	Nuclear Power Plant
PDS	Plant Damage State
pga	Peak Ground Acceleration
PSA	Probabilistic Safety Assessment
PRA	Probabilistic Risk Assessment
RCS	Reactor Cooling System
SAMG	Severe Accident Management Guidance
SSC	Structure System and Component
WP	Work Package

DEFINITIONS

These definitions come from IAEA and US NRC safety glossaries. Some harmonization will be done between all ASAMPSA_E reports in final versions.

/This table will be updated in the final version of the report./

(Seismic) Capacity	The ability of a component to sustain a load measured in terms of the load level (e.g., stress, moment, or acceleration) below which the component continues to perform its functions.
correlated hazard	Correlated hazards are class of hazards that vary together with seismic hazards, i.e. direct impact of seismic event can evoke further effect producing specific effects or additional hazards
Fragility	Conditional probability that a component would fail for a specified ground motion or response-parameter value as a function of that value.
HCLPF	High Confidence of Low Probability of Failure (95% confidence of less than 5% probability of failure).
induced event	Induced event is an initiating event caused by effect(s) of correlated hazard(s)
Impact analysis	A process (within seismic PSA) to estimate an effect of seismic or seismically induced failures on fulfillment of fundamental safety function.
Randomness	The variability observed from sample to sample of a physical phenomenon it cannot be reduced by more detailed evaluation or by gathering of more data.
Response spectra	A set of curves calculated from an acceleration time history that give the maximum values of response (acceleration, velocity, or displacement) of a damped linear oscillator, as a function of its natural period of vibration for given damping values.
Safety significant SSCs	SSCs that are necessary to ensure fundamental safety functions
Seismic Fragility Evaluation	A process to estimate the conditional probability of failure of important SSCs whose failure may lead to unacceptable damage to the plant.
Seismic Hazard Analysis	A process to develop frequencies of occurrence of different levels of earthquake ground motion (e.g., peak ground acceleration) at the site <i>including site surroundings that soil failures can influence plant safety</i> , as well as fragility curves (parameters) for relevant SSCs.

1 INTRODUCTION

The ASAMPSA_E project [1] offers an extended framework to discuss, at a technical level, how extended PSA can be developed efficiently and be used to verify if the robustness of NPP design in their environment is sufficient. It allows exchanges on the feasibility of “extended PSAs” able to quantify risks induced by NPPs site taking into account the following challenging aspects: multi-units site, risk associated to spent fuel pools and coupling with reactors, and the modelling of the impact of internal initiating events, and internal and external hazards on equipment and human recovery actions.

The ASAMPSA_E project pays a particular attention to the risks induced by the possible natural extreme external events and their combinations taking into account the lessons of the Fukushima Dai-ichi accident [5].

2 OBJECTIVES/SCOPE OF SEISMIC PSA

The aim of this section is to provide brief discussion regarding seismic PSA from ASAMPSA_E point of view as well as to take into account Fukushima lessons learned.

Seismic PSAs are usually focused only on nuclear reactors. Other facilities such as research reactors, fuel cycle facilities, gamma irradiation facilities and fuel storage facilities can use methods derived from those are used for NPPs. The main principles of seismic PSA have been already described in various guidelines, most of them are quoted in WP22.1 [2], and some of them are also referred in this report.

The objective of the presented report is to provide an advanced guidance describing how to model the external hazards, namely seismic hazard in this case, for extended PSA. Enhanced modeling has impact on many activities like on scope of considered SSCs, HRA, emergency and multi-unit response. Furthermore, good practices for external hazards modeling used by the ASAMPSA_E participants and their country specific experience are included.

2.1 GENERAL CONSIDERATION REGARDING OBJECTIVES AND SCOPE OF SEISMIC PSA

The majority of PSAs that include seismic event have found that seismic events represent a risk significant initiator group and consequently earthquake initiated sequences are among the largest contributors to evaluated risk at NPPs. Post Fukushima experience shows importance of understanding and familiarization with usage of methods to quantify seismic risk. Objective of this report is to address all important aspects of evaluation of seismic risk including correlated hazards (or events induced by seismic event).

The basic parts of a seismic PSA are identifying hazards, analyzing the systems, evaluating seismic fragility, and performing seismic risk quantification. Each of these four distinct areas requires a good engineering background and some level of specific training.

Nowadays seismic PSAs are relatively mature as compared to other external hazards. Also, various the best practice guidelines are available publically providing guidance on practical methodology to accomplished seismic PSA, e.g. [10], [19] and [20] which covers broad spectrum of PSA tasks. Available guidelines allow extension of standard PSA developed for internal events, e.g. PSA developed according [18], in such a way to be suitable to assess seismic risk.

On the other hand some basic seismic PSA elements are still analytically sophisticated and require extensive engineering judgment, e.g. seismic hazard analysis, evaluation of seismic load and seismic capacity etc. This report assumes that plant under evaluation is built in compliance with international guideline on seismic design and qualification of the NPPs [15], which facilitates evaluation of correlated hazards. Available results from seismic evaluation, as described in reference [17] should reduce work complexity and provide unified framework for PSA practitioners including seismologists, seismic engineers evaluating equipment qualification, PSA developers and utility engineers.

Except of above mentioned basic aspects the seismic PSA should also reflect extended requirements coming from Fukushima lessons learned. These requirements follow from main conclusions of [5] putting stress on consideration of more detailed scope of hazards, i.e. *requiring extended identification of potential hazards going more deeply beyond the already considered scope of hazards as are impact of seismically induced floods and fires*, which implies obligatory consideration of correlated hazards within seismic PSA. Another important issue following from conclusions of [5] is treatment of multi-unit hazards as well as simultaneous impact of seismic event on several parts of plant.

Above presented message of [5] implies that seismic part of the extended PSA should consider potential combinations of viable correlated hazards. On the one hand such requirement follows from general framework to analyse internal / external event provided by [18] (see bottom top right box in Fig. 3 from [18]: *Detailed analysis of accident scenarios aimed at realistic estimation of the damage potential from the initiating events induced by the hazards and calculation of the associated risk*).

Fig. 2-1 Overall approach to analyse external events in Level 1 PSA [18]

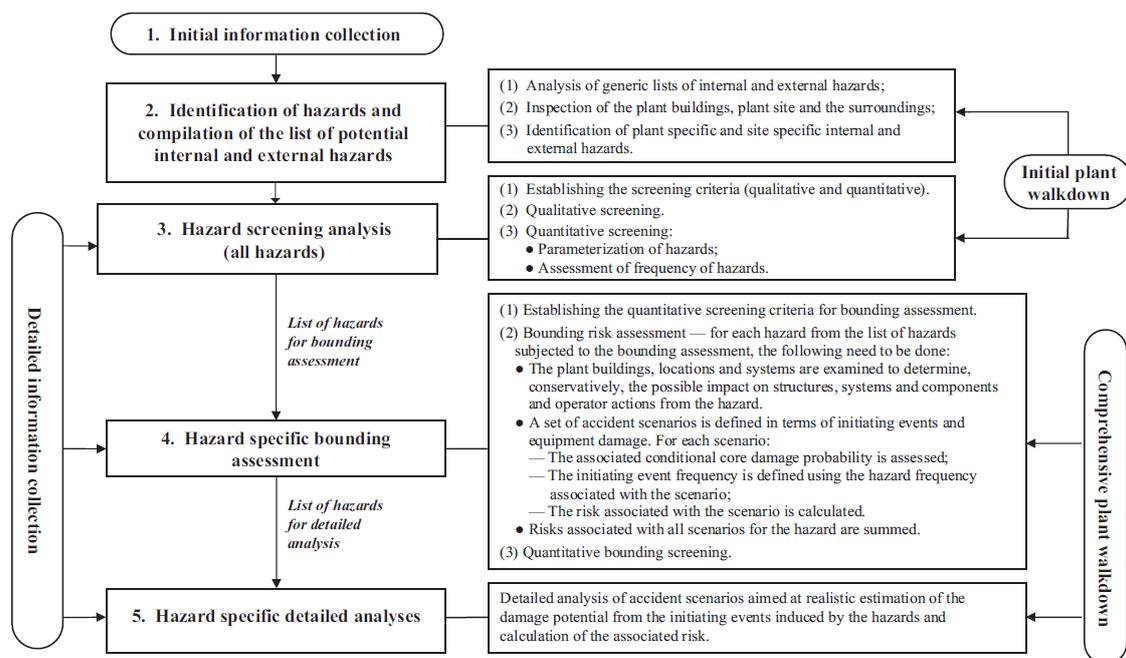


FIG. 2. Overall analysis approach for Level 1 PSA for internal and external hazards.

On the other hand majority of nowadays guidelines treat this requirement too general.

L1 PSA requirements following from main conclusions of ASAMPSA_E report on PSA lessons learned from Fukushima accident [5] emphasize topic of combinations of correlated hazards majority of available sources do not provide systematic approach how to cope with identification of such correlated hazards. Also, it should be noted that the consideration of combinations of correlated hazards is essential also for L2 PSA, as highlighted in [5].

It appears that developing appropriate extended seismic guideline is crucial to be supported by the multi-disciplinary team evaluating seismic hazard. This report covers followings sections:

- Section 3 - provides structure for extended seismic PSA

- Section 4 - provides an approach to modelling of earthquake in seismic PSA to cover all dependencies coming from correlated hazards including non-reactor radioactive sources, multi-unit effects and appropriate treatment of SSCs
- Section 5 - provides a framework to model specific aspects of the seismic PSA as are long term models, additional emergency response etc.
- Section 5 - provides conclusion, recommendations and list of open issues discussed in this report.

3 STRUCTURE OF SEISMIC PSA

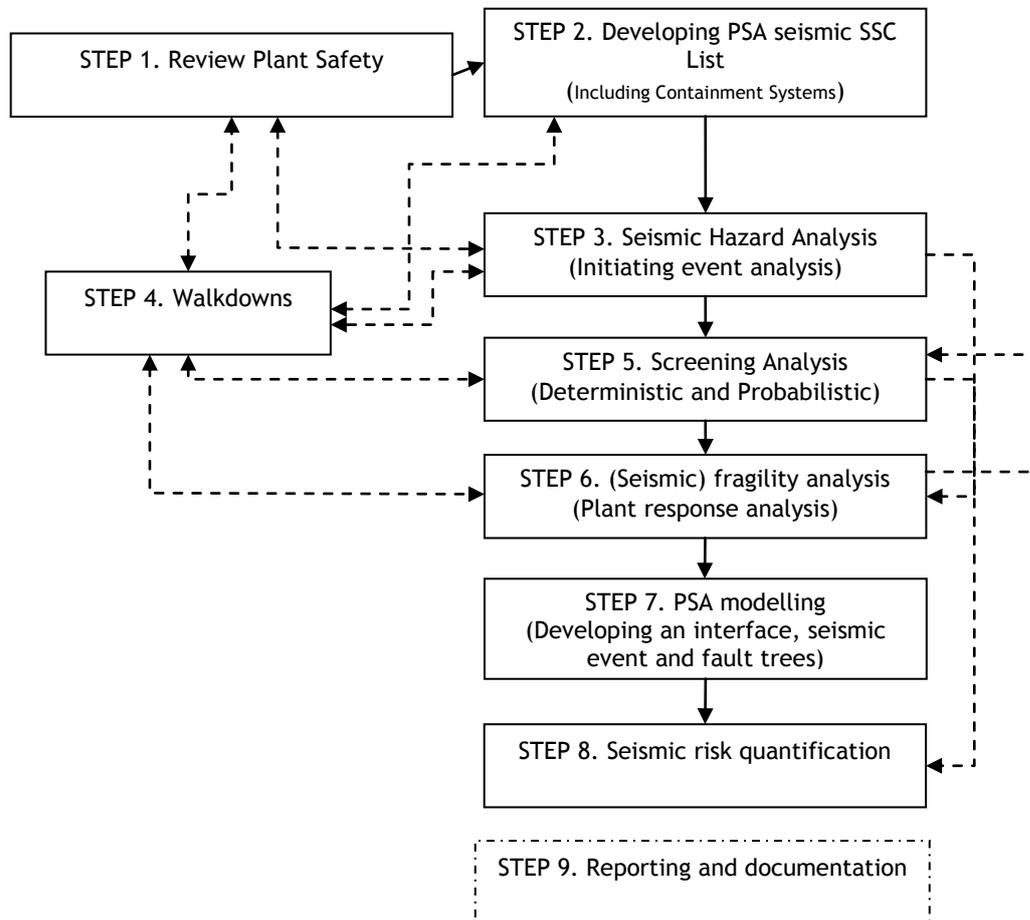
Aim of this section is to provide extended structure for seismic PSA.

Standard seismic PSA approach formulates the plant level fragility curve based on Seismic Hazard Analysis from individual SSCs fragilities using fault tree/event tree logic models of the plant systems to evaluate risk. A lognormal fragility model is used to define the fragilities in seismic PSA conducted for nuclear plants today. Detailed fragility model is developed in order to address the randomness and uncertainties in the various underlying response and capacity variables that contribute to the success or failure of relevant SSCs. Consequently, Seismic Hazard Analysis information are used to

- enhance list of SSCs and perform Seismic Fragility Evaluation;
- modify fault trees and develop specific seismic event trees (Systems and Accident Sequence Analysis); and
- assess seismic risk - Risk Quantification.

This report is not repeating information accessible in the available guidelines dealing with rudimentary seismic PSA and focuses mainly on the applicability of those standard methodologies to enhance a seismic PSA in such a way to cover topic of correlated hazards. In order to meet objectives stated in section 2, fundamental seismic PSA approach (e.g. published in [11]) is extended considering necessary pre-condition to perform any seismic PSA is available i.e. PSA for internal event. It should be obvious that such PSA enables to address specific SSCs and operator actions that ensure fulfillment of fundamental safety functions.

Fig. 3-1 Flow chart for extended seismic L1 PSA



Following text provides basic description of particular steps introduced in Fig. 3-1 (further implementation details and interactions are discussed in section 4).

STEP 1. Review Plant Safety (and modify Available Event Analyses):

The aim of this step is to determine list of all induced events that can be evoked by seismic event. Analysts shall review the plant safety systems from the viewpoint of any seismic specific event. This step should be based on site specific list of correlated hazards. For example, below listed generic table presented in [1], publishes matrix of feasible correlated hazards.

Tab. 3-1 Matrix of feasible correlated hazards, [1]

ASAMPSA_E			N1	N2	N3	N4	N5	N6
		Seismotectonic hazards	Vibratory ground motion	Induced vibratory ground motion	Fault capability	Liquefaction	Dynamic compaction	Ground displacement
D21.2 External Hazard Correlation Chart 2014-12-15								
Seismotectonic hazards								
N3	Fault capability		✓					
N4	Liquefaction		✓	✓				
N5	Dynamic compaction		✓	✓				
N6	Ground displacement		✓	✓	✓			
Flooding and hydrological hazards								
N7	Tsunami		✓					
N11	High ground water							✓
N12	Obstruction of a river channel							✓
N13	Changing river channel		✓		✓			✓
N15	Water containment failure		✓		✓			
N16	Seiche		✓					
N18	Sea: high tide, spring tide							✓
Meteorological events								
N47	Snow avalanche		✓	✓				
Geological								
N60	Slope instability		✓	✓	✓			
N61	Underwater landslide		✓	✓	✓			
N62	Debris flow, mud flow		✓	✓	✓			
External man-made hazards								
M1	Industry: explosion		✓	✓	✓	✓		
M2	Industry: chemical release		✓	✓	✓	✓		
M4	Military: explosion, projectiles		✓	✓	✓	✓		
M5	Military: chemical release		✓	✓	✓	✓		
M10	Ground transportation: direct impact		✓	✓	✓	✓		
M11	Transportation: explosion		✓	✓	✓	✓		
M12	Transportation: chemical release		✓	✓	✓	✓		
M13	Pipeline: explosion, fire		✓	✓	✓	✓	✓	
M14	Pipeline: chemical release		✓	✓	✓	✓	✓	
M19	Stability of power grid		✓	✓	✓	✓		
M24	Fire: human/technological activity		✓	✓	✓	✓		
	Internal fires (including explosions)		✓	✓	✓	✓		
	Internal floods		✓	✓	✓	✓		✓
	Heavy load drops		✓	✓	✓	✓		✓

	B
A	↗

A is prerequisite for B

	B
A	↙

B is prerequisite for A

	B
A	↗

A may cause B

	B
A	↙

B may cause A

	B
A	

Associated hazards: A and B
derive from common root cause

Note:

Only direct consequences of individual hazards are listed. Causal chains are not considered.

Combinations of independent phenomena with low severity which cause potential hazards by their contemporaneous occurrences are not identified.

Each analysis should evolve from such matrix of feasible correlated hazards considering site specific conditions as well as possible events induced by correlated hazards, e.g. fires of external industrial facilities can cause external fires. If we assume that matrix of potential correlated hazards represents only external hazards then such (plant specific) matrix should be also added by correlated internal hazards (e.g. three last extra rows (in BLUE color) in above presented table). This step should have several (iterative) stages, e.g.:

- Assembling list of all feasible induced events that can influence fundamental safety functions, e.g. see [16]:
 - Control of the reactivity;
 - Removal of heat from the core; and
 - Confinement of radioactive materials and control of operational discharges, as well as limitation of accidental releases.
- Particular event can be screened out only in the case if it has no impact on fundamental safety functions.
- Final list of 'not screened event' should be added by description of
 - effects that influence fundamental safety functions (e.g. internal fires / explosions in plant area can damage service water facility);
 - mechanisms (failure modes) leading to the adverse effects (e.g. internal fires can be caused by short ground of collapsed unit transformer not disconnected from outside grid).
- Final list shall also consider heat removal and releases from spent fuel pool.
- In the case of multi-unit site final list shall be reviewed to take into account adverse effects following from seismic failures of neighboring units or others nuclear facilities (e.g. fires, operability of control

room of analysed unit or its habitability if operator interventions are necessary to ensure fundamental safety functions etc.).

The output of this step is a final list of induced events caused by correlated hazards including seismic event itself. This list contains also basic information describing the effects of determined events on fulfillment of fundamental safety functions and mechanisms (failure modes) leading to the adverse effects. Some examples of such rigorous approach of combination of hazards are given in [25] even if this report does not deal with seismic event.

STEP 2. Developing PSA seismic SSC List (equivalent term is Seismic Equipment List):

Input of the step is basic information from PSA for internal events and final list of induced events determined in step 1. Based on step 1 - (Review Plant Safety) the analysts develop a preliminary SSCs list. Activities of this step can be performed simultaneously for several domains as follows:

- Assembling basic SSCs list for rudimentary PSA considering adverse effect of collapse of any SSCs on safety significant SSCs performance. Basic seismic SSC list forms standard activity which can be performed according available standard guidelines, see section 6 of [3] for further details.
- Assembling SSC list related to the internal fires and floods. This list should be based on results of PSA for internal hazards. In particular, the list of SSC shall be limited to SSCs required for ensuring fundamental safety functions. If PSA for internal hazards is not available the most reasonable approach to build such list is to perform particular analyses from scratch.
- Assembling SSC list for external induced events, see step 1 - (Review Plant Safety), should be oriented only on essential/key components affected by induced events that seismic induced failures can threaten plant safety (e.g. storages of flammable or poisoning substances, dam structures, (geological) formations that collapse can affect water mode (e.g. changing river bed) or land slice in site area etc.)

Output of this step 2 is a compound seismic SSCs list containing:

- Basic SSC list for rudimentary PSA intended as an input for fragility analysis. Considering failures of safety significant SSCs; and failures of insignificant SSCs surrounding and interacting with safety significant SSCs for impact analysis.
- SSC list related to the internal fires and floods effects intended as input for impact analysis.
- SSC list related to the multi-unit effects intended as input for impact analysis, if appropriate.
- SSC list related to the external correlated events/effects intended as input for impact analysis.

Each item in final SSCs list should contain followings:

- Item identification
- Brief description of item
- Item location
- Assumed failure modes including description of failure impacts.

STEP 3. Seismic Hazard Analysis:

Seismic Hazard Analysis forms specific complex step which is performed by specialized team, e.g. see [19] for further details. This step should provide parameterization of seismic hazard, i.e. the ground response spectrum in form of considered seismic area hazard curve with variability estimates.

Output of this step is plant area seismic hazard curve(s) including outside plant areas containing natural formation and external industrial facilities that could collapse or seismic induced failures can threat plant fundamental safety functions.

STEP 4. Walkdowns:

The plant walkdowns step of essential components and their locations is emphasized in all PSAs. The walkdowns are conducted by a team of system engineers and seismic fragility analysts. In order for the walkdown to be efficiently performed, review of the design basis, preparation of procedures, collection of design/qualification data and training of the walkdown team are essential. It is also necessary that the floor spectra be available. Walkdowns shall cover all SSCs (civil structures, industrial facilities like chemical plants, natural formations, distribution systems like gas, electricity etc.) determined within steps 1 and 2.

STEP 5. Screening Analysis:

As result of (extended seismic) L1 PSA has strong influence on L2 PSA and due to complexity of problem it is difficult to set some reasonable screening strategy by the same way which is used for internal hazards i.e. screening by contribution to the CDF when internal hazards having contribution below threshold value are screened out. However internal hazard analysis are performed case by case where (usually) only limited plant area is affected and rest of the plant is intact. Seismic event forms more challenging situation because plant as a whole is affected. Following spatial effects and induced events can lead to cliff-edge effects having deep impact on potential radioactive releases event if contribution to the CDF is low. This implies that only high capacity SSCs not threatened by others SSCs can be screened out of the PSA seismic SSC list. Such screening must be based on the review of seismic qualification criteria and qualification documents of relevant SSCs and verified by walkdown, if appropriate. For example, according to reference [10] *“Deterministic screening targets are typically based upon the lower tail of the component fragility. The reference point for screening is an acceleration level where there is 95% confidence of less than 5% probability of failure, commonly referred to as a HCLPF. Screening is primarily done by seismic fragility analysts using earthquake experience and plant specific qualifications criteria”*.

Output of this step is documented list of screened SSCs.

STEP 6. (Seismic) fragility analysis:

Fragility analysis is performed to evaluate conditional probabilities of SSCs seismic failures for a given level of seismic ground motion for the non-screened items from step 2 ‘Developed PSA seismic SSCs List’ to development of plant fragility curves. Even if this step is usually based on results coming from step 4 extended PSA shall enhance this activity in such a way to be capable of integrating induced events into PSA.

Typical inputs for this step are as follow:

- enhanced information from seismic hazard analysis (step 3);
- seismic response of civil structures including floor responses of structures containing safety significant equipment;

- Seismic load defining relevant SSC demands;
- SSCs seismic capacities.

Output of this step are data/parameters enabling assessment of conditional probabilities of SSC failures. Such data/parameters are usually expressed as:

- HCLPF or some other parameters to evaluate resistance of SSCs (It is assumed that these (or similar) parameters form sufficient background to evaluate probability of seismic failure and implementation of such evaluation depends on software used for particular PSA.
- Conditional probabilities assessing probability of seismically induced events or effects may be more appropriate way in case of multi-unit effects and correlated hazards.

STEP 7. PSA modelling (Developing an interface, seismic event and fault trees):

The aim of this step is the modification (or development) of fault and event trees in order to reflect conditions induced by seismic event and to catch effects of all considered induced events.

Output of this step is seismic L1 PSA model suitable for seismic risk quantification.

STEP 8. Seismic risk quantification:

This step involves evaluation of risk and assembling comprehensive output of the results of the seismic hazard analysis. The approach followed in recent seismic PSAs is to identify the dominant sequences, minimal cut-sets including uncertainty, importance and sensitivity analyses.

The output of this step is comprehensive information describing seismic risk, enabling to identify appropriate measure to decrease risk. The format of L1 PSA seismic risk quantification should contain potential requirement to perform L2 PSA to establish a straightforward interface between L1 PSA and L2 PSA.

STEP 9. Reporting and documentation:

Reporting represents overall PSA documentation of steps in order to provide set of documentation that enables to trace and reviewing performed work as well as to interpret result in a systematic manner. Reporting is ongoing task performed as an integral part of particular steps introduced above.

Majority of the steps or their parts of above discussed '*Structure of extended seismic PSA*' are part of standard seismic guidelines. Extended PSA is focused to enhance these standard steps in order to reflect requirements on seismic PSA following from section 2.

4 DEVELOPMENT OF EXTENDED SEISMIC PSA

This section provides further details and recommendations regarding steps 1 to 9 of methodology outlined in section 3. As it is noted in section 3, extended PSA is focused on enhancing standard seismic PSA in order to reflect requirements on seismic PSA following from section 2. So this section is focused mainly on the cases that are not fully covered by standard guidelines.

This section assumes that analysed plant/unit has available appropriate PSA for internal events as well as analyses of internal and external hazards except of seismic hazard. It is also assumed that analysed plant has appropriate defined fundamental safety function including list of safety significant SSCs necessary to ensure intended functions.

It should be noted that seismic PSA forms complex interdisciplinary process relying on suitable computer codes that can have specific features to support seismic risk evaluation, combining event tree results, enabling specific Monte Carlo Simulation involves random sampling techniques that combine plant hazard curve and component fragility curves into trials etc. Presented approach assumes usage of standard PSA software without any specific features. The only requirement is capability to work with linked fault and event trees. In such case, the seismic PSA can use standard approach consisting from discretization of continuous distribution into discrete probability distribution (DPD). (Seismic) hazard curve is approximate by finite number of doublets (e.g. peak ground acceleration versus probability), i.e. discretization of analytical probability density functions into discrete probability distributions what is referred as the DPD method, see Appendix C of [11]. Consequently the probability distributions for failure must be combined only two times at each discrete step and the process is repeated for each discrete interval.

Presented approach is focused on nuclear reactor units; however it can also be applied on the other facilities e.g. spent fuel pool, temporary and permanent fuel or radioactive waste storages, fuel preprocessing lines etc. Usage of this approach for specific cases requires precise definition of “*specific fundamental safety functions*” that ensures safety operation envelope for specific facilities.

In addition, even if approach for extended seismic PSA is presented as linear sequence of steps (mainly from methodological point of view), real PSA for arbitrary external hazard never forms linear process.

4.1 REVIEW PLANT SAFETY AND MODIFY AVAILABLE EVENT ANALYSES

The aim of this step is to determine list of all induced events that can be caused by correlated hazards. This step should be based on PSA for internal events, PSA for internal and external hazards and site specific list of correlated hazards. Seismic site specific hazards fall into several basic categories that are (internal) seismic failures, (internal) seismically induced initiating events and induced external events.

It is noted that within step 1, consideration regarding possibility of occurrence of earthquake and its magnitude is not performed. Step 1 is concerned to the question: What could happen if earthquake occurs?

4.1.1 (INTERNAL) SEISMIC INITIATING EVENTS

Several standard seismic PSAs guidelines recommend consideration small LOCA as standard part of response on seismic event as well as occurrence of plant shutdown if seismic ground motion is greater than the operating basis earthquake. However there are many potential small LOCAs, so PSA should consider most representative well justified case(s).

Except of obligatory small LOCA several category of seismically induced medium and large LOCA shall be considered. Their categorization should be consistent with PSA for internal events.

4.1.2 (INTERNAL) SEISMICALLY INDUCED INITIATING EVENTS

(Internal) seismically induced initiating events correspond to almost with internal hazards. Category of internal hazards covers following events [18]:

- (a) Internal fires;
- (b) Internal floods;
- (c) Internal missiles;
- (d) Internal explosions;
- (d) Turbine missiles;
- (e) Heavy load drops.

In general internal missiles are not considered as a significant problem. Heavy load drops shall be covered by collapse of SSCs within standard seismic PSA. Under such assumption probably only one open problem is occurrence of seismic event during transport of heavy reactor internals. However, cranes spend majority of time in parking position so coincidence of simultaneous transport of heavy load and seismic event will have very low probability.

Consequently internal hazards that shall be considered during seismic event are:

- Internal fires and explosions;
- Internal floods.

4.1.2.1 Internal fires and explosions

Basis to evaluate correlated hazards for internal fires and explosions is formed by Fire PSA. Both qualitative and quantitative analyses of Fire PSA performed according to references [23] and [18] by providing list of ignition sources and consequences of potential fires. Important electrical and I&C equipment's (e.g. bus bars, transformers, cabinets etc.) are usually located in dedicated compartments separated according to fundamental safety principles e.g. redundancies/safety trains etc. Plant has also limited number of specific ignition sources (unit transformers, storages of flammable substances and explosive gases). Based on data in Fire PSA all available information should be re-analyzed and relevant ignition/explosive sources capable to influence fundamental safety functions should be grouped into form that will be suitable for processing by extended PSA. The most optimal way consists of grouping ignition sources in such a way that information from fire PSA will be assigned to the particular compartments in order to reduce number of correlated events. This seismic oriented post analysis of fire PSA should take into account limited possibility of fire suppression due to hindered conditions as well as carefully re-evaluate assumptions that taken into account redundancy of safety trains because availability of safety trains can be affected by seismic effects.

Output of such activity should be as follows:

- Ignition source: based on above description this activity should contain list of ignition sources; sources can be aggregated by compartments (civil structures) containing particular ignition/explosive sources. However, information regarding particular sources must be available in order to assess conditional probability of fire,
- Affected SSCs: list of SSCs performing fundamental safety functions that can be affected by fire,
- Mechanisms (failure modes) leading to the adverse effects: description of mechanisms (scenarios) leading to consequences that could threaten the fundamental plant safety functions.

Tab. 4-1 Example of Output of event analysis for internal fires

Ignition source	Induced Event ID	Affected SSCs	Mechanisms (failure modes) leading to the adverse effects
SB2xxx	Fire_XXX	SB2xxx TR0xxx	Catastrophic fire of unit transformer SB2xxx can put out of order 2 nd electrical safety train Compartment of 2 nd electrical safety train is located 10 m from main unit transformer. In the case of catastrophic fire split oil can ignite fire of 2 nd electrical safety train compartment. Surrogating component for 2 nd train is bus-bar SB2xxx Surrogating component for unit transformer is TR0xxx

Presented approach provides no further details regarding fire/explosion analysis, as all necessary information to perform such activities is available in publically accessible guidelines.

Preparing a list of induced fire/explosion events is highly customized task which depends on composition of plant equipment (usage of dry transformers, fire resistance of electric equipment, fire qualification of cabling system etc.) and quality of fire PSA.

This step should take into account plant area as whole. For example, ‘catastrophic fire of main transformer of unit 2 can lead to deterioration of habitability of main control room of unit 1 which is necessary to put unit into safety state. In addition, hydrogen storage which is far away from analysed unit 1 but hydrogen storage blast can induce fire of main transformer of unit 2 etc’.

It should be obvious that one induced event should have several consequences, i.e. it affects several SSCs.

4.1.2.2 Internal floods

Similarly to the internal fires and explosions the basis to evaluate correlated hazards for internal floods is internal flood analysis. Both qualitative and quantitative analyses of floods, e.g. performed according to reference [18] by providing list of flooding sources, consequences of potential floods that are used to estimate likelihood of serious consequence of potential floods. Based on data in flooding PSA, all available information should be re-analyzed and relevant flood sources capable to influence fundamental safety functions should be grouped into form that will be suitable for processing by extended PSA. The most optimal way consists in grouping in such a way that information from flooding PSA will be assigned to the particular compartments in order to reduce number of induced events.

This post analysis of flooding PSA should take into account potential effects of seismic event, e.g. blockage of draining paths as well as a formation of new drainage paths due to collapse of civil structures. It is also expected re-evaluation of assumptions that took into account redundancy of safety trains because availability of safety trains can be affected by seismic effects.

Analysis should also take into account nature of flooding sources. If flooding source is formed by pumping cooling water from the sea (which level is usually below plant level) then impact of such source depends on available power source of pumps as well as on the activation of flooding alarms and protective automatics etc. If it is possible then convenient way is wrapping all such effects into severity factor. Particular severity factors should be based on separate analyses based on fragility analysis.

If flooding sources are formed by emergency tanks containing cooling water then the potential effects of flood are the same as assumed in flood PSA with exception of drainage paths that can be changed by seismic effects.

Output of such activity should be as follows:

- Flood source: based on above description this activity should contain mainly list of relevant flooding sources; these sources can be aggregated by compartments (civil structures) containing flooding sources, but information regarding individual flooding sources must be available in order to assess conditional probability of flood,
- Affected SSCs: list of SSCs performing fundamental safety functions that can be affected by flood,
- Mechanisms (failure modes) leading to the adverse effects: description of mechanisms (scenarios) leading to consequences that could threaten the fundamental plant safety functions.

Tab. 4-2 Example of Output of event analysis for internal flooding

Flood source	Induced Event ID	Affected SSCs	Mechanisms (failure modes) leading to the adverse effects
Circulating cooling train XXX in compartment YYY	IFXXX_YYY	P1xxx	Catastrophic rupture of train leads to over-flooding of 1 st safety system which is used to perform long term heat removal. Surrogating component for over-flooding of compartment ZZZZ is pump.

Presented approach provides no further details regarding flooding analysis, as all necessary information to perform such activities is available in publically accessible guidelines.

4.1.3 INDUCED EXTERNAL EVENTS

External correlated hazards form broad spectrum of events that could be triggered by seismic event. External hazards analysis should evolve from matrix of feasible correlated hazards considering site specific conditions, see Tab. 3-1 as well as by considering results of external hazard analysis. Convenient starting point for such activity is formed by available analysis of influence of external industry which is part of external hazard analysis performed as a part of full scope PSA. This step is performed as a qualitative analysis which should have several (iterative) stages. Aim of this activity is to build list of all possible correlated external hazards. Activity shall take into account followings:

- natural formations that collapse or change due to seismic event can disturb normal operational conditions which can influence fundamental safety functions of the analysed plant,
- industrial facilities, product lines (oil, gas etc.) that collapse due to seismic event can disturb normal operational conditions which can influence fundamental safety functions of the analysed plant.

The flow chart of this approach to analyse impact of external correlated hazards is presented in Fig. 4-1 and its steps are discussed below:

I. Identification of all civil structures and industrial facilities that accident can threat plant fundamental safety functions

The aim of this task is to evaluate impact of damaged industrial facilities like factories, pipelines, large storages of flammable or poisoning materials etc. that have potential to influence fulfillment of fundamental safety functions. This task involves similar activities as are performed within external hazard analysis, e.g. [14].

Task is overlapped with 'step 3 - Seismic Hazard Analysis'. Considered area will depend on potential severity of hazardous location and area affected by seismic event or specific seismic condition of relevant industrial facilities. It is noted that this task shall cover also all in site structures (neighboring units, other in site nuclear facilities) that are not covered by internal fires and flooding analyses.

II. Identification of all natural formation (including civil structures) or abnormal effects than can threat plant fundamental safety functions

The aim of this task is to evaluate impact of feasible natural hazards that have potential to influence fulfillment of fundamental safety functions. This task involves similar activities as that performed within part of external hazard analysis dealing with natural phenomena, e.g. [14].

This task shall also consider effects of collapsed civil structures like dams, bridges etc. capable evoking floods or blockage of water paths.

Task is overlapped with 'step 3 - Seismic Hazard Analysis'. Considered area will depend on area affected by seismic event as well as by topography of the country. And vice versa even if plant will not be hit by seismic event an

earthquake can affect some large dams or river paths far away from plant that damage can impact on plant operation.

Output of this task is a list of natural formations or pairs containing natural formation - civil structure that accident can form potential danger for safety operation of analyzed plant.

III. Determination the list of “single” correlated hazards

The aim of this task is established list of feasible single hazards that can be induced by seismic event. Tab. 3-1 can serve as a starting point to build such list. Initial table is adjusted on site specific conditions taking into account information from tasks II. and III.

Output of this task is a site specific matrix of feasible correlated hazards.

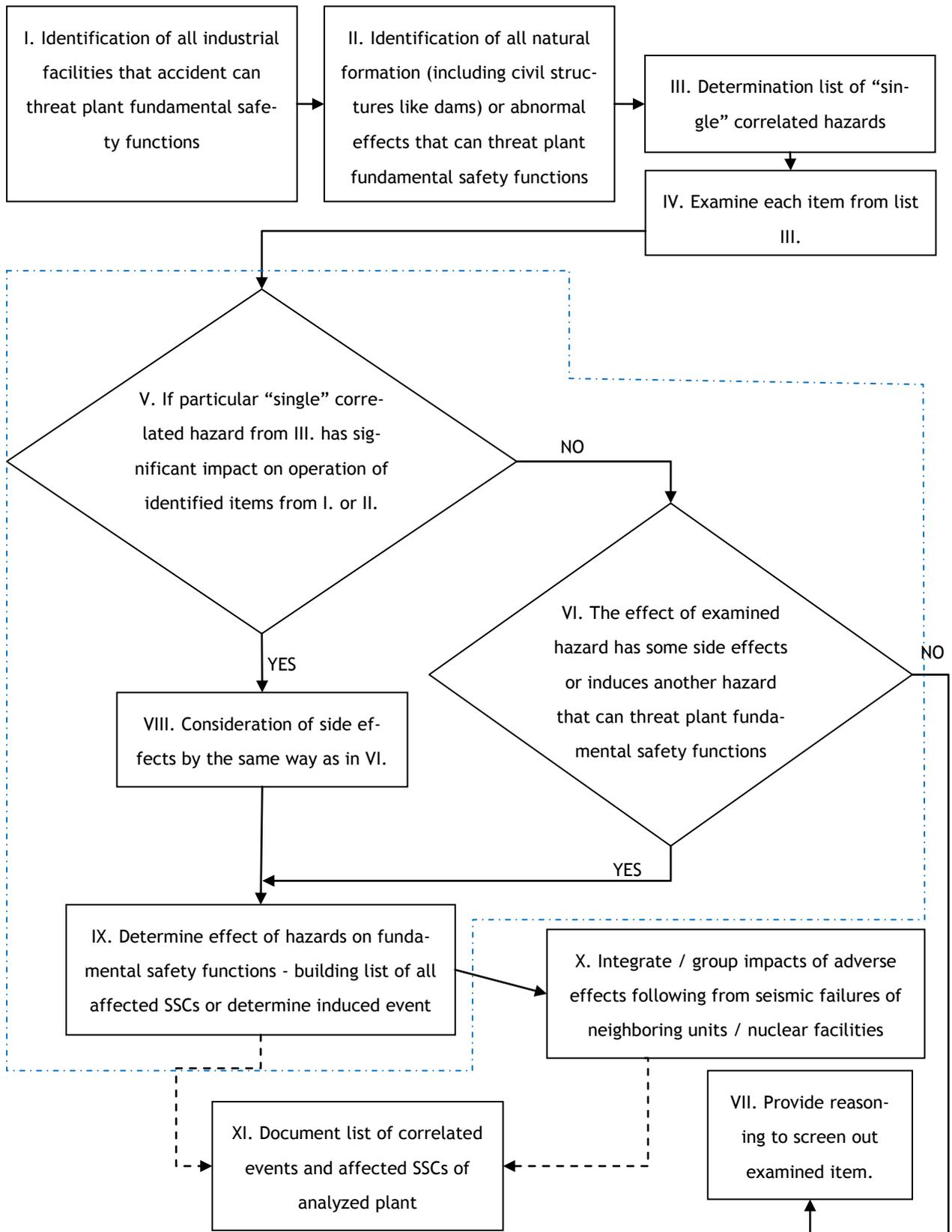
IV. Examine each item from list III

Aim of this task, which wraps tasks V., VI., VIII. to X. (dash dot line in Fig. 4-1), is to evaluate the impact of determined correlated hazards on items following from tasks I. to III. and consequently impact on fundamental safety functions. This task shall be performed by systematic manner in such a way that information from tasks I. to III. will be organized into this helper matrix. Number of rows corresponds with number of determined hazards from task III. and number of columns corresponds with number of items determined in tasks I. and II.

V. Evaluate if effects of examined correlated hazards from task III. have significant impact on operation of identified items from tasks I. or II.

The aim of this task is to evaluate potential impact of correlated hazards to industrial and civil structures and natural formations determined in tasks I. and II. Description of impact should provide expected failure mode as well as consequence of normal operation/behavior on industrial and civil structures and natural formations (e.g. Collapse of structures leads to accident of industrial factory, soil displacement causes pipe break and leads to oil release.). This can be observed in many cases direct causality between effect of seismic event, damage of particular facility and impact of this damage on environment.

Fig. 4-1 Flow chart of approach to analyse impact of external correlated hazards



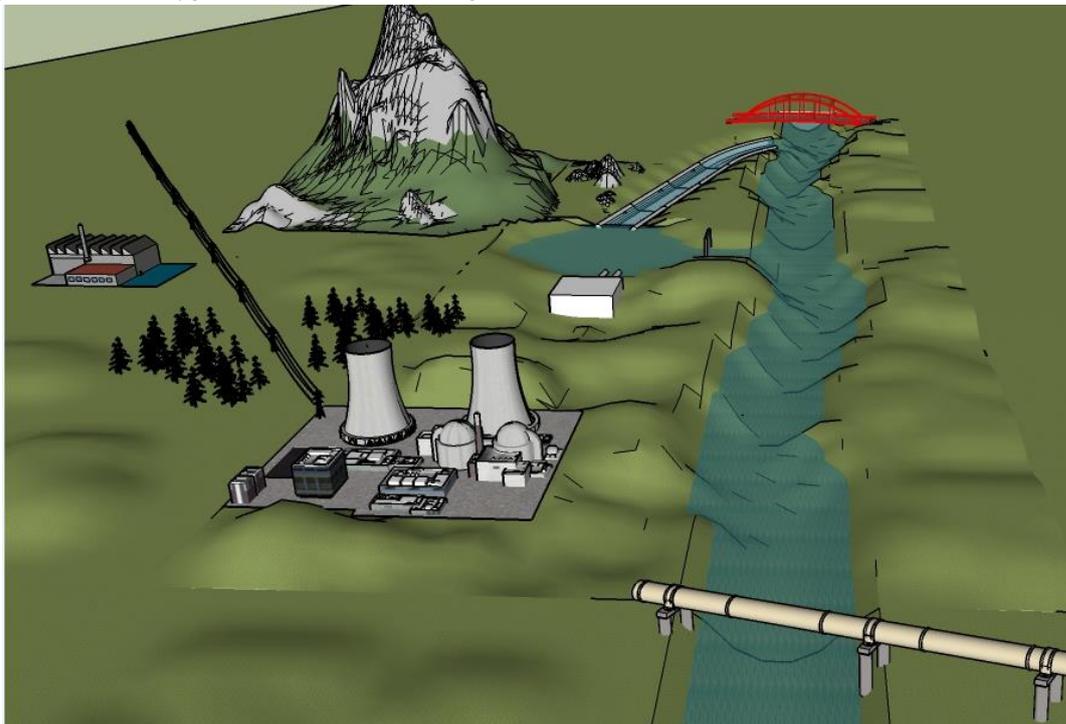
VI., VIII. The effect of examined hazard has some side effects or induces another hazard that can threaten plant fundamental safety functions

The aim of this task is to evaluate potential side effects that do not appear directly. For instance seismically induced damages of small industrial structures can induce wildfire; damaged oil pipe lines can degrade the quality of cooling water etc.

The output of this task as well as of task VIII. is description of consequences of correlated hazards on operation (stability, state) of items defined in tasks I. and II. as well as a description of events induced by side effects.

A hypothetical example of such activity is given in Fig. 4-2 and Tab. 4-3. This example assumes plant located in valley away from river. Plant has built cooling pond located near a hill. Water of this pond is supplied from river through intact channel. Level in pond is controlled by small dam. Somewhere near the plant is located chemical factory and gas line.

Fig. 4-2 Hypothetical location of plant in terrain



Tab. 4-3 Hypothetical example of plant correlated hazard

Item / Event	Hazard	Industrial facilities			Natural formation and civil structure		
		Factory	Distribution line	Gas line	Dam	Bridge	Hill
N3	Fault capability	Accident - poisoning gas, Accident - Wild-fire	Loss of grid, Wildfire	Explosive cloud	Damage cooling pond	Blockage intact channel of cooling water	N/A
N4	Liquefaction	N3	N3	N3	N3	N3	Blockage of intact of cooling pond Evoking a flooding wave Clocking of intact of pumping station
N5	Dynamic compaction	N3	N3	N3	N3	N3	N/A
N6	Ground displacement	N3	N3	N3	N3	N3	N/A
N7	Tsunami	N/A	N/A	N/A	N/A	N/A	N/A
N11	High ground water	N/A	N/A	N/A	N/A	N/A	N/A
N12	Obstruction of a river channel	N/A	N/A	N/A	N/A	N3	N/A
N13	Changing river channel	N/A	N/A	N/A	N/A	N/A	N/A
N15	Water containment failure	N/A	N/A	N/A	N3	N3	N/A
N16	Seiche	N/A	N/A	N/A	N/A	N/A	N3
N18	Sea: high tide, spring tide	N/A	N/A	N/A	N/A	N/A	N3
N47	Snow avalanche	N/A	Loss of grid	N/A	N/A	N/A	Evoking a flooding wave
N60	Slope instability	N3	N3	N3	N3	N3	N3
N61	Underwater landslide	N/A	N/A	N/A	N/A	N/A	N/A
N62	Debris flow, mud flow	N/A	N/A	N/A	N/A	N/A	Clocking of intact of pumping station
M1	Industry: explosion	N/A	N/A	N/A	N/A	N/A	N/A
M2	Industry: chemical release	N3	N/A	N/A	N/A	N/A	N/A
M4	Military: explosion, projectiles	N/A	N/A	N/A	N/A	N/A	N/A
M5	Military: chemical release	N/A	N/A	N/A	N/A	N/A	N/A
M10	Ground transportation: direct impact	N/A	N/A	N/A	N/A	N/A	N/A

Item / Event	Hazard	Industrial facilities			Natural formation and civil structure		
		Factory	Distribution line	Gas line	Dam	Bridge	Hill
M11	Transportation: explosion	N/A	N/A	N/A	N/A	N/A	N/A
M12	Transportation: chemical release	N/A	N/A	N/A	N/A	N/A	N/A
M13	Pipeline: explosion, fire	N/A	N/A	N3	N/A	N/A	N/A
M14	Pipeline: chemical release	N/A	N/A	N/A	N/A	N/A	N/A
M19	Stability of power grid	N/A	N3	N/A	N/A	N/A	N/A
N73	Wildfire	N/A	N3	N/A	N/A	N/A	N/A

Note to the multi-unit effects and in site nuclear facilities: If multi-unit site have some reasonable arrangement and design (e.g. sufficient fire distance, minimized fire load, high degree of independence and self-contained safety system etc.) then examined hazards from task III. should have significant impact only on habitability of control rooms (release of radioactivity) and potentially on cross-connections of cooling media and power as well as to challenge performance of digital I&C due to increasing radiation level.

IX. Determine effect of hazards on fundamental safety function - building list of all affected SSCs

Information from tasks V., VI., VIII. are re-evaluated to build unique list of (seismically) induced events caused by correlated hazards. Aggregation of event uses similar principles as a grouping of initiating events:

- similar failure mechanisms (having the same root cause evoked by one single event or which can be expressed as a sum of single events),
- similar impact on fundamental safety function and unit response.

For instance some of the determined hazards from Tab. 4-3 should be aggregated into a couple of consistent groups as follows.

Tab. 4-4 Example of aggregating hazards from Tab. 4-3

Item / Event	Facility / formation	Induced Event ID	Affected SSCs	Mechanisms (failure modes) leading to the adverse effects
N3, N4, N5, N6, N60, M3	Factory	Factory	Main control room	Poisoning cloud coming from factory accident challenge habitability of control room
N3, N4, N5, N6, N60, M19	Grid	LossOfGrid	TR0xxx	Loss of offsite power - Surrogating component for offsite power is unit transformer TR0xxx
N3, N4, N5, N6, N60	Grid	GridWildfire	XXX	Xxx
N47	Grid	LossOfGridW	TR0xxx	Loss of offsite power - Surrogating component for offsite power is unit transformer TR0xxx
N3, N4, N5, N6, N60	Gas line	ExplosiveCloud	TR0xxx Control room Containment	Explosion threatens main control room operation including operators performance (should be considered in HRA) Unit transformer TR0xxx Containment
...

Tasks XI, X and VII are formal activities covering documentation of work to provide background for traceability review as well as to provide documented input for next steps.

4.1.4 SUMMARY OF STEP 1 - REVIEW PLANT SAFETY

Output of this step is final list of induced events with corresponding list of affected SSCs. List of induced events shall be based on structures and formations to enable easy tracing of induced events, i.e. collapse of particular civil structure/industrial facility/formation due to correlated hazard can lead to the adverse effects on particular safety significant SSCs of analyzed plant, i.e. occurrence of induced event. List of corresponding safety significant SSCs shall be system oriented in order to have manageable set of information that can be considered by PSA model. Meaning of system oriented is that this list shall contain single parts of equipment that unavailability is capable putting into order safety train as whole, i.e. concept of surrogating components. For example induced flood can affect several valves and I&C circuits of particular train, but it is enough to consider just affecting of pump to put train out of the order.

Item “Mechanisms (failure modes) leading to the adverse effects”, which is part of output of this step, can provide useful information for fragility and HRA analysis.

It was mentioned that this step shall also take into account internal plant seismic effects in case of multi-unit location. The others nuclear facilities located within site must also be considered. This requirement means direct call to perform separate seismic analyses for all relevant site facilities where each facility is treated as a standalone object as much as possible and results of such analyses are incorporated into final list of induced events. However, if we assume some reasonable design of site facilities then in order to catch all spectrum of induced events analysis of such in-site nuclear facilities will require at least some assessment of L2 PSA results to evaluate radiation effects.

As it was stated at the beginning of this section the aim of this step is to determine list of all induced events that can be caused by correlated hazards simply say combination of events. It should be noted that even if section 4.1.3 presents flow chart to accomplish this activity the approach is not straightforward and many time more complex considerations and further method should be used which introduce interactions among particular steps of proposed approach. In terms of hazard combination frequency evaluation, the nature of combination has to be taken into account. As it was derived in [1]: "*Hazard correlations discriminate between: (1) Causally connected hazards (cause-effect relation) where one hazard may cause another hazard; or where one hazard is a prerequisite for a correlated hazard. (2) Associated hazards which are probable to occur at the same time due to a common root cause*" and in additional, hazard combinations of independent phenomena have been denoted.

IAEA Fault Sequence Analysis (FSA) Methodology

IAEA developed a complementary safety analysis FSA methodology and supporting tool to assist in evaluation of the impact of extreme events on NPPs [30] [31]. This method utilised both probabilistic and deterministic safety assessment methods to gain the insights of robustness of plant protection including impact on SSCs against the extreme external hazards and its combinations. The method also considers combined load conditions resulting from the simultaneous occurrence of these hazards. Fundamentally, the FSA method incorporates 'stress test' principles that have been performed in Europe after Fukushima accident. The method considers sufficiency of defence-in-depth provisions, including various dependencies, safety margins, application of specific design features, cliff edge effects, multiple failures, prolonged loss of support systems and the capability of safety important systems for long term operation [31].

The application of FSA method and supporting tools are implemented at Goesgen-Daeniken NPP, Switzerland and Medzamor NPP, Armenia. The methodology is described in detail in IAEA paper [31].

Extreme Event Analyzer (EEA) Methodology

Lloyd's Register Consulting (LRC), in cooperation with IAEA, has further developed the FSA method [32]. LRC developed a value added tool (ExtremeEventAnalyzer (EEA)) to systematically analyze the accident scenarios not explicitly addressed in the design extension conditions using integrated deterministic and probabilistic approaches. The tool has incorporated lesson learned from FSA methodology developed by IAEA, which has been verified by application on Goesgen-Daeniken NPP (Switzerland) and Medzamor NPP (Armenia).

This method utilise an internal initiating events PSA model for assessing the impact of extreme events, including the consideration of hazard susceptibility limits of SSCs and impact of extreme external hazards. In EEA method, a number of extreme events (including credible combinations) can be postulated, for example seismic, water levels, extreme temperature, weather conditions etc. The extreme event analysis is linked directly to the PSA model (in RiskSpectrum) to ensure that the whole PSA model is included in the evaluation of the impact of the event or combinations of events. The EEA perform re-quantification of the PSA model including the hazard susceptibility limits of the SSCs. The outcome of the analysis is to [32] [33]:

- identify sensitive scenarios for extreme events;
- analyse simultaneous extreme events;
- prove robustness of plant design, for individual components and for buildings.

Below is a list of sequential steps to perform while using the EEA method to identify scenarios sensitive for extreme events [32]:

1. Determine what hazards to include. This will be site specific and screening criteria may be applied.
2. Determine the components, buildings that can be susceptible to the hazards. Plant data collection and plant walkdowns are important inputs.
3. Determine initiating events which can be triggered by the hazard.
4. Determine the magnitudes of hazards that will fail the components, the buildings and trigger the initiators.
5. Generate the minimal combinations of events given the occurrence of a hazard or combinations of hazards.

EEA method and tool is utilised in a benchmarking study "Extreme Event Analysis - an application of RiskSpectrum EEA at Armenian NPP" is performed under co-operation project between LRC, Nuclear and Radiation Safety Center (NRSC) and Armenian Nuclear Power Plant (ANPP). The purpose of the study was to perform a comprehensive and systematic assessment of robustness and vulnerability of NPPs against the impact of extreme events using EEA method and tool.

This step has interaction with following steps:

STEP 2 - Developing PSA seismic SSC List. Some SSCs should belong to the safety components as well as to form flooding or ignition sources.

STEP 3 - Seismic Hazard Analysis. Scope of seismically examined area depends on the scope and features of relevant industrial facilities and natural formations.

STEP 6 - Fragility analysis. Probability and consequence of induced internal floods and fires will depends on pre-disposition of particular items. Similar statement holds for external events.

Even if this step as a whole should be performed by systematic manner, there is still space for subjectivisms and results of step will depend on skills of seismic PSA team.

In addition systematic work can reveal too many interactions, simultaneous events or too many of induced events that their manageable processing will require certain level of simplification in order to perform work with limited scope of resources which can tend to applying conservative assumptions and consequently lead to risk overestimation.

4.2 DEVELOPING SEISMIC PSA SSC LIST

The aim of this step is to build list of items that are necessary to ensure fundamental safety function as well as SSCs needed to address seismically induced events (like internal fires and floods, LOCAs and externally induced events). This step covers followings:

- assembling basic SSC list for rudimentary seismic PSA considering adverse effect of collapse of non-safety SSCs on safety SSCs performance; this activity is driven by standard guidelines as [11], [19], [20] etc.
- assembling SSC list related to the internal fires and floods based on the results of step 1, see section 4.1.2.;
- assembling list of pipes that can induce seismic LOCA;
- assembling list of civil structures and facilities inducing external seismic events including list of natural formation which is based on the results of step 1, see section 4.1.3.

Output of this step is compound list containing relevant inside and outside facilities and plant specific list of relevant SSCs.

Each item in final list should contain at least:

- item identification,
- item brief description,
- item location,
- assumed failure modes including description of failure impacts.

Optional information can be formed by item categorization, e.g.:

- basic internal items ensuring fulfillment of fundamental safety functions including (internal) seismic events (BI); plus a list of relays that chattering can evoke functional failures of SSCs,
- threatening internal item which collapse can affect performance of basic internal items (TI),
- flood internal items that failure can lead to internal floods (FI),
- fire internal items acting as potential ignition sources (II),
- external items capable evoking induced events (EI),
- special internal items that involve in-site effects like multi-unit effects, impact of seismic event on nuclear facilities located in-site area (SI).

All information should be stored in standard unified form to enable fast and effective querying and searching assembled list.

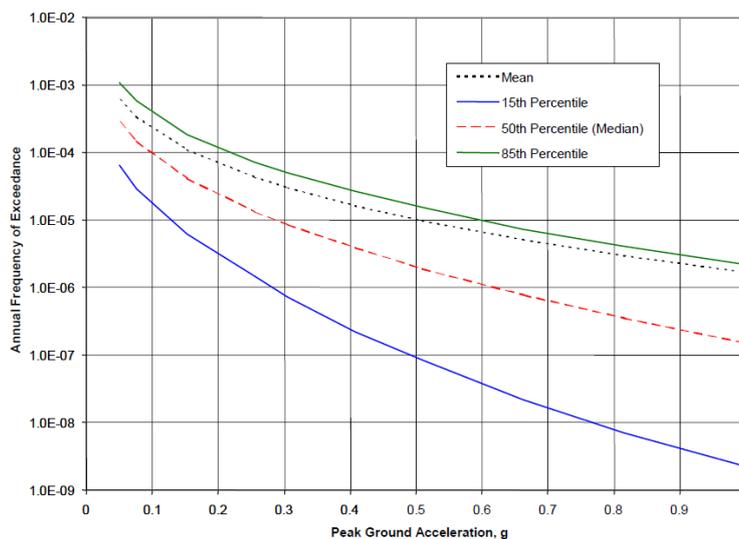
4.3 SEISMIC HAZARD ANALYSIS

/This chapter may be completed later using [4] - ASAMPSA_E deliverable D21.3-1 SEISMIC hazards modelling in extended PSA /

Seismic Hazard Analysis is performed in line with available guidelines e.g. [10], [19], [20] etc. The conduct of a Seismic Hazard Analysis represents a substantial effort involving the contributions of several specialists in the areas of geology, seismology, and geotechnical engineering. The ASAMPSA_E report [4] provides a review of existing practices.

This task shall take into account results of steps 1 and 2. Consequently, the identification and characterization of earthquake source zones which are capable of producing significant ground motions shall cover whole relevant site area where are located industrial facilities and natural formation than can affect analyzed plant. Integrated result of Seismic Hazard Analysis provides the hazard curve(s) for the determined site area with variability estimates.

Fig. 4-3 Example of seismic hazard curve, [11]



The result is usually expressed by the frequency distribution of the peak value of the ground motion parameter (usually pga^1) during a specified interval of time. Such parameterization of seismic hazard, i.e. the ground response spectrum of considered seismic area - Hazard curve(s) is approximated by finite number of discrete intervals (e.g. doublets containing pga versus probability), [10].

¹ In general, Seismic hazard analysis forms complex process based on the data provided by geologists, seismologists and earthquake engineers. Seismic hazard analysis process uses models of spatial and temporal occurrences of earthquakes based on identified seismic energy sources and analyses transmission of the energy from the seismic sources to the plant site considering attenuation.

Detailed data from Seismic hazard analysis form also input for fragility analysis, better say for process providing parameters describing SSC fragilities. This process as such needs more precise description of earthquake, so spectral ground acceleration is more appropriate quantity to prepare necessary inputs to evaluate seismic capacity of SSCs. However hazard curve and parameters describing SSC fragilities must be consistent.

Parameterization of seismic hazard for external items capable evoking induced external events (category EI) shall be based on specific seismic hazard analyses for such objects that could be performed in accordance with standard requirements on rudimentary PSA. However; it is assumed that some level of simplification will be necessary to reduce scope of work on manageable level. This work is driven by standard guidelines as [11], [19] etc.

Step 3 interacts mainly with fragility analysis (step 6).

4.4 WALKDOWNS

Walkdowns are an integral part of seismic PSA. One of the main reasons why a seismic walkdown was conducted in (probably) all seismic PSA performed in the past is tightly related to the goals of the extended PSA addressed by the ASAMPSA_E program, namely the **exclusion of internal hazards** induced by earthquake. The other major reason is to support the screening process discussed in section 4.5 below, with the objective to reduce - with a reasonable effort - the number of SSCs for which detailed fragility evaluations are performed.

Extensive guidance on how to perform seismic walkdowns has been developed in the USA both for seismic qualification, [24], and for seismic margin assessment, [13]; in the aftermath of Fukushima, an additional guidance document was issued, [12]. In these guidance documents, criteria for assessing the robustness of equipment are defined². These criteria fall into two categories:

- Criteria that are **specific** to a given class/type of equipment (e.g. for pumps, whether the shaft is restrained in both horizontal directions); these criteria address the seismic performance of the SSC itself and are more important for SSCs that are **not** seismically designed or for which the seismic design basis or seismic design criteria are **outdated**³; for seismically designed SSCs, the criteria are typically satisfied by default.
- Criteria that are **generally** applicable to **all** classes of equipment, addressing:
 - Anchorage
 - System interaction, i.e. sources of internal hazard in the vicinity of the SSC under consideration, such as flooding sources, overhead SSCs that may fall on and hence damage the SSC under consideration; **this set of criteria specifically addresses one of the major objectives of the ASAMPSA_E program, i.e. the impact of internal and external hazards on equipment and human recovery actions.**

For extended PSA, the following additional aspects are of relevance:

Multi-unit sites:

Earthquake is **inherently** an external event affecting all units at a multi-unit site, thus representing a **common-cause** for potential failures at **multiple units**. Conceptually, this observation is analogous to the observation that at a **single-unit** site a seismic event represents a potential common-cause failure in **multiple safety trains**. Seismic PSA practitioners are used to address this issue, typically by making conservative assumptions for the correla-

² Refer in particular to Appendix F in [13].

³ Recall that the motivation for developing the seismic verification criteria in [24] was that there were concerns regarding the seismic adequacy of older plants in the USA.

tions between seismic-induced failures (full correlation for components appearing under a common AND-gate in the fault tree model and no correlation for components appearing under a common OR-gate). Quantitative guidance for the correlation modeling is provided in [22], taking into account the **position/layout** of SSCs relative to each other and the **similarity** of SSCs.

There are also potential seismic-induced scenarios that are **specific to multi-unit sites**. In this regard, it is referred to section 3.5.5 in [5], in particular items 2 (loss of shared systems; this includes support systems, such as emergency diesel generators) and item 3 (events propagating from one unit to another). The **scope of a seismic walkdown at multi-units should thus be expanded to account for these potential scenarios**, as well as for other safety-relevant **cross-connections** between individual units, e.g. auxiliary power in-feeds, and other mutual dependencies among individual units, e.g. shared resources (fire brigade). It should be noted, however, that these mutual dependencies are **not only** relevant for seismic-induced scenarios, but more generally for L1 (and L2) PSA.

Spent fuel pool⁴:

A detailed general area review of the spent fuel pool is required, taking into account - among other potential system interactions - the fuel handling machine and its ancillary equipment, the temporary position of SSCs during outage (e.g. lifting equipment for moving RPV internals) and suspended support equipment in the vicinity of the spent fuel pool.

Furthermore, the walkdown shall include all SSCs that are relevant for the L1 PSA over all operational states/modes.

4.5 SCREENING

Seismic PSA screening process concerns two issues: screening of induced initiating events and screening of SSCs that are considered to fulfill fundamental safety functions. The screening topic is covered in ASAMPSA_E deliverable D30.3 [37].

Nowadays, two ways are used to screen initiating events. Screening by impact (i.e. none or negligible impact on safety) or screening by frequency. Usual way how to screen by frequency consists in evaluation of contribution of event to the overall CDF, see [18] for further details.

Regarding screening by impact, analysts are able to perform simple estimation of impact on safety (from PSA point of view) only in the case if magnitude of earthquake is so low that all relevant SSCs still have considerable safety margins.

4.5.1 INITIATING EVENTS SCREENING

Regarding screening by frequency this approach has several drawbacks:

- Common agreement regarding frequency threshold value and mainly the method how this threshold value should be set, e.g. criteria from [6] are not applicable because of

⁴ This paragraph draws on Post-Fukushima recommendations of the German Reactor Safety Commission from 26./27.09.2012

- LOCA is default event,
- Even if LOCA is omitted threshold 10^{-7} is not applicable due to reactor protection activation,
- Uncertainty connected with bounding analyses is large,
- Threshold values used within PSAL1 should not be capable of reflecting cliff edge effects.

Especially regarding seismic event :

- it is obvious that seismic event as such produces spatial impact affecting whole site including all plant SSCs as well as surrounding environment. This large scope impact can lead to serious consequences (from probabilistic point of view),
- there is no information on CDF following from particular discrete interval (see 4.3) at the beginning of any seismic L1 PSA (step 3).

Based on above presented discussion the setting of screening threshold value is matter of expert judgment which respects common practice and contains reasonable level of conservatism⁵. Consequently let assume following facts:

- conditional probability of large release⁶ of any discrete interval from set of intervals⁷ that are used to approximate hazard curve is equal one, i.e. conditional probability of large release is equal one,
- common value of safety target for large release is 10^{-6} ,
- based on current practice frequency of large early release is below 10^{-6} .

Screening value for frequency of seismic initiating events can be set under such assumptions to be less then to 10^{-11} in order to keep appropriate accuracy of results. If analysts would like to apply reasonable level of conservatism then they should define threshold level as upper bound stated at the 95% confidence level.

4.5.2 SSC SCREENING

Based on [11] screening (analysis) is a process to eliminate items from further consideration based on their negligible contribution to the probability of a significant accident or its consequences. However, important reason of screening is impracticality to develop detailed fragility descriptions of all potentially significant SSCs.

Two typical screening methods for SSCs are used:

- screening by contribution to the CDF, so called surrogating approach and
- screening based on seismic capacity.

⁵ It is matter of common understanding what is meaning of reasonable level of conservatism.

⁶ Fundamental safety principle expressed in SF-1 is *to protect environment*. In such case it is not important to divide releases between early and late, i.e. authors assumed that PSA considers any large release which can threat environment.

⁷ It is noted that authors have used DPD method, see introductory part of section 4.

4.5.2.1 Surrogating approach

Based on reference [10], typically a CDF screening threshold is established by the system analyst whereby the components can be screened out which are not modeled in detail, or else surrogate elements can replace groups of elements that are screened (at a high capacity level).

Simply say this approach consists in setting a target (limit failure probability) for the surrogate elements that replace real components and that have very small contribution to risk. In practice correct implementation of surrogating approach forms time consuming process and care must be taken to exact counting of potential failure of seismic components and careful treatment of the correlation of components represented by the surrogate elements in order to avoid under-estimation of results, see discussions in [10]. In addition, this approach should also consider impacts on L2 PSA results what introduces further complexity.

Based on above introduced reasoning as well as work intensity to perform well performed screening (e.g. correct implementation should also evaluate impact on L2 PSA) this way is not recommended.

4.5.2.2 Screening based on seismic capacity

Screening based on seismic capacity uses criteria for set of component, e.g. spectral acceleration, which ensures that only component having considerable safety margins are screened out. Used criteria shall be well justified and reasonable conservative because contribution to risk of screened components is hidden, e.g. reference [10] considers screening level about 0.8g of spectral acceleration. Reference [9] discusses possibility to screen out some type of SSCs having inherent seismic resistance. Based on mentioned discussion many of SSCs can screen out if acceleration does not exceed range 0.3-0.5g. Another way consists of screening SSCs having large HCLPF capacity. Output of the task is list of screened components including appropriate reasoning.

It should be noted that screening by capacity is also demanding task. This task interacts with steps 3, 6 and 4 as follow: seismic hazard analysis (basic inputs and definition of plant spectra), fragility analysis (especially definition floor response spectra and seismic demands) and walkdowns.

4.6 FRAGILITY ANALYSIS

The objective of a fragility analysis is to evaluate the capacity of SSCs defined within step 2 (Developing PSA seismic SSCs) and consequently to estimate conditional probability of failure of relevant SSCs.

This report assumes that conditional probability of failure will be evaluated by using HCLPF parameters, e.g. [10].

Fragility analysis is tightly coupled with steps 3 (Seismic Hazard Analysis) and 4 (Walkdowns) involving several activities. Fragility analysis covers all categories of PSA seismic SSC list assembled in step 2, section 4.2:

- basic internal items ensuring fulfillment of fundamental safety function including (internal) seismic events (BI),
- threatening internal items that collapse can affect performance of basic internal items (TI),
- flood internal items that failure can leads to internal floods (FI),
- fire internal item acting as potential ignition sources (II),
- external items capable evoking induced events (EI),
- special internal items that involve in-site effect like multi-unit effects, impact of seismic event on nuclear facilities located in-site area (SI).

Conceptual framework to perform fragility analysis for particular categories is introduced in further sections.

4.6.1 *BASIC INTERNAL ITEMS ENSURING FULFILLMENT OF FUNDAMENTAL SAFETY FUNCTIONS INCLUDING (INTERNAL) SEISMIC EVENTS (CATEGORY BI AND TI)*

Fragility analysis is a complex process, e.g. see Table 4-1 in [10]. Fragility analysis of basic internal items (SSCs) is driven by standard guidelines as [11]. Output of this task is conditional probabilities of seismic failure of basic

internal items ensuring fulfillment of fundamental safety functions and conditional probabilities of foreseen LOCAs determined within step 1, section 4.1.1. It is obvious that conditional probabilities of foreseen LOCAs are estimated as a sum of probabilities of particular pipe segments. Probabilities correspond with discrete intervals of plant hazard curve defined within step 3, section 4.3.

Tab. 4-5 Example of outline for output of fragility analysis for SSCs and seismic events

Category	Item ID/ Seismic Event	Description	Interval	Conditional probability of failure / seismic event	Affected SSCs	Severity factor
BI	SB2xxx	2 nd train busbar	1	1E-7		
			2	1E-6		
				
				
			N	...		

TI	Wxx	Partition wall electrical safety train compartment and corridor.	1	1E-7	SB2xxx	0.5
			2	1E-6		0.3
		
		
			N

BI	LL	Large LOCA	1	1E-7		
			2	1E-5		
				
				
			N	...		

In the case of internal items which collapse can affect performance of basic internal items (category TI) the output information shall be added by list of affected safety significant SSCs.

Even if there is a conditional probability of collapse of some structure the effect of such collapse does not have direct impact on safety significant SSCs. For example impact of collapse of partition wall depends on direction of wall drop. In the case of hypothetical example presented in the Tab. 4-5 drop of wall Wxx into corridor has none consequences. Such situations can be treated by severity factors that are used to assess/express severity of occurrence of such event.

It should be noted that:

- *It is convenient to express affected SSCs through limited set of surrogating components. Such approach facilitates developing of fault trees.*
- *Severity factor is just technical mean to tune specific condition of seismic event on expected working conditions. In actually any specific factors can be counted within conditional probability. However, introducing of severity factors can help to facilitate documentation process and maintenance of the model in future.*

4.6.2 FLOOD INTERNAL ITEMS WHICH FAILURE CAN LEAD TO INTERNAL FLOODS (CATEGORY FI)

Assessment of conditional probability of internal floods uses similar way as seismic LOCA in previous section. It means that: All flooding sources determined within step 1, section 4.1.2.2, are assigned by related probabilities of pipe break. This work is based on results of step 3, chapter 4.3.

Flooding sources are grouped according compartments (locations) to establish set of consolidated induced events. Appropriate surrogating components are assigned to each induced event to evaluate effect of particular flood, i.e. all floods having the same effect are represented by one “surrogating component” which conditional probability summarize conditional probabilities of all particular floods.

Specific conditions are reflected by using severity factors (e.g. damage of water source or pipe line outside critical locations prohibit flood of safety SSCs, seismic event can create extra drainage paths, effect of flood can be mitigated by isolation valves etc.)

Tab. 4-6 Example of outline for output of fragility analysis for flood induced event

Category	Flooding source	Induced Event ID	Interval	Conditional probability of induced event	Affected SSCs (Surrogating components)	Severity factor
FI	Source ₁	FL_01	1	1E-8	Pumpxx1 Pumpxx2	0.9
	Source ₁		2	1E-7		0.2

	Source _{nn}		N
...

4.6.3 FIRE INTERNAL ITEMS ACTING AS POTENTIAL IGNITION SOURCES (CATEGORY II)

Processing of internal ignition (explosion) sources uses similar approach and providing similar output as internal flooding sources. However severity factor is composed from several particular factors that reflect:

- 1) Conditional probability that seismic failure induces fire.
- 2) Spreading of fire outside of affected fire compartment, e.g. potential damage of fire barriers, fire loads, qualification of cabling system etc. Determination of this specific sub-factor can evoke extension of step 3 - Seismic hazard analysis to cover topic of fire barriers and consult internal fire hazard analysis to precise all relevant aspects.
- 3) Probability of fire suppression, e.g. damage of fire alarm, fixed extinguishing systems, activity of fire brigade during seismic conditions. Determination of this specific sub-factor can also evoke extension of step 3 - Seismic hazard analysis to cover topic of automatic fire systems.
- 4) Specific meteorological conditions like rain or wind to precise damage potential of fires and explosive cloud in-site area to affect neighboring civil structures can be reflected by using severity factors.

4.6.4 EXTERNAL ITEMS CAPABLE EVOKING INDUCED EVENTS (CATEGORY EI)

As it was stated in section 4.1.3 seismically induced faults of natural formations, civil structures, industrial facilities etc. (object(s) further from this point) can disturb plant normal operational conditions which can influence fundamental safety functions of analysed plant. Unpleasant point of this statement consists in fact that there may be necessary to evaluate many objects. In addition failure of relevant objects have not lead directly to the threatening of plant safety functions but safety functions are threatened by side effects that are triggered as a consequence of object failure, e.g. onshore plant can be affected by tsunami but tsunami height depends on earthquake magnitude and distance of its epicenter from plant as well as on profile of sea bed. So, in general probability/frequency of induced (external) event can be expressed as $P_s \cdot P_m \cdot P_a$. Where P_s represents probability of occurrence of earth quake in relevant area, P_m represents conditional probability that earthquake (better say object affected by earthquake) release some source of potential damage (e.g. fire, explosion, tsunami, such fault of natural or civil structure that can threat plant safety etc.) which has sufficient magnitude to threat plant safety and P_a is conditional probability that source of potential damage affects plant safety (e.g. earthquake can trigger several wild fires but real threat depends on the weather conditions).

Finally, in general case three tasks must be performed in order to assess probability of occurrence of induced (external) event. They are:

- assessment of probability of occurrence of seismic event, i.e. seismic hazard analysis of relevant area (analogy seismic hazard analysis),
- assessment of probability of releasing source(s) of potential damage(s) having magnitude threatening plant safety (analogy of fragility analysis),
- assessment of conditional probability that source of potential damage affects plant safety.

Accomplishment of above outlined tasks that are briefly discussed below presented subchapters, enables final assessment of probability of seismically induced external event.

4.6.4.1 Assessment of probability of occurrence of seismic event (P_s)

If object in interest is located in plant seismic area, i.e. plant and object shares the same epicenter or common seismic fault that can generate earthquake, then basic data from seismic hazard analysis as well as input used for fragility analysis can be utilized.

If this is not the case then seismic hazard analysis must be performed plus similar initial analyses as are performed within fragility analysis, i.e. field spectral response, soil interaction etc.

Output of this task is at least simple hazard curve presenting magnitude of earth quake versus probability or hazard curve as discussed in section 4.3 .

4.6.4.2 Assessment of probability of releasing source of potential damage (P_m)

In general two ways are available to assess probability of potential damage

1. Simple bounding fragility assumption, i.e. it will be assumed that object of interest is going to be damaged if earthquake (in area containing particular object) reaches value 4 (Slightly strong) or 5 (Strong) of Richter scale [24] or value VI. or higher according EMS-98 are reached.

2. (More or less) full scope fragility analysis of relevant object. Such analysis must be in compliance with standard approach, e.g. standard PSA methods described in section 3.6 or general approach as described in [26]. Scope of work will depend on the nature of object.

Probabilities of releasing source of potential damage will be assessed by using hazard curve gained within previous section and performed fragility analysis.

It should be noted that *Assessment of probability of releasing source of potential damage* have not been straightforward task, i.e. occurrence of earthquake leading to the failure of object in interest must not lead directly to the releasing of damage potential and same further conditions must be met, so usually some post-assessment have to be performed. For example, let's assume that plant power line goes through forest country and hazard curve of area where line is located is available as well as results of fragility analysis. It means that one is able to assess probability of damage of power line. However, forest fire can be initiated only in the case if power line is not disconnected from grid, e.g. there is a failure of short ground protection. Extent of such post-assessments will depend on nature of objects identified within tasks 1 and 3, see section 4.1.3.

4.6.4.3 Assessment of conditional probability of affecting plant safety (Pa)

Even if accomplishment of activities described in subsections 4.6.4.1 and 4.6.4.2 provide basic data to assess probability of occurrence of seismically induced external initiating event the extra analyses can be necessary to evaluate impact of the event on the plant. In some cases some additional factors like attenuating effect of induced event can take place. These additional factors depend on nature of induced event. Based on Matrix of feasible correlated hazards presented in Tab. 3-1 some of such additional factors can be as follows:

Tab. 4-7 Example of additional factors influencing plant safety

ID from Tab. 3-1	Correlated hazard	Factors	Comment
N12	Obstruction of a river channel - effect internal flood	Type of obstacle blocking river channel	Liquefaction of blocking material can lead to resume of flow
		Flow rate and country profile	Determine flood extent and flooding rate as well as dynamic properties of flooding wave
			Probable maximum flood can be based on generic data such as [27]
M1	Industry explosion - effect pressure wave	Wind intensity and wind direction, humidity or rain	Determine formation and content of explosive cloud (if this is the case)
		Distance of plant	Determine impact pressure wave
			Maximum can be estimated according generic guides as [28] Side effect can be formed by wild fire
M2	Industry: chemical release - effect main control room working conditions	Wind intensity and wind direction, humidity or rain	Determine formation and content of poisoning cloud
		Distance of plant	Determine impact concentration of chemical substance
M4	Military: explosion		The same as M1
M5	Military: chemical release		The same as M2

ID from Tab. 3-1	Correlated hazard	Factors	Comment
M13	Pipeline: explosion, fire		The same as M1
M14	Pipeline: chemical release		The same as M2
M19	Stability of power grid - Loss of offsite power		Side effect can be formed by wild fire

4.6.5 SPECIAL INTERNAL ITEMS THAT INVOLVE IN-SITE EFFECTS (CATEGORY SI)

It is assumed that fragility analysis of special internal items, defined within step 1, section 4.1.3 - task I., that involve in-site effects like multi-unit effects, impact of seismic event on nuclear facilities located in-site area will be part of separate seismic analyses of such items. If appropriate analyses examining standalone facilities are not available then they must be performed as extra tasks of the extended seismic PSA. (*Standalone* means that any relevant facility is analysed as isolated entity.) Results of these separate analyses are just transformed into specific format used for extended seismic PSA, e.g. similar format as used in Tab. 4-6.

4.6.6 CONCLUDING NOTES TO THE FRAGILITY ANALYSIS

At the end of this step we have prepared several basic categories of data. These data describe conditional probabilities, severity factors (if appropriate) or probability of occurrence of induced events:

- Internal items covering:
 - List of seismic initiating events containing conditional probabilities of occurrence of particular events, typically LOCA events (category BI)
 - List of conditional probabilities of seismic failures safety significant SSCs that are necessary to fulfill fundamental safety functions (category BI) including civil structures that collapse can affect safety significant SSCs (category TI)
- List of induced internal events containing conditional probabilities of occurrence (together with corresponding lists of affected components, see chapter 4.1.2) covering:
 - Floods (category FI)
 - Fires (category II)
- External seismically induced events (category EI)
- Conditional probabilities of occurrence of effects caused by multi-unit effects and others facilities located in site (category EI)

Fragility analysis as such highlights the importance of non-safety systems robustness. Weak components can have significant impact on conditional probabilities of occurrence of induced events. Fragility analysis has deep interactions with steps 1, 3, 4 and usually is performed by using specific methods like finite element method or supporting tools to facilitate and document work are used. Some examples of such supporting tools are introduced in the next chapter.

4.6.7 HAZARD AND FRAGILITY ANALYSIS PSA TOOL

RiskSpectrum® HazardLite [28] (hereafter called HazardLite) is a light tool for assessing hazard risks, e.g. earthquake, tsunami, extreme weather etc. The input to HazardLite includes definition of initiating events ranges, hazard curves and fragilities. The output is an excel workbook containing the results in form of Basic Events. This excel file can be imported into RiskSpectrum® PSA for further analysis. In addition, if the Monte Carlo method is selected in the analysis, a series of text files will also be generated for uncertainty analysis in RiskSpectrum® PSA. A probabilistic safety assessment of an external hazard is different from analysis of internal events e.g. seismic hazards. The differences are mainly that:

- The hazard (the initiator of the sequence) spans over a continuous range
- There is relation between the hazard and the failure of equipment (fragility). The stronger the external hazard e.g. earthquake, the more likely the equipment will fail.
- This is relevant also for other types of hazards, e.g. tsunami, extreme weather hazards.

HazardLite uses an EXCEL workbook to store the input necessary for fragility calculations of components over discreet ranges of peak ground accelerations, which are considered to be the initiating events. To capture the full uncertainty inherent in our knowledge, families of both hazard curves and fragility curves are used.

To capture the uncertainty of hazard curves, several hazards curves may be entered and each curve is given a probability, or weight, that it is the actual hazard curve. To capture the uncertainty of the fragility curve for each component, the user must enter the median acceleration where the component is expected to fail (called A_m), the logarithmic standard deviation (called B_R) which represents the random variability of the fragility, and the logarithmic standard deviation (called B_U) which represents the modeling uncertainty in the actual shape of the fragility curve. Fragility curves are modelled as lognormal probability distributions.

The hazard curves (and the fragility curves) are divided into discrete intervals by the analyst. In the PSA model, each of these intervals needs to be represented. HazardLite will generate the input necessary, with regard to hazard frequencies within each interval and fragilities to be used within each interval. These basic events are intended to be used as initiating events (frequency events) and as component failure in the PSA model (normal basic events in the fault tree structure).

It shall be noticed that fragilities may be grouped and combined. Grouping of equipment is performed to reduce the amount of necessary seismic fragility events and it represents OR-structures of components that need to be treated as fragilities. Combinations may be relevant when several fragility events are found in the same MCS. The reason for this is that the convolution approach used in HazardLite is more exact if the convolution is performed for the events together, rather than performing the convolution individually and then combining them in a MCS.

In the quantification, each of the defined intervals is subdivided into a number of sub-intervals. The chosen amount of subintervals is 100 in HazardLite.

Within each interval the hazard frequency, as well as the fragility for each component is calculated. The calculation of the fragility is convoluted with the frequency, to account for differences in the interval (both the hazard curves and the fragility curve will change value within the interval).

The quantification algorithm is described by following:

- Point estimate calculation
 - Quantification of the hazard frequency, the initiating events

- Fragility
- Calculation of fragility for group of events
- Calculation of fragility for combination of events
- Uncertainty calculation
 - Quantification of hazard
 - Quantification of fragility

Quantification of hazard, initiating events, point estimate calculation

HazardLite is calculating the frequency for the hazard by calculating the average frequency taking into account the weight of the hazard curve. The hazard frequencies are calculated by subtracting the exceedance frequency at the upper hazard boundary from the exceedance frequency corresponding to the lower boundary. Thereby a frequency within each interval is calculated. The calculation of hazard frequency is also performed for each sub-interval, since these frequencies are required for the convolution of hazard and fragility. Logarithmic interpolation is used when the definition of the interval does not match the user defined input data for the hazard curve.

Fragility

The HazardLite is used earthquakes as an example to illustrate how it works.

The fragility calculation is based upon following formula [1]:

$$f' = \Phi \left(\frac{\ln\left(\frac{a}{A_m}\right) + \beta_U \cdot \Phi^{-1}(Q)}{\beta_R} \right) \tag{1}$$

Where:

$\Phi()$ is the standard Gaussian cumulative distribution

a is the PGA

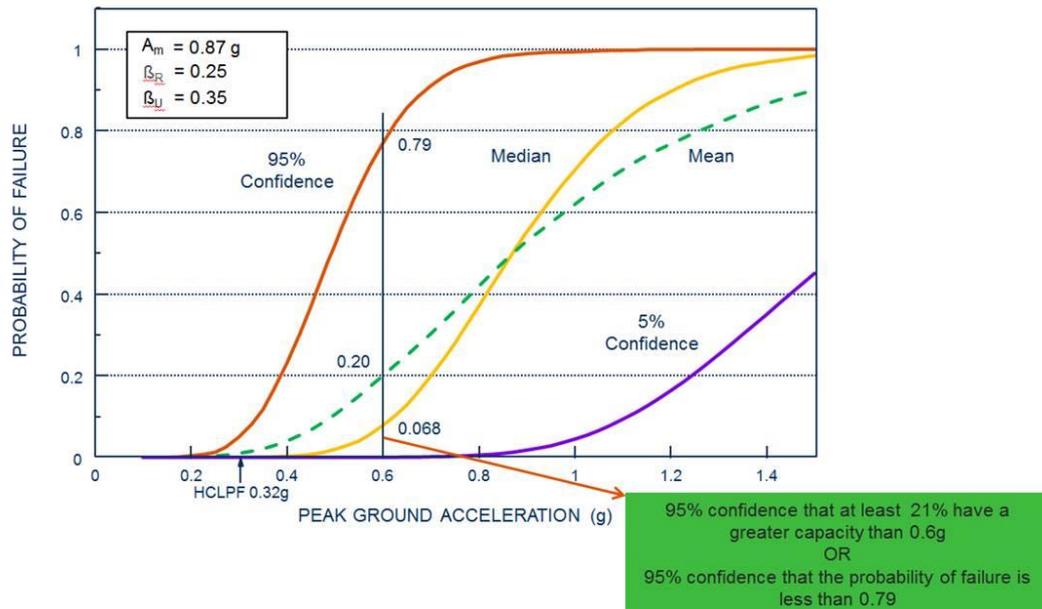
A_m is the median ground acceleration capacity of the component

β_R is the random variability

β_U is the state of knowledge uncertainty (uncertainty of fragility curve shape)

Q is the confidence that the conditional probability of failure, f , is less than f' for a given peak acceleration a .

Fig. 4-4 Example of fragility curve, [10]



A mean fragility curve can be calculated by replacing β_R by following

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2}$$

(2)

in the equation above and to set β_U to zero [1]. Then following equation can be defined:

$$f = \Phi \left(\frac{\ln \left(\frac{a}{A_m} \right)}{\beta_c} \right) \quad (3)$$

This equation is used in HazardLite to calculate the mean fragility (e.g. at a given PGA a).

Since the fragility is representing for particular range of PGAs, and over this range the hazard frequency is also changing, and the cut sets including fragilities will always include one hazard and at least one fragility, the proper calculation would be to integrate them over the interval (over which the hazard is defined). However, the calculation in RiskSpectrum PSA/RSAT does not allow for such evaluations and thereby the calculation of the fragility must take this into consideration. The calculation of the individual component fragility convolution is described below, and the calculation of groups and combinations is described in a separate section.

Assume following cut set H_1, F_1, B . Where H_1 is the frequency in an interval, F_1 is the failure probability of a component in the same interval, and B is an independent failure probability.

If H_1 and F_1 are calculated independently with regard to the frequency and probability within the interval, this will not necessarily yield the same result as the mean value computed by

$$\frac{1}{x} \int_0^x h(x) \cdot f(x) dx \quad (4)$$

And the mean value from the integral above is the correct mean value. Therefore HazardLite does the convolution through a numerical integration, and then divides it by the frequency in the interval. In this way a weighted fragility estimate is calculated, and when it is multiplied with the hazard frequency in the MCS again, it will yield the same result as if the integration would have been performed for the MCS itself.

To put it in formula, F_i the failure probability of the component due to seismic fragility in interval i is calculated by:

$$F_{i,h_k} = \frac{\sum_{j=1}^n (h_{ij} f_{ij})}{\sum_{j=1}^n h_{ij}} \quad (5)$$

Where:

F_{i,h_k} is the fragility calculated for interval i based on hazard curve k

h_{ij} is the hazard frequency for interval i , sub-interval j

f_{ij} is the fragility calculated for the interval i , sub-interval j

The value of the fragility f_{ij} is calculated at the upper end of the sub-interval, which is a slightly conservative approach taken. The probability is calculated by formula (3).

The fragility (failure probability) is calculated for each individual hazard curve as basis, and then the fragility (failure probability) results to be used in the PSA for the interval are calculated by multiplying the weight of the hazard curve with the F_{i,h_k} of that specific curve. The raw data are the hazard curves, and thereby these should be used as the basis for the convolution. The fragility (failure probability) for the component is calculated by:

$$F_i = \sum_{k=1}^n F_{i,h_k} \cdot W_{h_k}$$

Where:

W_{hk} is the weight of hazard curve k

$F_{i, hk}$ is the fragility in segment I for hazard curve hk

Component groups and combinations

A component groups is defined as a set of components that are grouped together and instead of representing them individually, they are represented as a group. These events could be considered to be represented under an OR-gate.

The quantification of the fragility for each component is according to the methodology above, but instead of representing each value in the PSA model by a basic event, they are combined according to following formula:

$$F_{Group} = 1 - \prod_{i=1}^n (1 - F_i)$$

Combination

A combination is defined as a set of basic events that are found in the same MCS. The process described above for components and groups of components generates a convolution of the hazard and the fragilities over the hazard range. This process is used to, as accurately as possible, calculate the values that should be produced by the MCS analysis whenever the cut set includes the hazard (which it should always do in the hazard analysis) and a fragility. However, when a cut set contains more than one fragility the convolution is no longer correct.

HazardLite gives the user the possibility to specify combination of events. There can be a prohibitively large number of combinations, so the process is intended to be used for the events that may have impact on the results.

The combinations defined are calculated simultaneously as the individual basic events, to ensure consistency of values used (e.g. with regard to uncertainty simulations - same value must be used for $f^{A(i)}$ (failure probability A in internal i) both when the individual basic event is computed and the combination event).

The combinations are intended to be included in the analysis using MCS post processing, replacing the events in the cut set by the combinations. The difference in results when applying combinations and not for individual MCS may be significant, and hence it is recommended to use the combinations for event combinations of importance.

Uncertainty calculation

The uncertainty calculation is built by the same methods as presented above. The equations are slightly different, when it is no longer the mean value that is computed. The method is:

1. Randomly select one of the hazard curves (according to its weight)
2. Randomly select one of the fragility curves in the group of fragility curves (for each component)
3. Calculate the hazard frequencies for all defined intervals
4. Calculate the fragilities for all intervals, under the condition of the selected hazard curve (convolute with the selected hazard curve only)
5. Calculate Component groups and combinations
6. Perform next sampling

4.7 DEVELOPING SEISMIC FAULT AND EVENT TREES

The aim of this task is in accordance with [18] to outline basic progression of accident scenarios as well as to determine specific human actions etc. It is assumed that majority of work will be adapted from PSA for internal events (e.g. success criteria). In such case event trees are adapted on seismic conditions to reflect specific seismic initiating events (usually LOCA) as well as induced events if such events can be treated as event disturbing performance of safety significant SSCs. Basic strategy how to fulfill this step depends on impact and scope of considered induced events (and possibilities offered by used software, which is beyond topic of this report).

Even if scope of systems, human interactions and recovery actions were determined within internal event PSA adopted assumptions shall be carefully evaluated in light of conditions introduced by seismic event. Human actions implementation depends on strategy adopted by model developer(s). Implementation of human actions that can be integrated within fault or event trees is part of standard PSA methodology including processing of dependency. Basic task connected with occurrence of in site seismic event is put plant into stable safety state, i.e. at least Control of the reactivity and Removal of heat from the core must be ensured according [16] during assumed mission time.

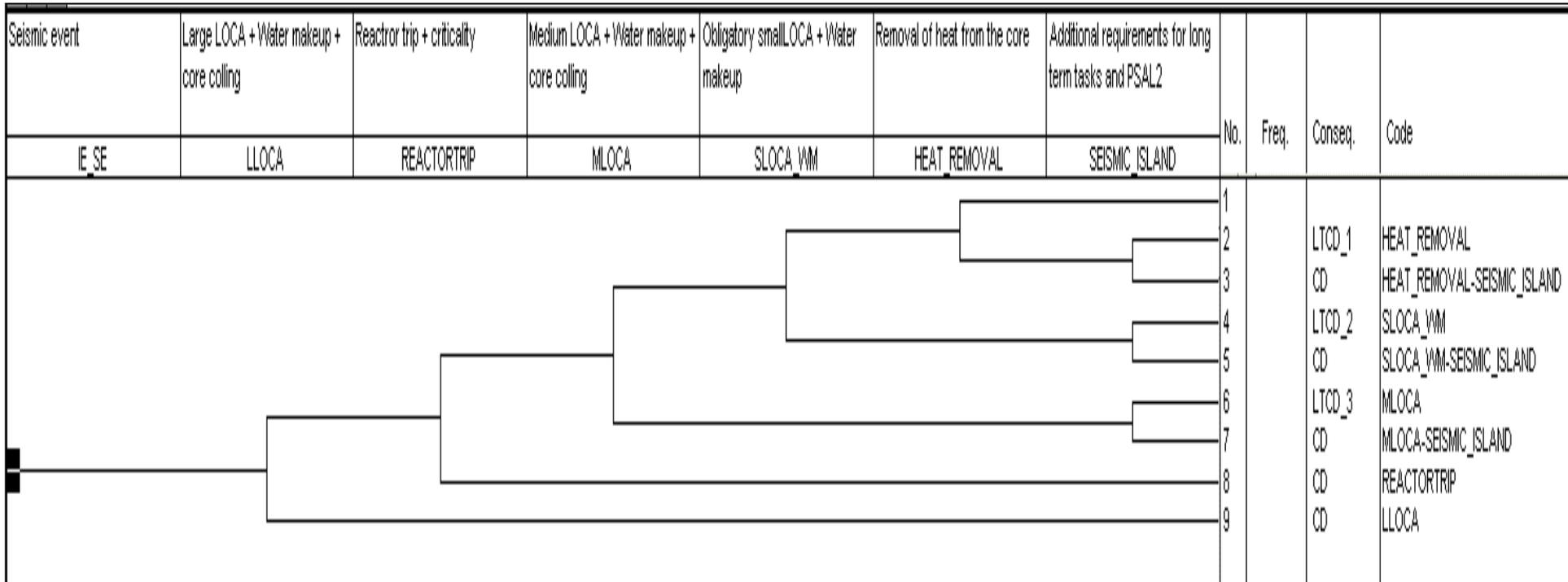
If it is assumed that in site and offsite seismically induced events have different source of earthquake, see section 4.6.4.1, then it is mutually exclusive and response on offsite seismic event within L1 PSA can be modeled as independent initiating event(s). Modeling of such independent seismically induced initiating events will be similar as L1 PSA models used for basic categories of external hazard. So, further sections deals only with case when all seismically induced initiating events have common earthquake source.

4.7.1 EVENT TREES

Development of event trees for L1 PSA can use two basic strategies:

- Usage of separate event trees to model basic response on seismic event and different categories of seismic LOCA determined within step 6, section 4.6.1. Consequently consequences of particular trees leading to the core damage are evaluated by means of common integration event tree. It should be also noted that due to many small pipes and tape lines consideration of small LOCA should be obligatory.
- Usage of one common event tree combining basic response and seismic LOCAs. Such option should be carefully evaluated, e.g. if event tree requires reactor trip at first branching point then such case can lead to slightly overestimation of the results, because large LOCA response may not require reactor trip for certain type of reactors.

Fig. 4-5 Example of hypothetical full power event tree combining basic response and LOCAs



Consequence CD stands for consequence which leads to the core damage to the time while plant is isolated from outside area (e.g. mission time). However; some earthquake magnitudes made this fact irrelevant.

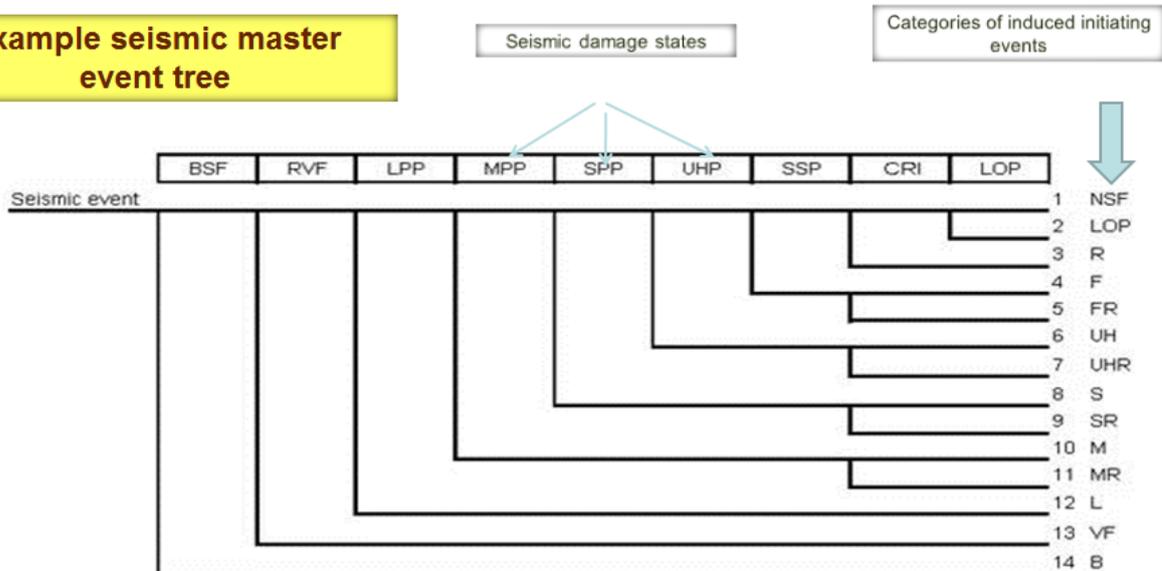
Consequences LTCD_n stand for consequence that can be further developed within long term scenarios to examine plant long time response.

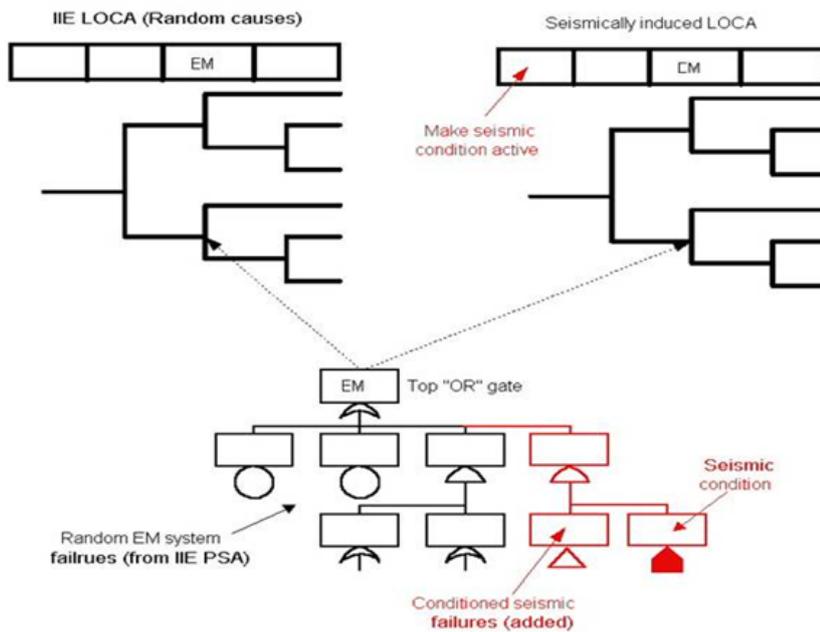
Examples of modelling of seismically induced initiators and accident sequences with master event tree are given below:

Top Events / Seismic Damage States	
BSF	Structural failures of buildings
RVF	Reactor vessel failure or any primary failure beyond ECCS capability
LPP	Large size primary piping or component failure
MPP	Medium size primary piping failure
SPP	Small size primary piping failure
UHP	UHS Pumphouse failure
SPP	Secondary side piping failure
CRI	Control rods insertion failure (including also failure modes such as fuel grid bending / crushing)
LOP	Switchyard or other failures causing loss of offsite power

End States / Seismically Induced IEs	
B	Direct CD (Building failure / collapse)
VF	Direct CD (Reactor vessel failure - breaks beyond ECCS capacity)
L	Large LOCA
MR	"M" with control rods not inserted
M	Medium LOCA
SR	"S" with control rods not inserted
S	Small LOCA
UHR	"UH" with control rods not inserted
UH	Total loss of UHS
FR	"F" with control rods not inserted
F	Steamline / Feedline break
R	Control rods not inserted
LOP	Seismically induced LOOP
NSF	No seismic failure

Example seismic master event tree





Organisation of seismic PSA in RS model

Full scope PSA requires specific event trees covering all POSs. Low power trees can resemble on presented full power tree. Particular event trees for different POSs shall carefully evaluate POSs conditions, e.g. seismic event together with specific maintenance configuration can induce such rupture of pipe line that turns LOCA into inter-facing LOCA etc.

Additional trees can be necessary to cover other nuclear sources as spent fuel pool etc. Basic task joined with occurrence of seismic event for any nuclear source is similar as in the case of reactor unit, i.e. to put nuclear source into stable safety state.

4.7.2 FAULT TREES

Fault trees are used to perform systems model to incorporate seismic aspects that are different from corresponding aspects found in the internal events PSA model. The seismic model shall reflect the as-built and as-operated plant being analyzed. So, aim of this task, within the seismic PSA, is to adjust system analysis to reflect:

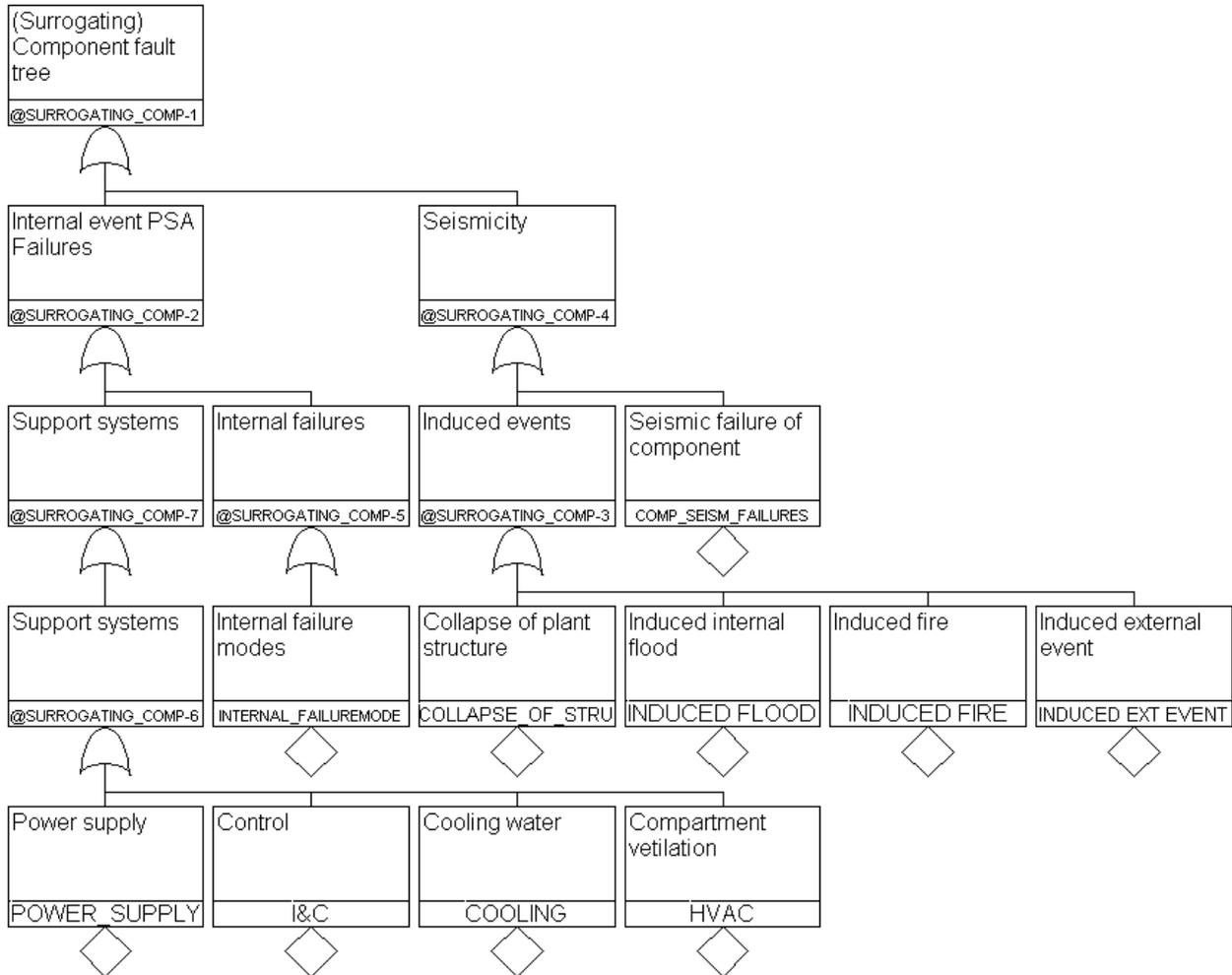
- Seismic failures of safety significant SSCs including internal seismic initiating events
- Collapse of specific plant structures that can affect safety significant SSCs
- Effect of induced events on performance of safety significant SSCs

If necessary then appropriate fault trees are added by HEPs to model operator interventions (recovery actions, in situ operator manipulations etc.). It should be noted that HEPs can be also integrated into event trees.

Based on the results of step 2 - Seismic SSC list, section 4.2 and step 6 - Fragility analysis, section 4.6.1 and on the precondition to use none specific software this task can be accomplished by using linked fault trees. It means that fault trees of any determined SSCs are added by seismic failures via OR gates that link related conditional probability of seismic failures. It is noted that this one is standard approach for rudimentary PSA. Induced events, better say effects/impacts of induced events are treated by similar way.

It is also noted that there are more and more frequent requirement to consider 72 hours mission time, e.g. discussion in chapter 5 of [17].

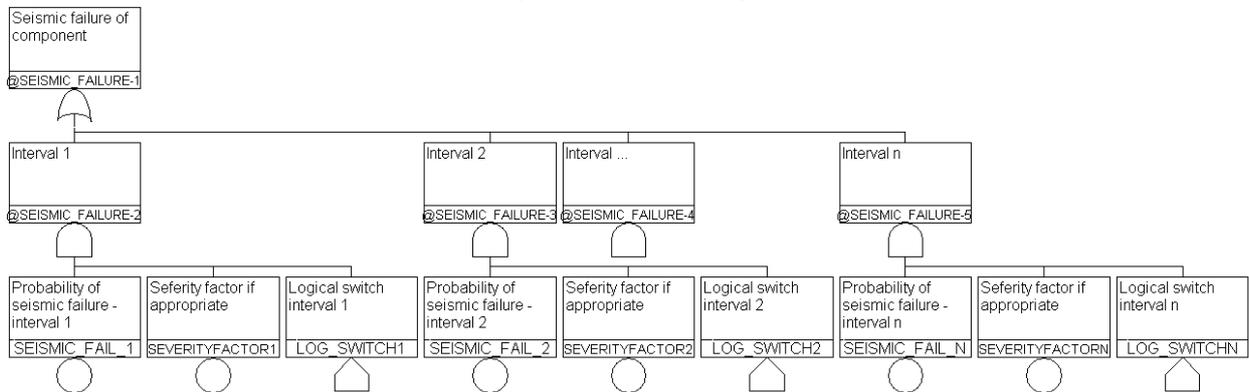
Fig. 4-6 Outline of fault tree reflecting seismic failures and induced events



Potential drawback of such approach is double counting of basic events, e.g. break of cooling line leads to the unavailability of cooling systems as well as to flooding of this system, seismic failure of bus-bar as well as seismic fire of the same equipment.

Particular conditional probabilities (frequencies) are also treated by using linked trees, see Fig. 4-7.

Fig. 4-7 Treatment of conditional probabilities (frequencies)



We assume that any relevant seismic component from SSC list determined within step 2 has linked fault tree connected to appropriate position (e.g. gate COMP_SEISM_FAILURES in Fig. 4-6). Any particular component seismic fault tree has OR top gate (e.g. @SEISMIC_FAILURE-1). Top gate is used to link all relevant seismic failure across predefined discrete seismic intervals determined within step 3. Intervals are represented by AND gates (e.g. gates @SEISMIC_FAILURE-2 to @SEISMIC_FAILURE-N in Fig. 4-7). Consequently each interval gate contains:

- Conditional probability of component due to seismic effect estimated in step 6 (e.g. gates SEISMIC_FAIL_1 to SEISMIC_FAIL_N)
- Severity factor that enables to discriminate seriousness of seismic effect if appropriate (e.g. gates SEVERITYFACTOR1 to SEVERITYFACTORN), see also usage of severity factors in chapters 4.1.2, 4.1.3, 4.6.1 etc.
- Logical switch that is used to put into effect particular discrete seismic interval (e.g. gates LOG_SWITCH1 to LOG_SWITCHN)

Similar approach can be used to provide frequencies for particular seismic intervals as well as to integrate effects of induced events.

Benefit of such approach consists in its application without usage of specialized software. However such approach leads to large PSA model and double counting of events, e.g. trip of buss bar avoids its failure. On the one hand such cases can be treated by severity factors on the other hand this increases complexity and decreases traceability of model.

Limitation of this approach follows from classic PSA features i.e. problem to follow exact timing of scenario (so called snapshot effect, i.e. all analyzed variants of particular scenarios occur simultaneously⁸) and disability to cope with open loops.

⁸ It should be noted that assumption of simultaneous occurrence of several variants of seismic scenarios is not too conservative due to spatial effect of seismic event. However one should be careful to model recovery action performed by crew because plant shift resources are usually limited and outside help can be unavailable for long time.

4.7.3 HUMAN ERROR PROBABILITIES (HEP)

General experience, expressed in many works, address human factor as an important contributor to the overall risk (of NPP performance); when plant design requires response of operator to mitigate the consequence of postulated initiating events. Topic related to the HRA is covered by many guidelines. The most important of them are summarized in [3]. In general we can expect two basic situations in HRA area:

- operator actions performed to mitigate consequence of seismic event are similar or almost the same as actions performed within a response on postulated initiating events / transients; such situations are discussed within this chapter,
- long term mission time can consider actions that are beyond scope of standard HRA analysis like equipment repairs / restorations, usage of special temporary equipment as are mobile power sources and pumps, providing cooling water and working media etc. Such situations are briefly discussed within section 5.

Based on high diversity in this area, only general HRA requirements can be stated similarly as done in [6]. Such general (but highly important) requirements can be summarized as follows.

- Justify the basis of suitability of non-seismic scenario for seismic conditions, i.e.
 - Scenario can be substantially changed by simultaneous occurrence of several adverse factors. For instance operators maintain operation of equipment to cooldown the unit as well as cooperate in response on a fire. This can lead to reclassification step-by-step tasks into dynamic tasks.
 - Changing the context of HRA scenarios can requires reevaluate screening of human-errors performed within internal event PSA. This one is similar situation as in previous paragraph, e.g. conditions to perform simple well trained action are disturbed by induced.
 - Changing the context of HRA scenarios can affect conditions assumed for recovery actions. For instance induced events can make recovery actions as manual initiation of equipment more difficult or impossible, e.g. rule based actions turn into knowledge base actions. Foreseen actions of in situ operator can be prohibited by damage of access paths.
 - Changing context of HRA scenarios can affect foreseen recovery of human-errors, e.g. simultaneous performing of several actions reduces opportunity for self-recovery, the same holds for inter-crew recovery. Consideration of independent checker, like safety engineer, can be affected by limited access of control room and simultaneous occurrence of the seismic effects in multi-unit site.
- Review the suitability of operating procedures for non-seismic scenario for seismic conditions, i.e. non-seismic procedures shall be replaced by specific seismic procedures if they are available. Otherwise all assumptions regarding rule-based tasks must be reclassified.
- Justify the assumptions used for cognitive part of actions. Operators can challenge many simultaneous symptoms including incomplete or missing information and false alarms. This can lead to the reclassification of skill or rule based tasks into knowledge based tasks and to increasing working stress.
- Justify the assumptions used for manipulation part of actions. Operator can perform several simultaneous tasks and challenge increasing malfunctions rate of control systems. This can lead to the reclassification of step-by-step tasks into dynamic tasks as well as to increasing time stress.

- Review expected working conditions that can be affected by adverse external factors as releases from neighboring in site nuclear facilities or from external industrial facilities. This aspect requires tight connection fault trees used to model such effect with HRA, e.g. work of ventilation systems.
- It also necessary to take into account that (limited) crew will be forced to work several tenths of hours without relaxation.

Above mentioned requirements should ensure consistency between seismic and internal event PSAs. They also imply necessity to tailor any HEP on specific conditions evoked by magnitude of seismic event. Simply say any discrete seismic interval, see item a) of Result of seismic hazard analysis in section 4.3, should use its own specific HRA. However except of above described requirements there is none common guideline how to proceed HRA for seismic case. An interesting example is formed by guideline [8] which offers quite straightforward approach how to cope with this task. Quoted guideline states: In case of earthquake, the HEPs can be adjusted as follows:

- Up to an earthquake intensity of 0.2 g (maximum horizontal ground acceleration at the foundation level of the reactor building), the failure probabilities for personnel actions can be taken over without modification from the model for internal events (transients and LOCAs).
- In the case of an earthquake with intensity from 0.2 g to 0.6 g, a linear interpolation between the values for 0.2 g and 0.6 g (guaranteed failure) shall be performed. Special case: for actions that must not be carried out within an hour after the earthquake, the failure probabilities up to an earthquake of magnitude 0.6 g can be taken over without modification from the model for internal events.
- From 0.6 g, all personnel actions shall be considered as guaranteed failed.

4.8 SEISMIC RISK QUANTIFICATION

The aim of this step is to quantify risk (core damage and large early release frequencies) by appropriate integrating of the seismic hazard, fragility and the systems-analyses.

Based on the work performed within steps 1 to 7 quantification of seismic PSA is standard (mainly software based) activity like in PSA for internal events, see. [18] for further details.

Integral part of quantification process is sensitivity (and importance) analysis. Except of obvious evaluation of importance of basic events (components, systems etc.), which is based on Fussel-Vessely and risk achievement worth factors and sensitivity of used parameters, care should be taken reviewing of used simplification assumptions. For example, conclusion of sections 4.1.4 states that systematic work within step 1 can require certain level of simplification which can tend to the applying conservative assumptions and consequently lead to the risk over-estimation. Importance analysis (even if does not evaluate interaction of factors) forms handy tool to estimate contribution of induced events to the overall results in this case. If this analysis reveals some significant risk contribution then relevant cases should be reviewed in order to avoid adopting some ineffective corrective measures. Another controversial situation can be caused by double counted basic events, see section 4.7.2. Such potential over counting should be checked by detailed analysis of minimal cutsets.

4.9 REPORTING

Reporting is standard part of any PSA which aim is to provide comprehensive and traceable documentation of the work.

4.10 SPECIFIC ASPECTS OF EXTENDED PSA

This section briefly highlights some points regarding particular steps of proposed approach when specific consideration should be taken into account, e.g. development of extended seismic PSA for L2 PSA (which is beyond the scope of this report) or spent fuel pool.

4.10.1 INTERFACE PSA LEVEL 1 AND PSA LEVEL 2

This section provides recommendations regarding the definition of Plant Damage States (PDSs), which are used as boundary conditions in the Level 2 analyses, for the earthquake initiators groups that have been identified to be of most interest by the end-users groups after collection and discussion of results from the ASAMPSA_E end-users survey [34]. The general discussion on definition of PDSs and protocols and recommendations for performing PSA are to be found in the ASAMPSA2 guidelines ([35] and [36]).

Most of the discussion is the same for each of the external events initiator groups, according to experience gained from performing and/or reviewing complete and integrated analyses, and therefore the sections are given for completeness and to make the discussion self-contained for each initiator group and with small variations from each other, according to initiator group expected consequences.

4.10.1.1 Definition of Plant Damage States (PDS) for seismic initiating events

The definition of, and collection of data for the PDSs are tasks that fall upon different teams that perform the analyses (Level 1 and Level 2 teams). Therefore it must be stressed, as was done for analyses of internal events ([35] and [36]) that this task involves close interaction between the teams performing the analyses. Level 2 personnel has knowledge about what boundary conditions are necessary for characterization of accidents after core damage, and Level 1 personnel knows how accidents progressed up to that point and why core damage occurred. Therefore, this part of the works profits from feedback and potentially iterative work between the two teams in the course of defining the PDSs.

To this point, it is recommended that the Level 2 team in general takes cognizance and understands thoroughly the definition of systems success criteria used in the Level 1 study, and in particular for accidents initiated by earthquakes, what are the potential initiator-dependent systems failures (failure of systems that occurred as a direct impact from the initiator) and -independent failures (failure of systems that may have occurred after accident initiation, at a time that for the most part cannot be specified by Level 1 analyses).

It is also strongly recommended that the Level 2 team familiarizes themselves with the results of Level 1 in terms of individual accident sequences or Minimal CutSets (MCSs) that show the chain of failures (initiator, initiator severity, dependent systems failures, component failures, and operator errors) that ended in core damage. Operator errors in Level 1 are of particular importance for Level 2 analyses if operator interventions that could be considered as part of SAMGs are introduced in Level 1 in conjunction with interventions that are part of EOPs. This is the case for instance for containment venting, initiation of containment sprays, or initiation of firewater (or equivalent emergency system) injection in the RCS prior to core damage in BWR plants. Since many (but not all) of the accident sequences from earthquakes result in Level 1 consequences similar to complete Station Blackout acci-

dents with failure of all injection systems, the only option for preventing core damage (for BWRs) would be to depressurize the RCS and initiate firewater as soon as possible. The danger is that this system may be over-credited in Level 2, if accident progression to the time of core damage is not thoroughly understood by the Level 2 teams.

In addition, it is also strongly recommended that the Level 2 team responsible for the definition of PDSs understand the role of auxiliary systems (such as compressed air, auxiliary and component cooling water systems) in the process of preventing core damage in particular accident scenarios, since these systems may fail as dependent on the initiator, without immediate failure of the primary safety systems.

The definition of PDSs that has been used for the internal events analysis has to be verified for applicability to Level 1 accident sequences that are initiated by earthquakes. The combination of dependent and independent systems failures due to seismically induced sequences may require the definition of additional PDSs that were not considered possible for internal events. In addition, earthquakes may induce additional failures that were not considered for internal events (such as direct containment failure, containment isolation failure, piping failure inside or outside the containment). Finally, operators may be required to perform actions (such as venting of the containment prior to core damage) that would not be considered under accidents initiated by internal events and that change the status of the containment before the beginning of Level 2 analyses.

Preliminary discussion of this topic within WP40 has led to the conclusion that for the purpose of “presentation of results” and “analysis of results” (especially for importance analysis) it is strongly suggested to include one additional characteristic in the definition of PDSs that describes the group of initiators. Apart from this additional information, the traditional PDS characteristics seem to be suitable also for earthquake characterization.

Additional characteristics with particular importance for L2 PSA do not seem to be needed. Any example we could think of would be an accident with somehow catastrophic consequences in Level 1 (everything fails), so that any issue impacting Level 2 would be “mute”. For instance fires in the reactor building after an earthquake of very high intensity would have no additional meaning, since in this case either the containment is bypassed (failure of all pipes assumed due to failure of reactor building and systems located in the building), or the fire should have been taken into consideration in Level 1 (failure of equipment due to fire following the seismic event).

As a preliminary conclusion of the present document it seems that - apart from the initiating event itself - no additional PDS characteristics are needed.

4.10.2 LEVEL 2 PSA

Step 1: It is convenient if sizes of seismically induced LOCAs correspond with division of LOCAs considered for severe accidents. In such case some LOCAs will have *positive* effect consisting in automatic depressurization of primary circuit.

Step 2: Even if this report deals with PSAL1 it is convenient to develop an extended list of component in initial stage to cover also L2 PSA needs, e.g. containment structure, hydrogen recombiners, filtered containment venting

system, containment isolation system, recirculation circuits, containment heat removal system, instrumentation, etc.

4.10.3 SEISMIC HAZARD ANALYSIS

Section 4.3 states that parameterization of seismic hazard for external items capable evoking induced events shall be based on specific seismic hazard analyses. If safety of analyzed plant can be threatened by instability or collapse of external natural formation or seismic failure of industrial facilities and sources of threat are far away from analyzed plant then it can tend to the situation that it will be necessary to perform several seismic hazard analyses and consequently corresponding number of seismic PSAs, i.e. one specific PSA for particular source of external seismic hazard, see also discussion in section 4.7.

4.10.4 SPENT FUEL POOL AND OTHER NUCLEAR FACILITIES (MULTI-UNIT EFFECTS)

Step1: Potential of pipe breaks should be evaluated in detail especially for cases where spent fuel pool and its piping are located outside containment. Pipe breaks even if not serious can lead to over-flooding compartments containing cooling pumps etc. Loss of cooling of a SFP can also lead to its overflow (due to water thermal expansion).

Topic of multi-unit effect is briefly covered by Step 1, section 4.1. In general scope of multi-unit effect always depends on plant design (level of resource sharing and cross connection points) and plant layout (usage of common building, distance and fire distance of civil structures etc.). Consequently consideration of multi-unit effect will be always plant specific. Assumed approach for multi-unit case prefers separate analyses for particular facilities in analyzed location (without consideration neighboring facilities) and particular facilities results will be implemented into analyzed case via specific basic events that will express conditional probabilities of occurrence effects that influencing analyzed case (e.g. break of pipes that put out of order common cooling lines, fires and explosion threatening analyzed unit, releases of radioactive and poisoning substances that affect habitability of control room etc.).

4.10.5 CORRELATION OF SEISMIC FAILURES

Question of interest is if failures of similar components (e.g. the same design and provider) subjected by the same earthquake are correlated. Even if there are none clear evidence that such *common cause failures* take place general opinion is that correlation of seismic failures should be considered in the cases if similar components have common floor slab, e.g. [11].

If such correlation is assumed then it requires extra work to implemented correlated failures into fault trees. However there is not common agreement how such correlation effect should evaluated (analytically or used some unified methodology).

5 POST-SEISMIC PSA

The specific aspects of extended seismic PSA are formed by requirements to model long term response on seismic event when plant is operated as isolated island without or with limited external support. Such approach requires models that are used to evaluate situation beyond the used mission time including effects of emergency response. This part provides brief discussion regarding post-seismic PSA and introduces outline of methodology for such analyses.

5.1 DISCUSSION REGARDING POST-SEISMIC PSA

If we assume that plant should withstand certain period of time (mission time) without outside support then post-seismic PSA can only develop sequences that were not finished with core damage during mission time (e.g. *LTCD* sequences in Fig. 4-5) to demonstrate the capability to return plant into normal or long term stable safety state.

The aim of such models is to assess probability of successful recovery in combination with emergency response.

Any post-seismic model should be based on realistic scenario clearly describing:

- expected final (safety) state,
- initial conditions including expected scope of damages and adverse effects,
- list of recovery tasks to mitigate adverse effects and restore desired state,
- implementation strategy for each tasks including time frame (critical time to finish some partial tasks), i.e. scope of one-off and continuous activities that shall be performed in order to achieve final state ; any task can have several alternative strategies.

Following hypothetical scenario is introduced as an example: Restoration of normal operation of spent fuel pool.

- expected final state: spent fuel pool heat removal is performed by using standard systems having available normal power supply and standby emergency power supply
- initial conditions including expected scope of damages and adverse effects are:
 - loss of offsite grid and only one stabile emergency generator is available,
 - loss of all pool heat removal systems that are damaged by internal flood,
 - leak of spent fuel pool and released water is collected in storage tanks and several compartments which forms adverse conditions from radiological consequences point of view,
 - pool is cooled by injected fire water which covers leak loses.
- List of tasks to mitigate adverse effects and establish desired state:
 1. establishing temporary power supply (alternatives: mobile diesels or temporary electric line)
 2. restoration available emergency diesel-generators
 3. managing cooling water supply (alternatives: usage of cisterns or temporary pipe line)
 4. establishing temporary spent fuel pool cooling (alternatives: mobile injection pumps or temporary cooling station)
 5. fixing of spent fuel pool leak
 6. restoration spent fuel pool heat removal system including renovation of relevant compartments affected by flood
 7. removing and cleaning contaminated water from spent fuel pool and decontamination of affected compartment.

It is reasonable to assume that recovery tasks form serial system (at least formulation of set of recovery tasks should be done in such a way that their represent serial system), which enables to analyse one top event.

If potential scope of damages is taken into account, e.g. Fukushima experience, then any post-seismic PSA can contain large scope of independent tasks related to many different areas as emergency response and planning, traffic and logistics management, civil engineering, maintenance, radiological protection, decontamination etc. Moreover analysed period can exceed several months and particular tasks are performed simultaneously and any task can consider their own internal recoveries. Analysis of such case by using classic PSA technique relying on fault trees can reach some limits of classic PSA like dynamic response and closed loops. Some other methods as Program Evaluation and Review Technique (PERT network charts); reliability block diagrams; decision trees or dynamic programming can be more appropriate to perform such analyses in specific situations.

5.2 OUTLINE OF METHODOLOGY FOR POST-SEISMIC ANALYSIS

Based on above introduced discussion recommended approach for post-seismic PSA is as follows:

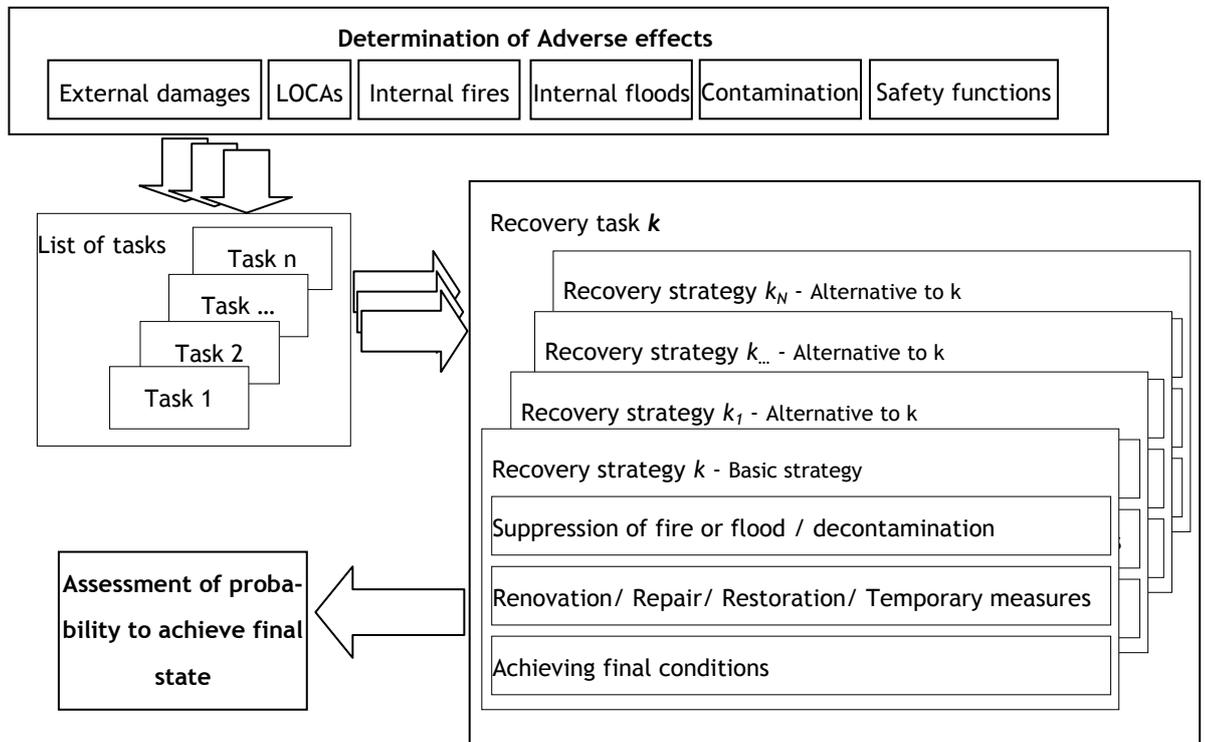
- evaluation of initial conditions including expected scope of damages and determination of all significant adverse effects,
- definition of final (safety) state,
- determination of a list of recovery tasks to mitigate adverse effects and restore desired state,
- definition of implementation strategy for each tasks including time frame (critical time to finish some partial tasks), i.e. scope of one-off and continuous activities that shall be performed in order to achieve final state ; any task can have several alternative strategies,
- assessment of probability to achieve final state.

Assessment of probability to achieve final state within post-seismic PSA is based on evaluation of all determined recovery tasks. Each recovery task of post-seismic PSA can be treated as separate “*small PSA*” (even if classic PSA could not be appropriate method). Better say, preparatory work to evaluate particular tasks can be based on the same principles that are used in classic PSA. Under such assumptions each task should have clearly distinct and well documented stages that have equivalent in [18]:

- definition of task scenario (equivalent of the accident sequence analysis; however mainly oriented on system identification and success criteria),
- determination the method to model task failures (equivalent of system analysis; in actually definition of critical activities and their “*failure modes*”),
- human reliability analysis (role of HRA will depend on available resources and task time schedule; if there are available resources and large time window then potential human errors are almost negligible and can be recovered; standard HRA approaches can be used in opposite cases; on the one hand appropriate modification of standard HRA method can be used one other hand such activity brings some uncertainty regarding assessed HEPs for tasks that are not regularly evaluated in classic PSA, e.g. maintenance tasks.),
- data analysis (equivalent of data required for PSA to assess reliability of equipment will form standard work; data to access success of building and logistic activities etc. can be derived from project management area),

- assessment of probability (equivalent of quantification of the analysis; including uncertainty and sensitivity analysis).

Fig. 5-1 Outline of post-seismic PSA



6 CONCLUSION, RECOMMENDATIONS AND OPEN ISSUES

/The conclusions will be discussed during the End-users reviews and workshop. This chapter will be improved in the final version. /

The report provides guideline how to extend traditional methodology used for seismic PSA in order to produce extended seismic PSA. It provides a structured approach to perform extended seismic PSA and comments link between standard PSA methodology and enhanced methodology to incorporate requirements following from ASAMPSA_E extended PSA framework, e.g. mission time extension, mobile equipment, multi-units and inaccessibility of location at seismic event, which is covered by post-seismic analyses. Post-seismic PSA analyses situation beyond the used PSA mission time and shall include the role of emergency response.

It is noted that application of the proposed framework can be considerably time consuming and that some reasonable simplifications should be used. The application can also show a lack of specific method to estimate conditional probabilities of occurrence of some specific phenomena that can be connected with seismic event, namely seismically induced fires and explosion.

7 LIST OF REFERENCES

- [1] EC - Grant agreement no: 605001 for Coordination and support action - ASAMPSA_E - Advanced Safety Assessment : Extended PSA - Fission-2013-2.1.2-Consequences of combination of extreme external events on the safety of Nuclear Power Plants (NPPs)], July 2013, updated in June 2016.
- [2] List of external hazards to be considered in ASAMPSA_E, Technical report ASAMPSA_E / WP21 / D21.2 / 2014-12
- [3] Summary report of already existing guidance on the implementation of External Hazards in extended Level 1 PSA, Technical report ASAMPSA_E / WP22 / D22.1 / 2014-05
- [4] SEISMIC hazards modelling in extended PSA, Technical report ASAMPSA_E / WP22 / D21.3-1/ 2016-27 - IRSN PSN-RES/SAG/2016-00232
- [5] Lessons of the Fukushima Daiichi accident for PSA, Technical report ASAMPSA_E / WP30 / D30.2 / 2014-08
- [6] ASME/ANS RA-Sa-2009 Addenda to ASME/ANS RA-S-2008 Standard for Level 1 /Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, 2009
- [7] WENRA RHWG, Report Safety of new NPP designs, March 2013
- [8] ENSI-A05/e, Guideline for Swiss Nuclear Installations: Probabilistic Safety Analysis (PSA): Quality and Scope, March 2009
- [9] EPRI NP-6041-SL, A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1), August 1991
- [10] EPRI 1002988, Seismic Fragility Application Guide, December 2003
- [11] EPRI 1002989, Seismic Probabilistic Risk Assessment Implementation Guide
- [12] EPRI 1025286, Seismic Walkdown Guidance For Resolution of Fukushima Near-Term Task Force Recommendation 2.3: Seismic, June 2012
- [13] EPRI NP-6041, A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1), August 1991
- [14] IAEA NS-G-1.5 External Events Excluding Earthquakes in the Design of Nuclear Power Plants, 2003
- [15] IAEA NS-G-1.6 Seismic Design and Qualification for Nuclear Power Plants, 2003
- [16] IAEA NS-R-1 Safety of Nuclear Power Plants: Design
- [17] IAEA SRS-28 Seismic evaluation of existing Nuclear Power Plants, 2003
- [18] IAEA SSG-3 Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, 2010
- [19] IAEA-TECDOC-724 Probabilistic safety assessment for seismic events
- [20] NUREG/CR-2300, Volume 2 PRA Procedures Guide, 1983
- [21] NUREG/CR-4334 An Approach to the Quantification of Seismic Margins in Nuclear Power Plants, 1985
- [22] NUREG/CR-4840, Procedures for the External Event Core Damage Frequency Analyses for NUREG-1150, November 1990
- [23] NUREG 6850, EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities
- [24] Seismic Quality Utility Group, Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Power Plant Equipment, December 2001
- [25] SKI Report 02:27 Guidance for External Events Analysis, February 2003
- [26] T.K. Datta, Seismic Analysis of Structures, ISBN 978-0-470-824661-0, 2010
- [27] US NRC Regulatory Guide 1.59, Design Basis Floods for Nuclear Power Plants, Rev. 2, August 1977
- [28] US NRC Regulatory Guide 1.91, Evaluations of explosions postulated to occur at nearby facilities and on transportation routes near Nuclear Power Plants
- [29] Lloyd's Register Consulting, RiskSpectrum HazardLite, User guide version 1.1.0, 26th February 2015, Sweden.
- [30] Kuzmina I., Lyubarskiy A., El-Shanawany M., An Approach for Systematic Review of the Nuclear Facilities Protection against the Impact of Extreme Events (Proceedings of the Nordic PSA Conference - Castle Meeting 2011, 5-6 September 2011, Stockholm, Sweden).

- [31] Kuzmina I., Lyubarskiy A., Hughes P., Kluegel J., Kozlik T., Serebrjakov V., The Fault Sequence Analysis Method to Assist in Evaluation of the Impact of Extreme Events on NPPs (Proceedings of the Nordic PSA Conference - Castle Meeting 2013, 10-12 April 2013, Stockholm, Sweden)
- [32] Sörman J., Bäckström O., Yang L., Kuzmina I., Lyubarskiy A., El-Shanawany M., Method for analysing extreme events, PSAM 12, June 2014, Honolulu Hawaii.
- [33] Kumar M., Sörman J., Bäckström O., Tool for extreme events analysis, IAEA technical meeting 7-11 July 2014, Vienna.
- [34] Minutes of the ASAMPSA_E WP10 WP 21 WP22 WP30 technical meetings 8th-12th September 2014 Hosted by Vienna University in Vienna, Austria, WP5/2014-06.
- [35] ASAMPSA2, IRSN-PSN/RES/SAG 2013-0177, Best Practices guidelines for L2 PSA development and applications, Volume 1- General, April 2013.
- [36] ASAMPSA2, IRSN-PSN/RES/SAG 2013-0177, Best Practices guidelines for L2 PSA development and applications, Volume 2- Best practices for the Gen II PWR, Gen II BWR L2 PSAs. Extension to Gen III reactors, April 2013.
- [37] A. Wielenberg et. al., "ASAMPSA_E D30.3, Methodology for Selecting Initiating Events and Hazards for Consideration in an Extended PSA," 11th May 2016.
- [38] Technical report ASAMPSA_E WP10. Minutes and recommendations of the ASAMPSA_E Uppsala End-Users workshop (26-28/05/2014).
- [39] ASAMPSA_E D10.3 Report on external hazards with high amplitude that have affected NPP in operation (in Europe or in other countries).

8 LIST OF TABLES

Tab. 3-1	Matrix of feasible correlated hazards, [1].....	18
Tab. 4-1	Example of Output of event analysis for internal fires	25
Tab. 4-2	Example of Output of event analysis for internal flooding	26
Tab. 4-3	Hypothetical example of plant correlated hazard	31
Tab. 4-4	Example of aggregating hazards from Tab. 4-3.....	33
Tab. 4-5	Example of outline for output of fragility analysis for SSCs and seismic events	43
Tab. 4-6	Example of outline for output of fragility analysis for flood induced event.....	44
Tab. 4-7	Example of additional factors influencing plant safety	46

9 LIST OF FIGURES

Fig. 2-1	Overall approach to analyse external events in Level 1 PSA [18].....	14
Fig. 3-1	Flow chart for extended seismic L1 PSA.....	17
Fig. 4-1	Flow chart of approach to analyse impact of external correlated hazards.....	29
Fig. 4-2	Hypothetical location of plant in terrain	30
Fig. 4-3	Example of seismic hazard curve, [11]	37
Fig. 4-4	Example of fragility curve, [10]	49
Fig. 4-5	Example of hypothetical full power event tree combining basic response and LOCAs.....	54
Fig. 4-6	Outline of fault tree reflecting seismic failures and induced events.....	57
Fig. 4-7	Treatment of conditional probabilities (frequencies)	58
Fig. 5-1	Outline of post-seismic PSA	66