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

Volume 2 (implementation in Level 1 PSA)

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Summary :

The objective of this report is to provide guidance for the implementation of seismic hazards in extended L1 PSA. This report is a deliverable of the ASAMPSA_E 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 seismic events in L1 PSA, having as a perspective the development of extended PSA from an existing (internal events) L1 PSA (event trees).

The following topics are addressed :

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			
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MODIFICATIONS OF THE DOCUMENT

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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.
V2	05.11.2016	J. Prochaska (VUJE)	All	Addressed and incorporated end users comments from September 2016 workshop in Vienna.
V3	04.01.2017	E. Raimond (IRSN)	Few	Approval reading, modifications for consistency with other ASAMPSA_E reports

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EXECUTIVE SUMMARY

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” provides 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 details 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 [41]), this guidance includes considerations for the extension of seismic PSA, including the methods to model the combinations and dependencies of hazards, possible secondary effects, multi-unit response, mitigating and aggravating factors. Approaches for building hazards curves and fragility curves are described in the guidance by presenting relevant references, as well as approaches for site response analysis (SSCs failures, induced failures 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	LR	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

ABBREVIATIONS

BWR	Boiling Water Reactor
CDF	Core Damage Frequency
DPD	Discrete Probability Distributions
EOP	Emergency Operating Procedure
EPRI	Electric Power Research Institute
ET	Event Tree
HCLPF	High Confidence of Low Probability of Failure (95% confidence of less than 5% probability of failure).
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
LOCA	Loss of Coolant Accidents
LOOP	Loss of Off-Site Power
MCS	Minimal cut set
NPP	Nuclear Power Plant
PDS	Plant Damage State
pga	Peak Ground Acceleration
POS	Plant operational state
PSA	Probabilistic Safety Assessment
PRA	Probabilistic Risk Assessment
RCS	Reactor Cooling System
SAMG	Severe Accident Management Guidance
SMA	Seismic Margin Assessment
SSC	Structure System and Component
WP	Work Package

DEFINITIONS

Some of these definitions come from IAEA and US NRC safety glossaries.

(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 (Seismic)	Correlated hazards is class of hazards that vary together with seismic hazards, i.e. the direct impact of a seismic event can trigger further effects or additional hazards
Correlation	This report uses term of correlation, if it is not stressed, only to describe dependency of failures of SSCs having similar design and plant location that are affected by the same seismic load.
Discrete Probability Distributions	Discretization of analytical probability density function into discrete probability distribution
Fragility	Conditional probability that a component would fail for a specified ground motion or response-parameter value as a function of that value.
Induced event	(Seismically) Induced event is an initiating event caused by effect(s) of seismic hazards strongly correlated with seismic effect, e.g. tsunami, or caused by damages of any SSC or natural formation due to earthquake impact
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 *including site surroundings that soil failures can influence plant safety*, as well as fragility curves (parameters) for relevant SSCs.

1 INTRODUCTION

Seismic PSA differs from internal initiating events PSA due to complex characteristics of the hazard. The range of ground motion levels form a continuous scale and the failure probabilities of SSCs depends on particular ground motion. The following specificities can be highlighted:

- seismic events may damage also passive components as well as structures having in normal condition extremely low failure probabilities which can generate specific failure modes that are not reflected in the accident sequence models for other initiators,
- seismic event can have large spatial impact damaging multiple structures, redundant systems and multi-unit areas,
- mitigation of the effect of seismic event may require more complex action than other initiators,
- seismic PSA uncertainties are larger (follows from hazard and fragility analysis) and must therefore be carefully considered,
- the large seismic event may cause ground motions at the plant that exceed the design basis criteria; an assessment of failure probabilities for SSCs must therefore consider ground motions beyond the design basis, even if it is difficult to interpret such results as well as to propose reasonable provisions due to uncertainties joined with seismic PSA.

The ASAMPSA_E project [1] offered 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 allowed 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 paid 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 the 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.

2.1 GENERAL CONSIDERATIONS 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.

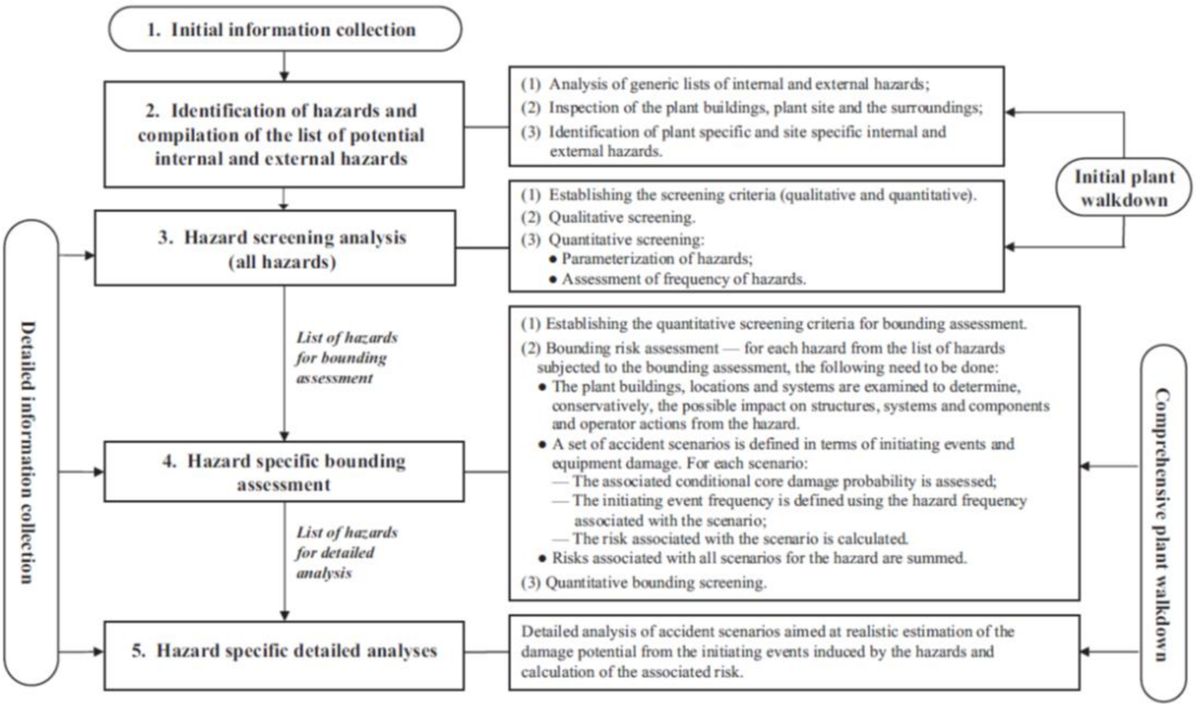
The basic parts of a seismic PSA are identifying hazards, analyzing the systems, evaluating seismic fragility, and performing seismic risk quantification. Each of these four distinct areas requires a good engineering background and some level of specific training.

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. [9], [21] and [24] which covers broad spectrum of PSA tasks. Available guidelines allow extension of standard PSA developed for internal events, e.g. PSA developed according [19], 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 induced hazards. Available results from seismic evaluation, as described in [18], [16] should reduce work complexity and provide unified framework for PSA practitioners including seismologists, seismic engineers evaluating equipment qualification, PSA developers and utility engineers. Especially [16] presents, except of brief description of general steps for seismic PSA, common points of SMA and seismic PSA.

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. The treatment of multi-unit hazards [5] implies that seismic part of the extended PSA should consider potential combinations of viable correlated hazards. Such requirement follows from general framework to analyse internal / external event illustrated by IAEA [19] (see bottom right box in Fig. 2-1: *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*). Nowadays majority of the guidelines treat this requirement in a too general manner.

Fig. 2-1 Overall approach to analyse internal and external events in Level 1 PSA [19]



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 brief introduction into structure for (extended) seismic PSA
- Section 4 - provides an approach to modelling of earthquake in seismic PSA to cover all dependencies coming from seismically induced events 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 6 – provides conclusion, recommendations and list of open issues discussed in this report.

2.2 OBJECTIVE OF THE REPORT

The objective of the presented report is to provide some guidance describing how to model the seismic hazard for extended PSA, with the idea to address all important aspects of evaluation of seismic risk including induced hazards (or events induced by seismic event).

Enhanced modeling covering combination of induced events has impact on activities like considered scope of SSCs, HRA, emergency and multi-unit response.

STRUCTURE OF SEISMIC PSA

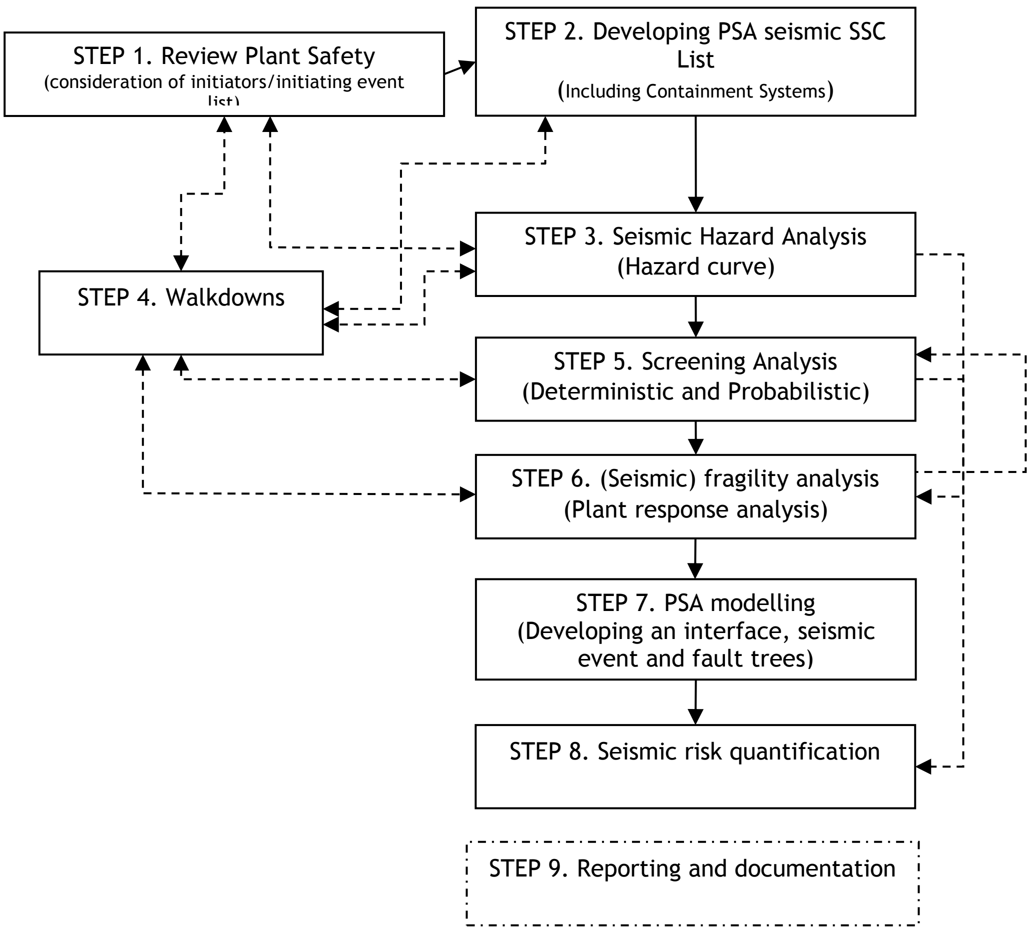
The aim of this section is to propose a structure for extended seismic PSA.

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 today to define the fragilities in seismic PSA conducted for nuclear plants. Detailed fragility models are 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 based on standard PSA approach is not repeating all information accessible in the available guidelines dealing with standard 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 and combination of induced events. In order to meet objectives stated in section 2, fundamental seismic PSA approach, Fig. 3-1 (published in [10]), is extended. It is assumed that that necessary pre-condition to perform any seismic PSA is availability of PSA for internal events. It should be obvious that such PSA facilitates addressing specific SSCs and operator actions that ensure fulfillment of fundamental safety functions.

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



Dotted lines in Fig. 3-1 represent interactions and dependencies between particular steps. 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 triggered 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 D21.2 External Hazard Correlation Chart 2014-12-15	Seismotectonic hazards	N1 Vibratory ground motion	N2 Induced vibratory ground motion	N3 Fault capability	N4 Liquefaction	N5 Dynamic compaction	N6 Ground displacement
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 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 external events induced by correlated hazards, e.g. fires of external industrial facilities can cause external fires[1]. If we assume that matrix of potential correlated hazards represents only external hazards then such (plant specific) matrix should be also added by induced internal events (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 [17]:
  - 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 the impact on fundamental safety functions is negligible.
- 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

[1] Meaning of *external events induced by correlated hazards* and *external induced event* is almost the same.

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 seismic event. 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 [29] 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 standard 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 [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 threat 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 standard 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 induced 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 [21] for further details. This step should provide parameterization of seismic hazard, e.g. hazard curve in terms of peak ground acceleration or spectral acceleration 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 that 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. 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 even 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 [9] "*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 some cases as well as in case of multi-unit effects.

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 based on the results of the seismic hazard analysis, fragility analysis and PSA modelling. 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 a 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 - mainly combination of events.

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 the analysed plant has appropriately 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 approach consisting from discretization of continuous distribution into discrete probability distribution. (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. 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, further details are discussed in chapter 4.8.

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*”.

In addition, even if approach for extended seismic PSA is presented as a linear sequence of steps (from a 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 a complete list of induced events that can be caused by a seismic event, i.e. to identify all feasible combinations of seismically induced internal and external events. This step should be based on PSA for internal events, PSA for internal and external hazards and site specific list of correlated hazards, see also Tab. 3-1. Seismic site specific hazards fall into several basic categories that can induce (internal) seismic failures, e.g. failures of safety systems, (internal) seismically induced initiating events, e.g. LOCA, and induced external events, e.g. industrial accidents. In general there is always a tiny border between correlated hazards and induced events. Categorization of these events and hazards is arbitrary and it is on responsibility of PSA developer.

It is noted that within step 1, consideration regarding the possibility of occurrence of earthquake and its magnitude is not performed. Step 1 is concerned with 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, e.g. [10], 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 categories of seismically induced medium and large LOCA shall be considered. Their categorization should be consistent with PSA for internal events. There can be also induced more specific events like loss of offsite power. In general the way how such events are considered depends on overall strategy. They can be considered like initiating events or reflected in fault trees as specific seismic failure modes, see also chapter 4.7.

4.1.2 INDUCED INTERNAL EVENTS

Seismically induced internal events correspond mostly with internal hazards. Category of internal hazards covers following events [19]:

(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 <u>Internal fires and explosions</u>

Basis to evaluate induced events for internal fires and explosions is formed by Fire PSA. Both qualitative and quantitative analyses of Fire PSA can be performed according to [26] and [19] 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 separated dedicated compartments according to fundamental safety principles e.g. redundancies/safety trains etc. Each 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 in 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 induced 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 (see also example in Tab. 4-1):

- Ignition sources: 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 threat 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 2nd electrical safety train Compartment of 2nd electrical safety train is located 10 m from main unit transformer. In the case of catastrophic fire split oil can ignite fire of 2nd electrical safety train compartment. Surrogating component for 2nd 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 induced events for internal floods is internal flood analysis. Both qualitative and quantitative analyses of floods, e.g. performed according to [19] 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 the 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[14]. Severity factor expresses expected our confidence regarding real impact of event. For example, if a plant has flow-through cooling system fed by river then rupture of circulating water pipes at high pga is very probable. However, there is also high probability of loss of offsite power. So severity of such induced internal flood will be very low. 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 (see also example in Tab. 4-2):

- Flood sources: 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 threat 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 1st 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 induced events 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 induced external events. 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:

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

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 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.

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

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. Even if the plant is not be hit by seismic event, an earthquake can affect some large dams or river paths far away from plant with damages that 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 the safe operation of the analyzed plant.

III. Determination of the list of “single” correlated hazards

The aim of this task is to establish 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 I. and II.

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

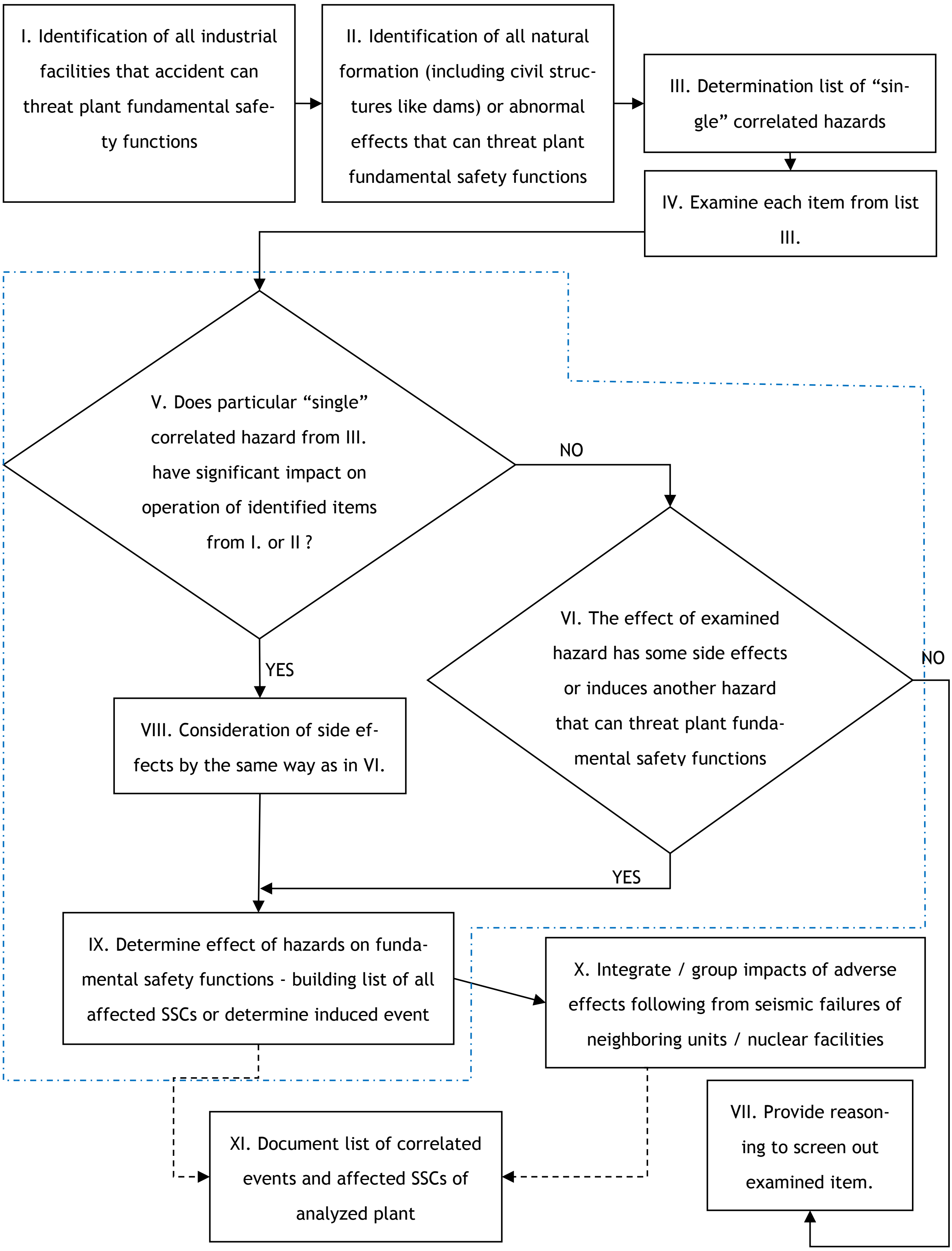
IV. Examine each item from list III

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 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 a 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



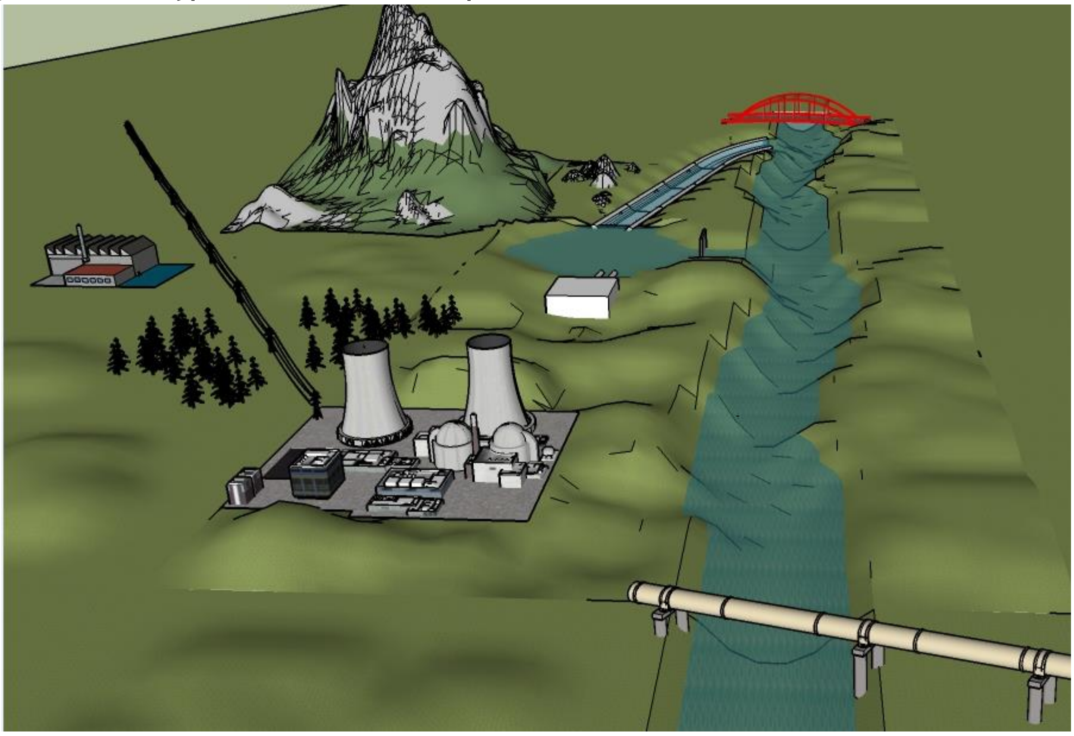
VI., VIII. The effect of examined hazard has some side effects or induces another hazard that can threat plant fundamental safety functions

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. are 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 / Induced 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 cool-ing 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
M11	Transportation: explosion	N/A	N/A	N/A	N/A	N/A	N/A

Item / Induced event	Hazard	Industrial facilities			Natural formation and civil structure		
		Factory	Distribution line	Gas line	Dam	Bridge	Hill
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:

It is necessary to take into account that in the case of multi-unit site correlated hazards (or induced external events) have also impact on the other nuclear facilities and accident of these facilities have potential to threat analyzed unit.

However, 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 / Induced Event	Facility / formation	Induced Event ID	Affected SSCs	Mechanisms (failure modes) leading to the adverse effects
N3, N4, N5, N6, N60, M1, M2	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, M13	Gas line	ExplosiveCloud	TR0xxx Control room Containment	Explosion threats 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 out of order safety train as whole, i.e. concept of surrogating components[2]. For example induced flood can

[2] Surrogating component is such real or symbolic component that can represents group of SSCs. Usual way is to use only one key component to put out of order whole train (system), e.g. failure of pump of high pressure injection train to simulate failure of train. Drawback of such approach can consists in biasing of results of importance analysis because surrogating components will have highest significance.

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 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 c*orrelations 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 and Extreme Event Analyzer (EEA) Methodology are briefly introduced as the examples of methods for complex evaluation of the impact of extreme events.

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 [33] [34]. 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 [34].

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 [34].

Extreme Event Analyzer (EEA) Methodology

Lloyd's Register Consulting (LRC), in cooperation with IAEA, has further developed the FSA method [35]. LRC developed a value added tool (ExtremeEventAnalyzer (EEA)) to systematically analyze accident scenarios even if they are 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 [35] [36]:

- identify sensitive accident NPPs scenarios coming from 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 [35]:

1. Determine what hazards to include. This is 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. The EEA method, result and conclusion of this benchmarking study are presented in [36].

This step has interaction with following steps:

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

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

<u>STEP 6 - Fragility analysis.</u> Probability and consequence of induced internal floods and fires will depends on predisposition 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 the skills of the 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 a 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, Loss of Offsite Power, reactor pressure vessel (RPV) rupture and externally induced events). This step covers the followings:

- assembling basic SSC list for standard seismic PSA considering adverse effect of collapse of non-safety SSCs on safety SSCs performance; this activity is driven by standard guidelines as [10], [21], [24] 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 relevant 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),
- internal items that failure can lead to internal floods (FI),
- 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

Seismic Hazard Analysis can be performed in line with available guidelines e.g. [9], [21], [24], [43] 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 formations than can affect analyzed plant. Probabilistic Seismic Hazard Analysis (PSHA) method is described in [4], which considers all possible earthquake events, resulting ground motions and probabilities of occurrences. Probabilistic seismic analysis comprised the following steps [44]:

- Identify all possible earthquake sources resulting ground motions.
- Characterize the distribution of earthquake magnitudes from each source.
- Characterize the distribution of source-to-site distances associated with potential earthquakes.
- Predict the resulting distribution of ground motion intensity as a function of earthquake magnitude, distance etc.
- Combine uncertainties in earthquake size, location and ground motion intensity, for instance using a calculation known as the total probability theorem.

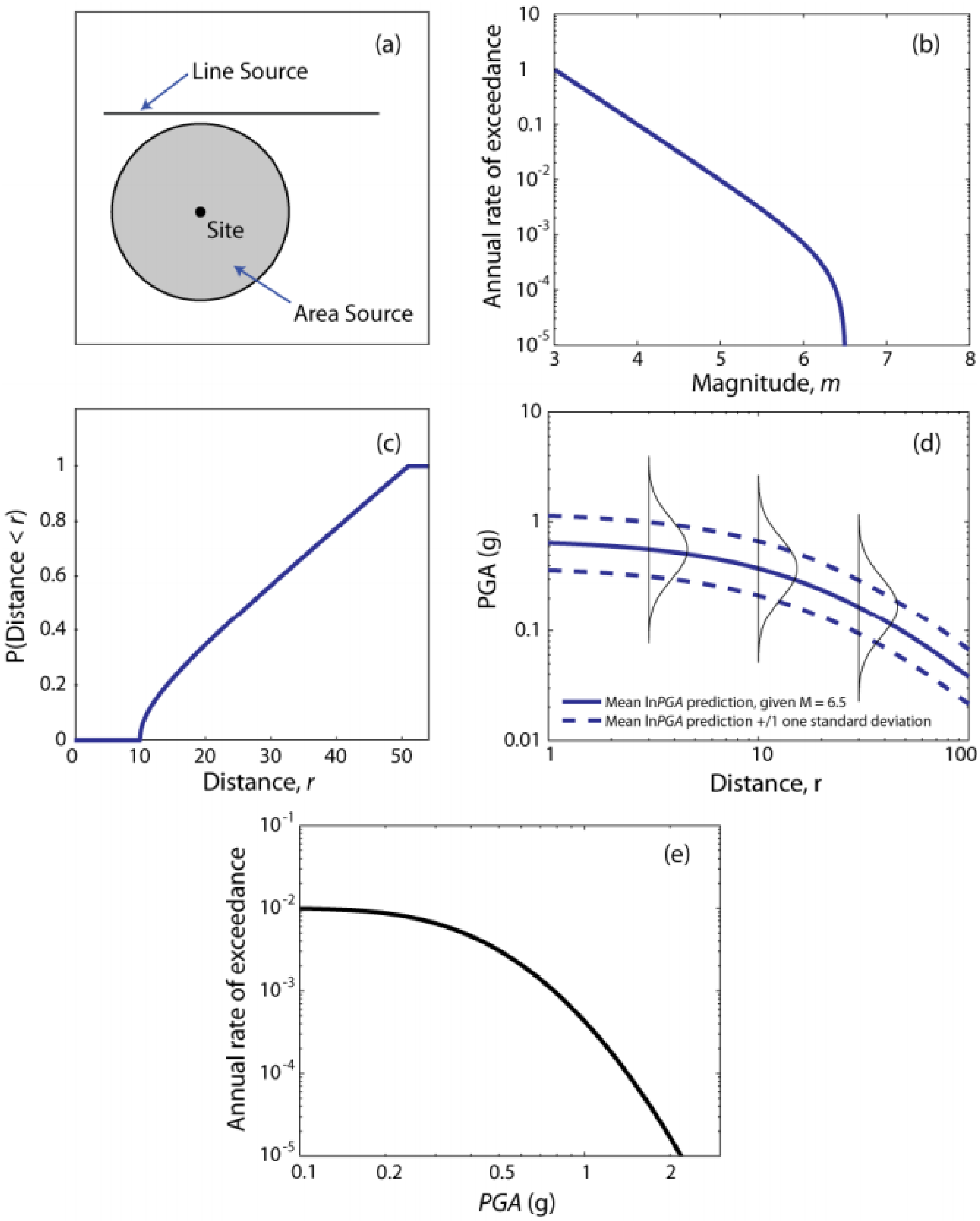
PSHA steps are schematically illustrated in **Fig. 4-3**, (a) identify the earthquake source areas[3] or zones of potential earthquake. The source area should be homogenous in respect to spatial distribution, frequency content of earthquakes and their upper magnitudes. (b) Characterize the distribution of earthquake magnitudes from each source. (c) Characterize the distribution of source-to-site distances from each source. (d) Predict the resulting distribution of ground motion intensity. This distribution is called as magnitude-recurrence relationship, where the rate of earthquake occurrence is estimated by using the historical data. The historical data gives only weak estimation of the probability of large magnitudes; this uncertainty related to the probabilities of the large magnitudes is taken into account by varying the limit value of the upper bound magnitude. (e) Combine information from (a) to (d) to calculate the annual rate of exceedance for a given ground motion intensity.

For example, two kinds of seismic hazards are defined and can develop two hazard curves, a near field (within 25 km from the site and dominant peaks of 10 Hz at the plant site) and a far field earthquake (>25 km from the site and dominant peaks about 3 to 6 Hz at the plant site) [42]. The continuous seismic ground motions on the hazard curves can be discretized/ divided into several **intervals** to determine frequency for particular seismic events.

[3] Earthquake sources are also sometimes quantified as line sources. It is also common to treat the earth structure in 3 dimensions, meaning that faults will be represented as planes rather than lines.

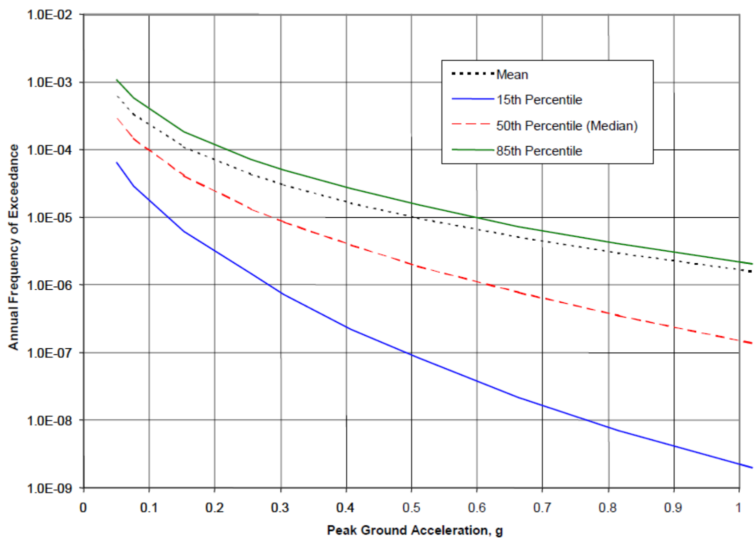
Seismic initiating event frequencies are estimated by mean value of interval the exceedance frequencies corresponding to the minimum and maximum ground motions of each interval [43].

Fig. 4-3 Example of probabilistic seismic hazard analysis steps [44]



Seismic hazard analysis provides many outputs that are necessary to evaluate plant behavior, e.g. typical outputs are listed in [20]. However for PSA, main results of probabilistic seismic hazard analysis is formed by seismic hazard curve(s), see example in Fig. 4-4, for the determined site area(s) with variability estimates. Hazard curves are reported for each ground motion parameter of interest in tabular as well as in graphic format.

Fig. 4-4 Example of seismic hazard curve, [10]



The curve is usually expressed by the frequency distribution of the peak value of the ground motion parameter (usually pga[4]) during a specified interval of time. Such parameterization (also called discretization) 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) [9].

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 standard PSA. However; it is assumed that some level of simplification will be necessary to reduce scope of work on manageable level.

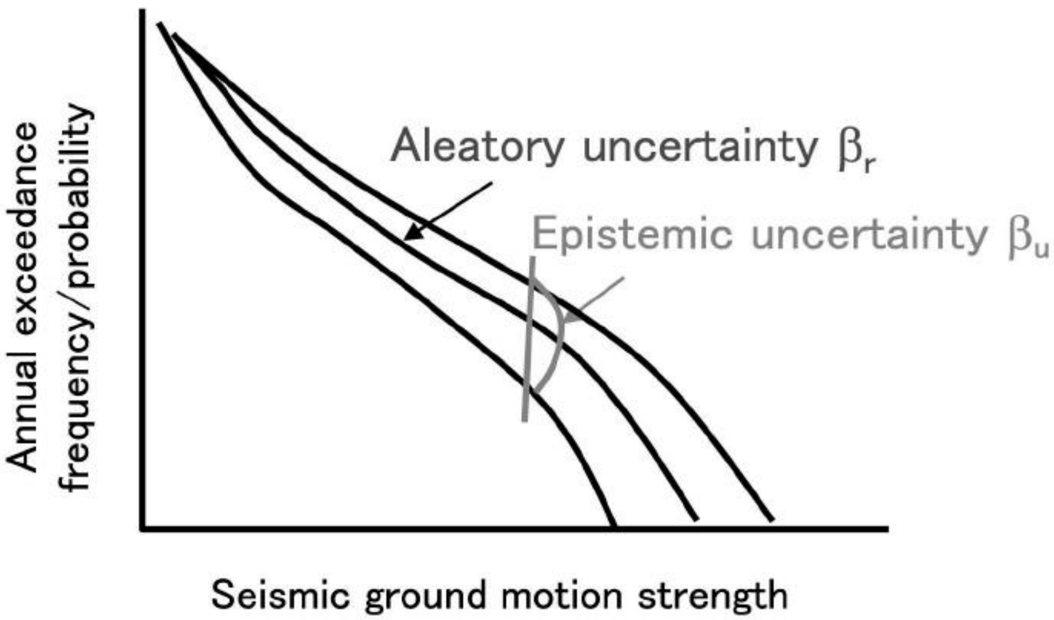
Even if this work is driven by many standard guidelines as [10], [20], [21] etc. it forms complex activity which considers large scope of input data and uses specific analytical models. Overview of main stages and methods for seismic hazard analysis is covered by [4].

It should be noted that seismic hazard analysis can possess many source of uncertainty. Briefly the uncertainty is categorized by two factors: aleatory uncertainty related to physical phenomena-specific randomness (βr) and epistemic uncertainty related to lack of knowledge or awareness (βu). βr is related to the dispersion characteristics that are intrinsic to the targeted phenomena. The level of dispersion cannot be reduced any more. βu is relat-

[4] 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.

ed to the lack of knowledge or the uncertainty and difference in interpretation included in the modeling and evaluation process.

Fig. 4-5 Schematic Chart - Treatment of Uncertainty on Seismic Hazard Evaluation, [22]



Consequence of this is that median of hazard curve is random variable, e.g. there can be several realization of hazard curve.

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 the reasonable effort to identify the number of SSCs for which detailed fragility evaluations are performed. Therefore, the main objective of seismic capability walkdowns is to screen all equipment items that have sufficiently high seismic capacities. Also, to clearly define the failure modes of equipment which are not screened out.

Extensive guidance on how to perform seismic walkdowns has been developed in the USA both for seismic qualification, [28], and for seismic margin assessment, [13]; in the aftermath of Fukushima, an additional guidance document was issued, [11]. In these guidance documents, criteria for assessing the robustness of equipment are defined[5]. 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**[6]; 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 and ignition 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 **correlations** 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 [25], 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.

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[5] Refer in particular to Appendix F in [13].
[6] Recall that the motivation for developing the seismic verification criteria in [28] was that there were concerns regarding the seismic adequacy of older plants in the USA.

Spent fuel pool[7]:

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

In general purpose of screening process is to limit number of components and seismically induced events that must be considered in seismic PSA. Any screening approach adopted should ensure that the final seismic CDF and LERF would not change appreciably, if any of the screened components were instead to be included.

Seismic PSA screening process concerns two issues: screening of induced initiating events, like LOCA, and screening of SSCs that are considered to fulfill fundamental safety functions. Screening and walkdowns are performed to minimize effort and represent realistic conditions of SSCs. The screening topic is also covered in ASAMPSA_E report [40].

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 impact consists in evaluation of contribution of event to the overall CDF, see [19] for further details.

Component screening can use two options. The first of them is based on seismic capacity and the second is screening by impact by the same way as for induced (initiating) events.

Regarding screening by impact, both screening of events and SSCs use common technique, i.e. bounding analyses to demonstrate low risk contribution. But this method is applicable only in the case when conservative bounding analyses can be performed without extensive effort. However such simple approach is possible only in the case if magnitude of earthquake is so low that all relevant SSCs still have considerable safety margins and component probabilities of seismic failures will be significantly lower in comparison with component random failures, i.e. almost of SSCs have significantly high HCLPF which as almost the same like screening by seismic capacity.

If any reasonable screening shows that seismic capacity of plant as whole is sufficient then seismic PSA can be terminated at this point as safety irrelevant (e.g. SSC seismic capacities have considerable safety margins or frequency of such seismic events that can cause serious damages is negligible).

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

4.5.1 (INITIATING) EVENTS SCREENING BY FREQUENCY

Regarding screening by frequency of event this approach has several drawbacks for seismic PSA and can be almost impossible :

- 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
  - common criterion 10^{-7}(see criterion) is not applicable because LOCA is a default event in seismic PSA. In addition [6] uses further preconditions like availability at least two safety train, slow progress of event etc.,
  - further limitation is formed by reactor protection activation, see criterion.
- Threshold values used within L1 PSA should not be capable of reflecting cliff edge effects, especially those considered in L2 PSA where specific damages like reactor vessel or containment can lead to large releases,
- If multi-unit site is evaluated then above mentioned aspects can play more and more important role in screening considerations, i.e. to determine some reasonable screening value.

Especially regarding seismic event:

- It is obvious that seismic event as such produces spatial impact affecting whole site (area) 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 prior information on CDF following from seismic event as whole (e.g. over particular discrete intervals, see 4.3) at the beginning of any seismic L1 PSA (step 3). Setting screening threshold without knowing all CDF contributors is questionable.

Based on above presented discussion the setting of frequency screening threshold value is a matter of expert judgment which respects common practice and contains reasonable level of conservatism[9]. Consequently let assume following case:

- Conditional probability of large release[10] of any level of earthquake from set of intervals[11] 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 should be below 10^{-6},
- If a seismic PSA uses 6 - 10 discrete intervals then contribution to large release of couple of screened events with screening value 10^{-7} or 10^{-8} can be about 10^{-6}, which can be equal to safety target.

---

8 Quotation of IE-C6 from [6]: USE as screening criteria no higher than the following characteristics (or more stringent characteristics as devised by the analyst) to eliminate initiating events or groups from further evaluation:
(a) the frequency of the event is less than 1E-7 per reactor year (/ry), and the event does not involve either an ISLOCA, containment bypass, or reactor pressure vessel rupture

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

10 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.

11 If we assume usage of DPD method.

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

Consequently if we take into account above presented information as well as the fact that the considered frequency of seismic event will be below 10^{-11},then screening by frequency of seismic event is hardly applicable.

4.5.2 SSC SCREENING

Based on [10] 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 analysis of all potentially significant SSCs. Other important aspect in the screening analysis is to assess the impact of relay chatter, which may result in trip of switchgears, confusing indications in the control room etc. Therefore, in some NPPs approaches are considered to screen out all the relays those chattering results in the fail safe operation of components (e.g. RPS relays leading to SCRAM) and include only relay those chattering could result in failure of components (e.g. relays required for safety relief valve (energize to open)).

Two typical screening methods for SSCs are used:

- screening by impact, i.e. contribution to the CDF,
- screening based on seismic capacity

4.5.2.1 Screening by risk impact

Based on reference [9], typically a CDF screening threshold is established by the system analyst whereby the components which are not modeled in detail, can be screened out, or else surrogate elements can replace groups of elements that are screened (at a high capacity level).

In simple terms, this approach consists in setting a bounding (limit) fragility for the SSCs that replaces real seismic fragility of SSCs. Then convolution of this bounding fragility curve with the hazard curve results in a (bounding) failure frequency of these SSCs.

If the bounding fragility is suitably chosen, it can be demonstrated that those SSCs for which the bounding fragility is applicable, have very small contribution to risk[12] and such low significant SSCs can be screened out.

Alternatively, so called surrogate elements can be used. Such elements represent whole groups of seismic components, with the objective to retain the risk contribution of those SSCs whose individual risk contribution is negligible.

[12] In reference [9] a failure frequency two orders of magnitude below the expected CDF is recommended.

In the case of seismic PSA, the correct implementation of screening by risk impact forms a time consuming process (which can require similar amount of resources as normal analysis). Care must be taken to ensure an exact counting of potential failure modes of seismic components and an adequate treatment of the correlation of component seismic failures, see discussions in [9]. In addition, this approach should also consider impacts on L2 PSA results what introduces further complexity.

Another drawback consists in difficulties to set some reasonable screening threshold for contribution to the CDF similarly as for event screening by frequency, chapter 4.5.1.

Based on the above introduced reasoning, in particular the work intensity required for a well performed screening (e.g. correct implementation should also evaluate impact on L2 PSA) this method is not recommended, unless it is used in combination with the screening method based on seismic capacity, described in the following subsection.

4.5.2.2 Screening based on seismic capacity

Screening based on seismic capacity uses criteria for sets of components, e.g. spectral acceleration, which ensures that only components with a sufficient capacity are screened out. Used criteria shall be well justified and reasonably conservative because the risk contribution of screened components is hidden, e.g. [9] considers screening level of about 0.8 g spectral acceleration in the free field. Comprehensive guidance on how to assess whether components meet a given screening level is included in [8] (see in particular Table 2-4 and Appendices A and F therein). Reference [8] also discusses possibility to screen out some classes of SSCs having inherent seismic resistance. 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, 4 and 6 as follows (see Fig. 3-1): seismic hazard analysis (basic inputs and definition of plant spectra), walkdowns and fragility analysis (especially definition floor response spectra and seismic demands).

The screening method based on capacity can be tuned so that it meets also the intention of the screening method based on risk impact. More specifically, the component failure frequency associated with a given screening capacity level can be easily evaluated by convolution, once a (generic) fragility curve associated with that screening capacity is defined. The screening capacity level can then be adjusted so that the risk impact of each screened component remains below a target value (e.g. two orders of magnitude below the expected total seismic CDF).

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 the probability of failure of relevant SSCs as well as to assign probability of events that are discussed in chapter 4.1.

This report assumes that conditional probability of failure will be evaluated by using HCLPF parameters, e.g. [9].

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 whose collapse can affect performance of basic internal items (TI),
- internal items whose failure can leads to internal floods (FI),
- internal item acting as potential ignition sources of internal fires(II),
- external items whose failure may result in a correlated external event (EI),
- special internal items that involve on-site effect like multi-unit effects, impact of seismic event on nuclear facilities located in-site area (SI).

Fragility analysis for standard seismic PSA is a complex process, e.g. see Table 4-1 in [9]. Fragility analysis of basic internal items (SSCs) is driven by standard guidelines as [9], [10] where fragilities are determined by using standard methods, e.g. [12], [27]. It should be noted that fragility analysis is specific work performed by specialized engineers.

Based on [9], with perfect knowledge of the failure mode and parameters describing the ground acceleration capacity, random variability β_R,the conditional probability of failure for a given peak ground acceleration having level a, is given by:

$$\mathrm{f} = \Phi\left[\frac{ln\left(\frac{a}{A_m}\right)}{\beta_R}\right] \qquad \text{E4-1}$$

Where

$\Phi[.]$ the standard Gaussian cumulative distribution,

A_m median ground acceleration capacity,

a given peak ground acceleration level.

When the modeling uncertainty β_u is included, the fragility f itself becomes a random variable. The subjective probability, Q (also known as “confidence”) of not exceeding a fragility f′ is related to Q by:

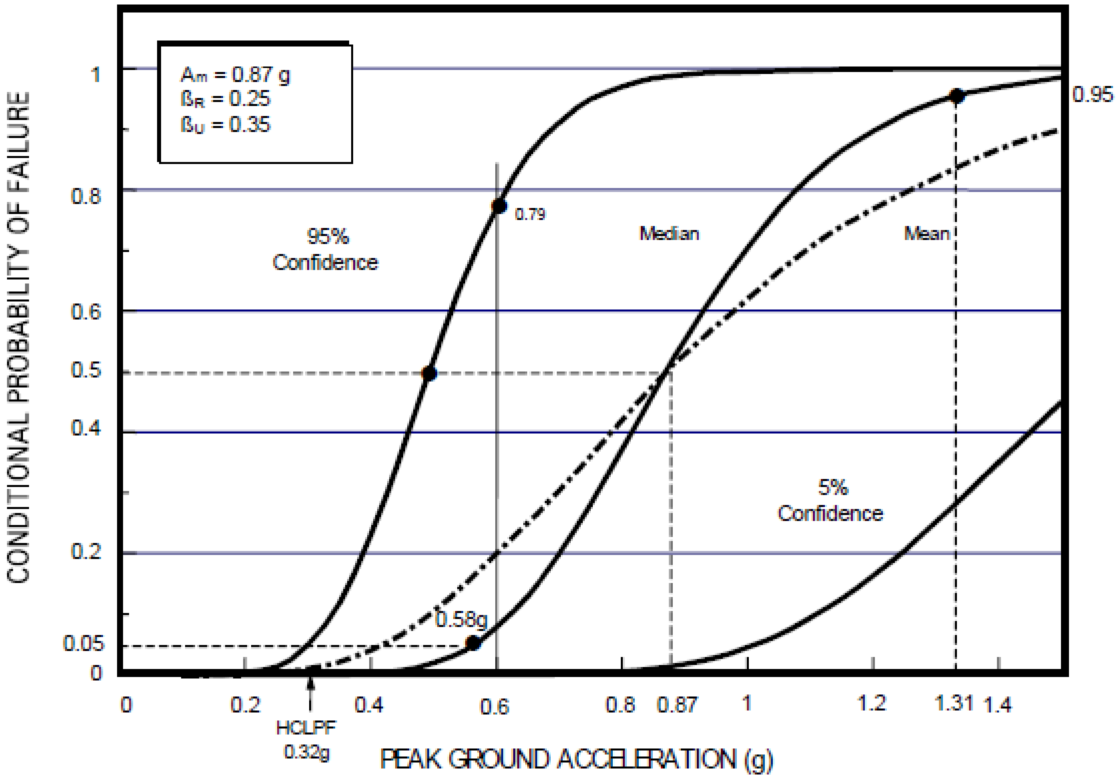
$$\mathrm{f}' = \Phi\left[\frac{ln\left(\frac{a}{A_m}\right)+\beta_u\Phi^{-1}(Q)}{\beta_R}\right] \qquad \text{E4-2}$$

Where

Q = P[f <f’|a] the subjective probability (confidence) that the conditional probability of failure, f, is less than f′

$\Phi^{-1}[.]$ the inverse function of the standard Gaussian cumulative distribution.

Fig. 4-6 Mean, Median, 5% Non-Exceedance, and 95% Non-Exceedance Fragility Curves for a Component, (Figure 2-4 of [9])



The mean fragility is obtained by using E4-1 but replacing β_R with composite variability $\beta_C = \left(\beta_R{}^2 + \beta_U{}^2\right)^{1/2}$, see example in Fig. 4-6.

The HCLPF capacity can be calculated by using the below equation [12]:

$$HCLPF\ capacity = A_m \exp[-1.65\ (\beta_R + \beta_U)]$$
$$= A_m \exp[-2.33(\beta_c)]$$

Since the main purpose of seismic PSA is to quantify the seismic risk (see section 4.8), hazard and fragility curves must use the same parameter to characterize the level of the earthquake. The most commonly used parameter is the peak ground acceleration, although other parameters such as the average spectral ground acceleration in the frequency range from 1 to 10 Hz are also used.

For active components more time is spent in developing fragilities. For some passive equipment, e.g. piping and supports, cable trays and supports, HVAC ducting and supports etc., generic fragilities are mostly used. Experience has shown that there is a tendency to be conservative when developing generic fragilities as opposed to plant specific fragilities [42].

4.6.1 SSCS AND INTERNAL SEISMIC INITIATING EVENTS

<u>This chapter covers basic internal items ensuring fulfillment of fundamental safety functions including (internal) seismic initiating events (category BI and TI[13])</u>

Fragility analysis for basic internal items ensuring fulfillment of fundamental safety functions is performed in accordance with methodology outlined in introduction of chapter 4.6.

The output of this task is formed by conditional probabilities of seismic failure of basic internal items ensuring fulfillment of fundamental safety functions and conditional probabilities of foreseen seismic induced initiating events determined within step 1, section 4.1.1.

It is obvious that conditional probabilities of foreseen seismically induced LOCAs can be estimated as a sum of probabilities of particular pipe segments, i.e. fragility analysis of related pipes is performed. An alternative source for LOCA fragility is formed by [25]. Output of fragility analysis enables estimation of probability of LOCA occurrence based on particular pga.

Similar approach is also used for civil and support structures whose stability may influence the performance of safety relevant SSCs.

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

Category	Item ID/ Seismic Event	Description	Seismic interval	Conditional probability of failure / seismic event	Affected SSCs	Severity factor[14]
BI	SB2xxx	2nd 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		
			. . .	... ...		

13 See chapter 4.2

14 Severity factor is used as a measure of the importance of expected consequence based on overall conditions during earthquake. It can be based on technical and statistical reasoning as well as to express our confidence based on engineering judgement. It is noted that this concept is also applied in [26].

Category	Item ID/ Seismic Event	Description	Seismic interval	Conditional probability of failure / seismic event	Affected SSCs	Severity factor[14]
			N	…		
	…	…	…	…	…	…

In the case of internal items whose collapse can affect performance of basic internal items (category TI) the output information shall include a 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 necessarily have a direct impact on safety significant SSCs. For example the impact of collapse of a partition wall depends on the direction in which the wall collapses. In the hypothetical example presented in Tab. 4-5 a collapse of the wall Wxx into the corridor has no consequences. Such situations can be treated by severity factors[14] that are used to asses/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 factors[14] if used are a convenient technical means to model the effects of a seismic event, depending on the expected working conditions. Without doubt any specific factors could alternatively be accounted for by modifying the conditional probability. However, introducing severity factors can facilitate the documentation process and the maintenance of the model in future, e.g. new experience/knowledge can easily be incorporated via modification of severity factors.*

4.6.2 INTERNAL FLOODS (CATEGORY FI[13])

<u>This chapter covers internal items whose failure can lead to internal floods (category FI[13])</u>

The assessment of conditional the probability of internal floods can be evaluated in a similar way as the seismically induced LOCA described in the previous section, i.e. the probability of occurrence of internal floods can be derived by fragility analysis. 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 1, chapter 4.6.2. Tab. 4-6 provides an example of the results.

Flooding sources are grouped according to compartments (locations) in order to establish a set of consolidated induced events.

Appropriate surrogating components are defined, taking into account the effect of a particular flood. More specifically, all floods having the same effect are represented by one “surrogating component” whose conditional probability cumulates the conditional probabilities of all particular floods.

Again, specific conditions are reflected by using severity factors[14] (e.g. damage of a water source or a pipe line outside critical compartments will not lead to a flooding of safety SSCs, the seismic event can create extra flooding paths, the effect of flooding 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	Flooding Interval	Conditional probability of induced event	Affected SSCs (Surrogating components)	Severity factor[14]
FI	$Source_1$	FI_01	1	1E-8	Pumpxx1 Pumpxx2 … … …	0.9
	$Source_1$		2	1E-7		0.2
	… … …		. . .	… … …		… … …
	$Source_{nn}$		N	…		…
…	…	…	…	…	…	…

4.6.3 INTERNAL FIRES (CATEGORY II)

This chapter covers internal item acting as potential ignition sources of internal fires (category II[13])

The evaluation of internal ignition (explosion) sources uses a similar approach and provides similar output as the approach used for internal flooding sources. However severity factor[14] must take into account many aspects in order to assign the severity of potential fires:

1) Conditional probability that a seismic failure induces a fire.
2) Spreading of fire outside of the affected fire compartment, e.g. potential damage of fire barriers, fire loads, qualification of cabling system etc. Determination of this specific sub-factor can require the extension of step 3 - Seismic hazard analysis to cover topic of fire barriers and consult internal fire hazard analysis to analyze 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 require the 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 EVENTS (CATEGORY EI)

This chapter covers items capable evoking induced external events (category EI)

As it was stated in section 4.1.3 seismically induced faults of natural formations, civil structures, industrial facilities etc. (henceforth referred to as object(s)) can disturb plant normal operational conditions and therefore influence fundamental safety functions of the analysed plant. The unpleasant implication of this statement consists in the fact that it may be necessary to evaluate many objects. In addition, the failure of relevant objects may not lead directly to the threatening of plant safety functions, but safety functions may be threatened by side effects that are triggered as a consequence of object failure, e.g. sea sites can be affected by tsunami but the tsunami height depends on earthquake magnitude and the distance of its epicenter from the plant as well as on the coast topography. So, in general probability/frequency of induced (external) event can be expressed as $Ps \cdot Pm \cdot Pa$, where Ps represents the probability of occurrence of an earthquake in the relevant area, Pm represents the conditional probability that the earthquake causes some source of potential damage (e.g. fire, explosion, tsunami, failure of a natural or a civil structure that can threat plant safety etc.) which has a sufficient magnitude to threat plant safety, and Pa is the conditional probability that the source of potential damage affects plant safety (e.g. an earthquake can trigger several wild fires but their evolution to a real threat depends on the weather conditions).

Finally, in general three tasks must be performed in order to assess the probability of occurrence of an induced (external) event, namely:

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

The accomplishment of the above outlined tasks, briefly discussed in the subchapters presented below, enables the final assessment of the probability of a seismically induced external event.

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

If the object of 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, i.e. it is evaluated whether the seismic hazard curve developed for the plant site is adequate for the object of interest.

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. This emphasizes time consumption of extended seismic PSA.

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 .

4.6.4.3 Assessment of probability of releasing source of potential damage (Pm)

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

1. Simple bounding fragility assumption, i.e. it will be assumed that the object of interest is going to be damaged if the earthquake (in area containing particular object) reaches intensity VI. or higher according to the EMS-98 intensity scale at the site of the object of interest.
2. (More or less) full scope fragility analysis of the relevant object. Such analysis must be in compliance with the standard approach, e.g. the standard fragility methods described in section 4.6 or the general approach as described in [10]. The scope of the work will depend on the nature of object.

Probabilities of releasing a source of potential damage will be assessed by using the hazard curve of the object, as introduced in the previous section, and performed fragility analysis.

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

In general the number of possible combinations can be huge. Hence the option number 1 will be only the feasible way to cope with this task.

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

Even if though the activities described in subsections 4.6.4.1 and 4.6.4.2 provide basic data to assess the probability of occurrence of a seismically induced external initiating event, additional analyses can be necessary to evaluate the impact of the event on the plant. In some cases some attenuating factors can take place. These additional factors depend on the nature of the induced event. Based on the matrix of feasible correlated hazards presented in Tab. 3-1 some additional factors can be as follows (see also example in Tab. 4-7):

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

ID from Tab. 4-3	Correlated hazard	Factors	Comment
N12	Obstruction of a river channel - effect “internal flooding”	Type of obstacle blocking river channel	Liquefaction of blocking material can lead to flow resumption
		Flow rate and local topography	Determine flood extent and flooding rate as well as dynamic properties of flooding wave
			Probable maximum flooding can be based on generic data such as [30]
M1	Industry explosion - effect “pressure wave”	Wind intensity and wind direction, humidity or rain	Determine conformation and content of explosive cloud (if this is the case)
		Distance from the plant	Determine impact of the pressure wave
			Maximum impact can be estimated according to generic guides such as [31]
			Side effect can be represented by wild fire
M2	Industry: chemical release - effect “main control room working conditions”	Wind intensity and wind direction, humidity or rain	Determine conformation and content of poisoning cloud
		Distance from the plant	Determine concentration of chemical substance when it reaches the plant
M4	Military: explosion		Same as M1
M5	Military: chemical release		Same as M2
M13	Pipeline: explosion, fire		Same as M1
M14	Pipeline: chemical release		Same as M2
M19	Stability of power grid - Loss of offsite power		Side effect can be represented by wild fire

4.6.5 IN-SITE EFFECTS (CATEGORY SI)

<u>This chapter covers special internal items that involve in-site effects (category SI)</u>

It is assumed that the fragility analysis of special internal items, defined within step 1 section 4.1.3 - task I., i.e. those which may cause in-site effects like multi-unit effects or may have an impact on other nuclear facilities located in-site, will be subject of separate seismic analyses. If appropriate analyses examining standalone facilities are not available then they must be performed as additional tasks of the extended seismic PSA. (Standalone means that any relevant facility is analysed as an isolated entity.) The results of these separate analyses merely need to be transformed into specific format used for extended seismic PSA, e.g. a similar format as the one used in Tab. 4-6.

4.6.6 CONCLUDING NOTES TO THE FRAGILITY ANALYSIS

At the end of this step several basic categories of data are available. These data describe conditional probabilities, severity factors[14] (if appropriate) or (conditional) probabilities of occurrence of induced events:

- Internal items covering:

    - List of seismic initiating events including conditional probabilities of occurrence of particular events, typically LOCA events (category BI)
    - List of conditional probabilities of seismic failures of safety significant SSCs that are necessary to fulfill fundamental safety functions (category BI) including civil structures whose collapse can affect safety significant SSCs (category TI)
- List of induced internal events including 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 multi-unit effects and of effects on other facilities located at the site (category SI)

Fragility analysis is important for quantifying the robustness not only of safety systems, but also of non-safety systems. Indeed, weak components can have a significant impact on the conditional probabilities of occurrence of induced events.

Fragility analysis involves deep interactions with steps 1, 3, 4 and is usually performed by using standard computational methods, e.g. the finite element method. In particular cases, specific methods or supporting tools are used to perform the work and/or for documentation.

4.7 DEVELOPING SEISMIC FAULT AND EVENT TREES

The aim of this task is in accordance with [19] 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 (or off site seismic event which can affect safety of plant) 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 [17] during assumed mission time.

If it is assumed that in site and offsite seismically induced events have different source of earthquake (i.e. source of such earthquake does not affect plant directly), 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.

It is also noted that event trees are used to outline accident progression and they are tightly connected with used fault trees that form core of the seismic PSA model. Even if we use special software or some event-fault tree software (which is preferred in this report) there must be clearly stated expected conditions or scenarios for earthquake as whole or for particular intervals hazard curve is approximated by finite number of discrete intervals, see chapter 4.3. Typical assumption is loss of offsite power. In addition there must be clear strategy how implement such assumptions. For example:

- Loss of offsite power can be represented by separate branch in event tree or it can be treated by conditional probability based on fragility analysis within fault trees.
- If fire compartments have excellent seismic capacity then seismically induced internal fires can be treated within fault trees. In opposite case they should be treated as specific branch in event trees.
- Potential radioactive releases from neighboring units can be treated as separate initiating event or as conditional probability, within fault trees containing operator actions, that control room(s) working condition must be maintained.

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 seismically induced events, like LOCA determined, within step 6, chapter 4.6. 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.

Example of hypothetical event tree is presented in Fig. 4-7. Presented example uses one integrated tree where:

IE-SE	Initiating seismic event for particular POS (usually this event represents particular discrete interval from hazard curve, Fig. 4-4).
LLOCA	Response on large LOCA - Response as such is modeled by linked fault trees that evaluate performance of water makeup / injection systems including heat removal. Conditional probability of large LOCA is estimated upon fragility analysis of relevant pipes, chapter 4.6.1.
REACTORTRIP	This header links fault trees for reactor shutdown. If there are evidence that REACTORTRIP success is high then this branch must not be further developed. However; it is necessary to

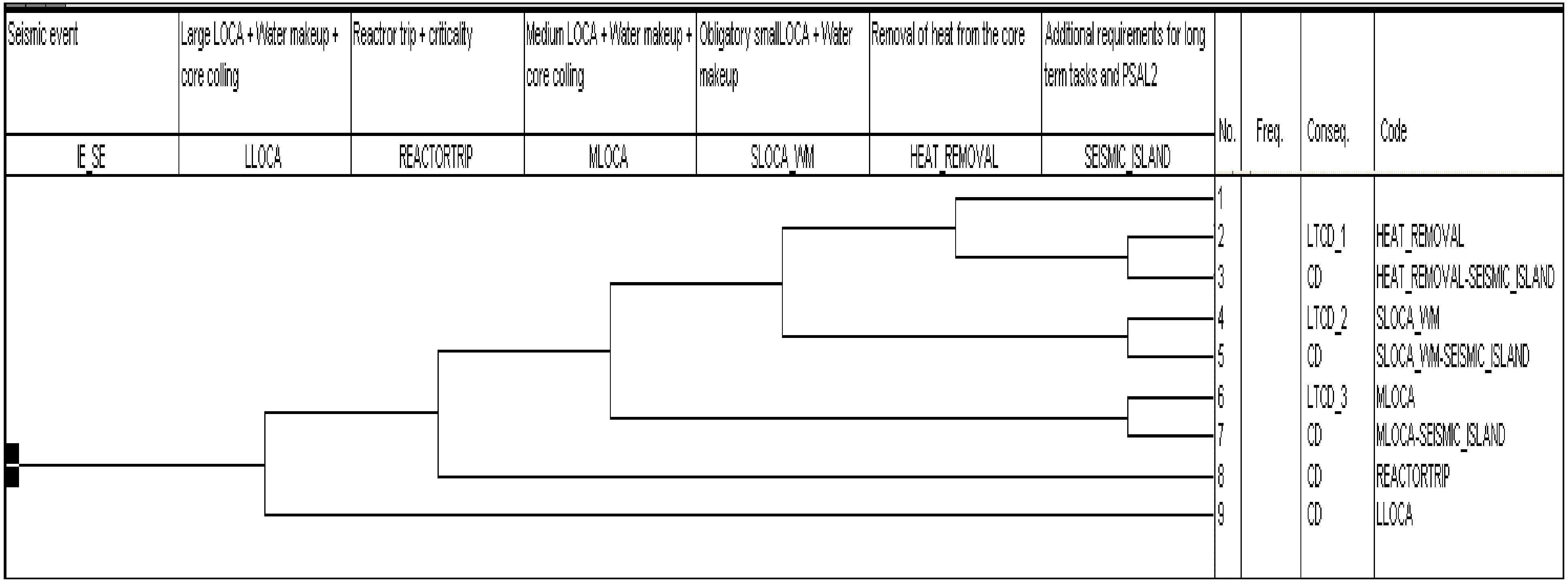
	take into account response on severe accident. If necessary branch should be developed in more detail.
MLOCA	Response on medium LOCA - Response as such is modeled by linked fault trees that evaluate performance of water makeup / injection systems including heat removal. Conditional probability of medium LOCA is estimated upon fragility analysis of relevant pipes, chapter 4.6.1. Determination of medium LOCA size should be consistent with assumptions used in L2 PSA if appropriate, e.g. reactor vessel depressurization.
SLOCA_WM	As it was noted earlier consideration of small LOCA should be obligatory. Linked fault tree evaluates response on this kind of LOCA by similar way as MLOCA.
HEAT_REMOVAL	Even if there is small LOCA energy released by LOCA size can be insufficient to cool core, LOCA can be isolated etc. In any case there will be necessary to establish reliable (long-term) residual heat removal.
SEISMIC_ISLAND	Except of basic response on LOCA events and establishing of heat removal there should be required further specific activities to keep plant in safe state that must be performed after shutdown or in several hours after seismic event occurence, e.g. isolation of plant non seismic parts, shutdown boron concentration after sub-cooling etc.

Consequence CD, in presented example, 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 (Long Term Core Damage_n) stand for consequence that can be further developed within long term scenarios to examine plant long time response, see section **5**.

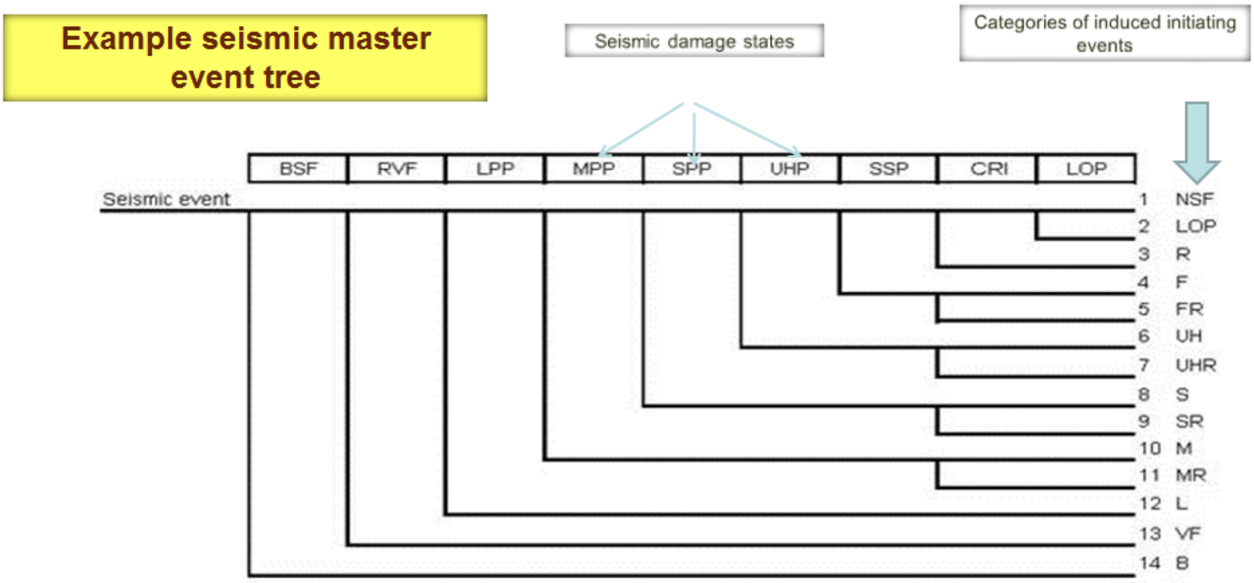
Example given in Fig. 4-7 also assumes that potential loss of offsite power will be evaluated within fault trees, i.e. model uses specific sub-model for power supply and particular consumers are just linked to the power sources. Internal fires, floods, structure collapses etc. are treated as specific seismic failures within fault trees.

Fig. 4-7 Example of hypothetical full power event tree combining basic response and LOCAs



Another strategy is based on so called master event tree. This case is outlined in the Fig. 4-8.

Fig. 4-8 Examples of modelling of seismically induced initiators and accident sequences with master event tree

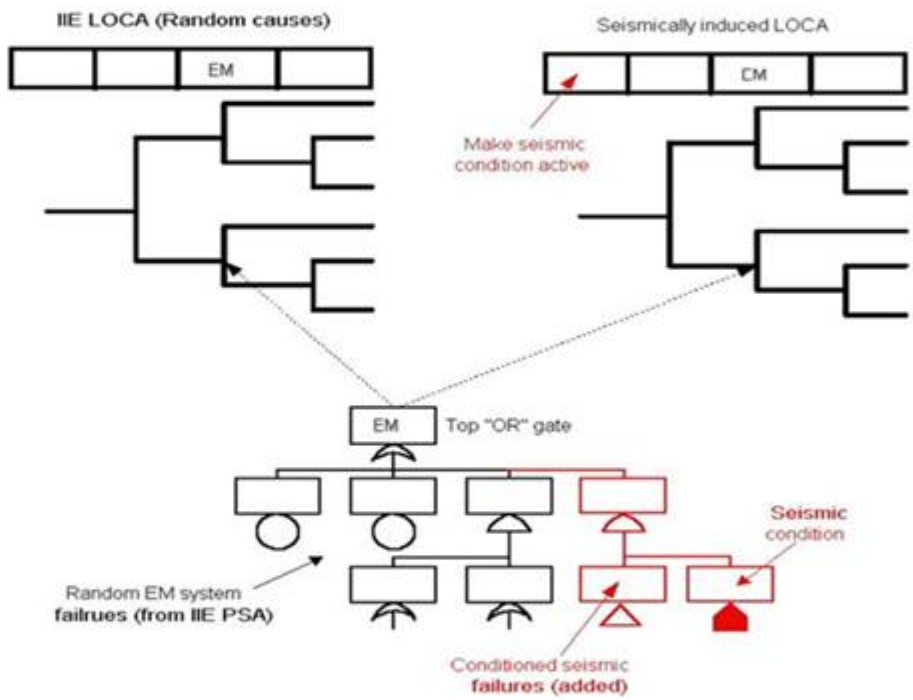


Top Events / Seismic Damage States	
BSF	Structural failures of buildings
RVF	Reactor vessel failure or any primary failure beyond ECCS capability
LPP	Large size primary piping or component failure
MPP	Medium size primary piping failure
SPP	Small size primary piping failure
UHP	UHS Pumps house failure
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

Particular categories of induced initiating events can be further developed by specific event trees. However there must be always considered dependencies between event trees and fault trees, Fig. 4-9. Overal composition of event trees and fault trees should be consistent with adopted assumptions, see. discussion in chapter 4.7.

Fig. 4-9 Example of dependencies between Event and Fault trees



Full scope PSA requires specific event trees covering all POSs. Low power POSs trees (especially for closed reactor states) can resemble on presented full power POS tree, e.g. Fig. 4-7. 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 interfacing LOCA due to maintenance of isolation valves 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.

Particular implementation of seismic event tree(s) depends on adopted assumptions mentioned in chapter 4.7 as well as on overall strategy discussed in introductory part of this chapter. In addition, composition of event tree(s) will be also affected by used software as well as by software used for convolution process, see chapter 4.8. Further important aspect is formed by intended interface between L1 PSA and L2 PSA.

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:

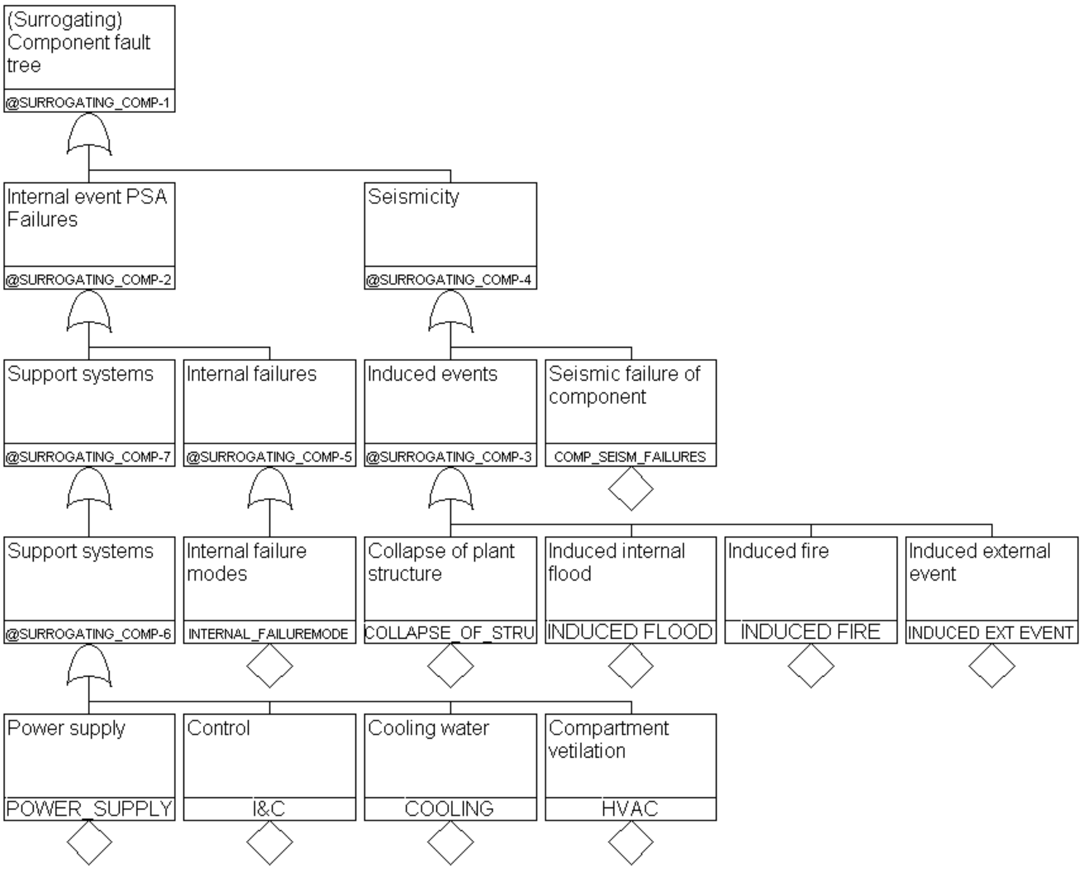
- Seismic failures of safety significant SSCs including internal seismic initiating events;
- Collapse of specific plant structures that can affect safety significant SSCs;
- Effect of induced events on performance of safety significant SSCs.

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, see example in Fig. 4-10 . It is noted that this one is standard approach for standard PSA. Induced events, better say effects/impacts of induced events are treated by similar way.

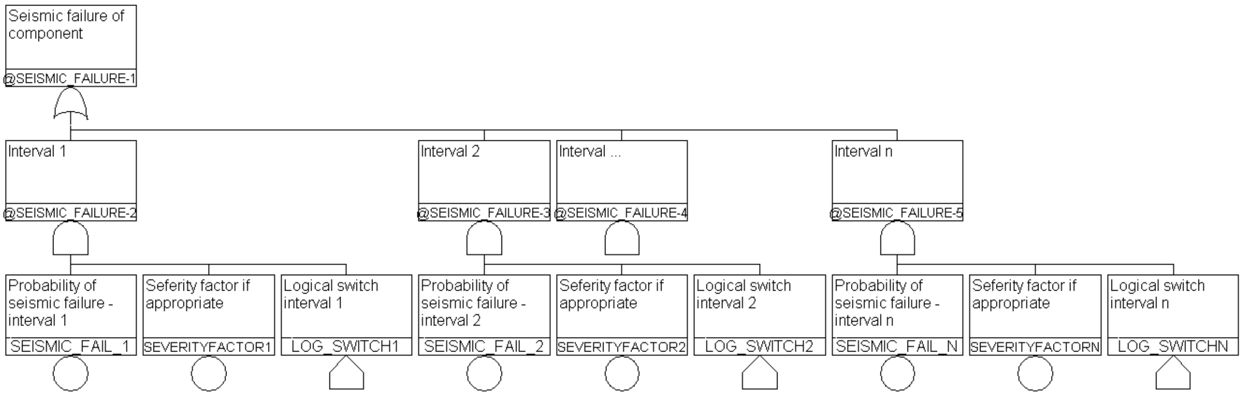
It is also noted that there are more and more frequent requirement to consider 72 hours mission time, e.g. discussion in chapter 5 of [18].

Fig. 4-10 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. 4-11.

Fig. 4-11 Treatment of conditional probabilities of component seismic failures



We assume that any relevant seismic component from SSC list determined within step 2 has linked seismic fault tree connected to appropriate position (e.g. gate COMP_SEISM_FAILURES in Fig. 4-10). 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. 4-11). Consequently each interval gate contains:

- Conditional probability of component due to seismic effect estimated in step 6 chapter 4.6 (e.g. gates SEISMIC_FAIL_1 to SEISMIC_FAIL_N)
- Severity factor[14] 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. Drawback is impossibility to perform real uncertainty analysis. However, such approach leads to large PSA model and to double counting of events, e.g. trip of section buss bar can avoids its fire or fire of subsequent bus bars which cannot be reflected correctly. On the one hand such cases can be partially neglected 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 simultaneously[15]) and disability to cope with open loops.

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[15] It should be noted that assumption of simultaneous occurrence of several variants of seismic scenarios is not too

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.

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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.

- 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.

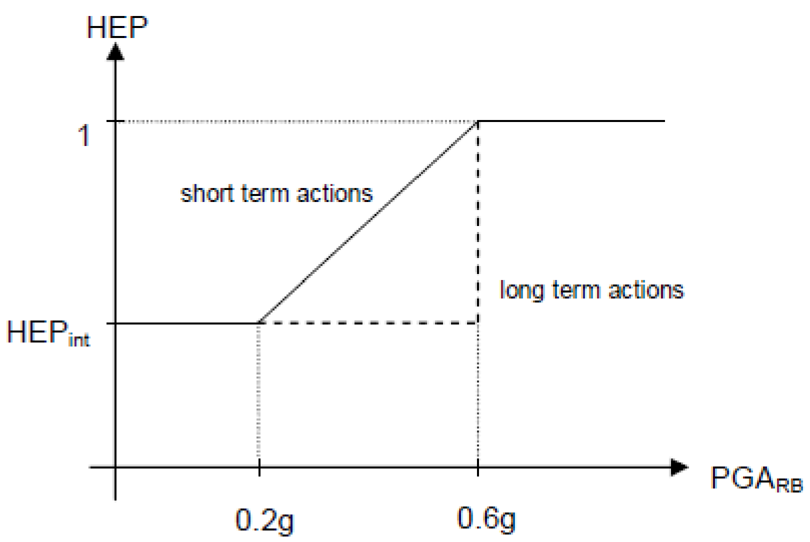
Above mentioned requirements should ensure consistency between seismic and internal event PSAs. They also imply necessity to tailor any HEP on specific conditions evoked by magnitude of seismic event. Simply say any discrete seismic interval, see item a) of Result of seismic hazard analysis in section 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 [7] 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:

a. 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), HEPint in Fig. 4-12.

b. 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.

c. From 0.6 g, all personnel actions shall be considered as guaranteed failed.

Fig. 4-12 Dependence of HEPs on the earthquake intensity (Figure 1 in [8])

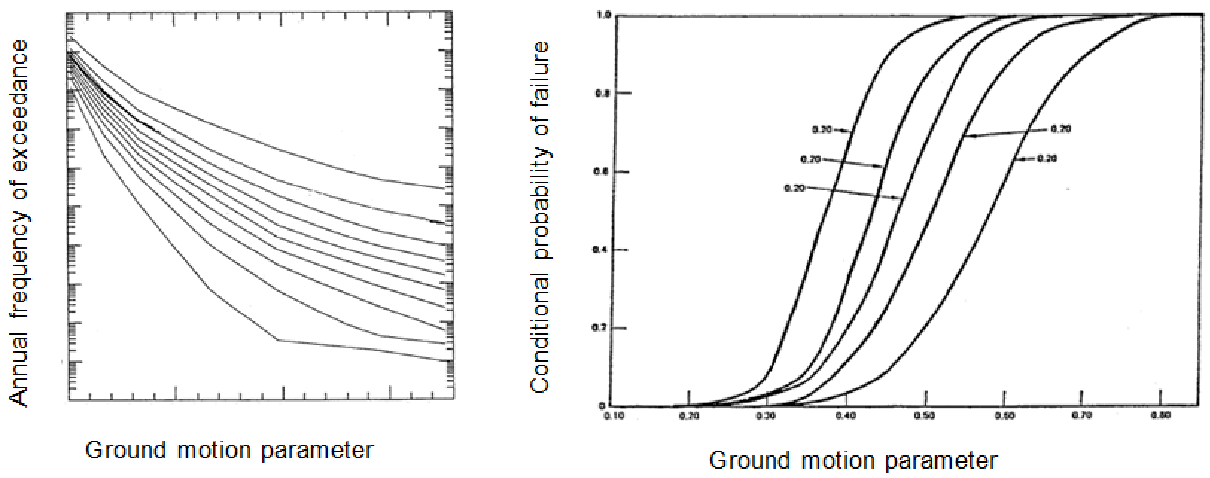


4.8 SEISMIC RISK QUANTIFICATION

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

Based on [12], once hazard curves and fragility curves for a failure event are obtained the two sets of curves are combined two at a time (i.e. one hazard curve and one fragility curve, see Fig. 4-13) to obtain the probability distribution of the unconditional CDF, P_f.

Fig. 4-13 Example of hazard and fragility curves that are combined[16]



$$P_f = \int_0^{\infty} P_{f|a} \frac{dH}{da} da \qquad \text{E4-3}$$

Where:

$P_{f|a}$ Conditional probability of failure (fragility curve - right part of Fig. 4-13)

$\frac{dH}{da}$ Derivative of the hazard curve with respect to the ground motion variable (left part of Fig. 4-13)

In general seismic risk quantification involves assembling the results of the seismic hazard analysis, fragility analysis, and seismic event trees (that link plant system response) to estimate the CDF. It is obvious that quantification considers both seismic failures (chapter 4.6 and 4.7.2) and non-seismic failures, and the applicable operator actions (chapter 4.7.3).

Quantification is commonly based on numerical integration. The numerical schemes for risk quantification fall into two broad categories. The first category uses simulation techniques such as Latin Hypercube Sampling and Monte Carlo Simulation. The second category involves the discretization of continuous functions into discrete intervals.

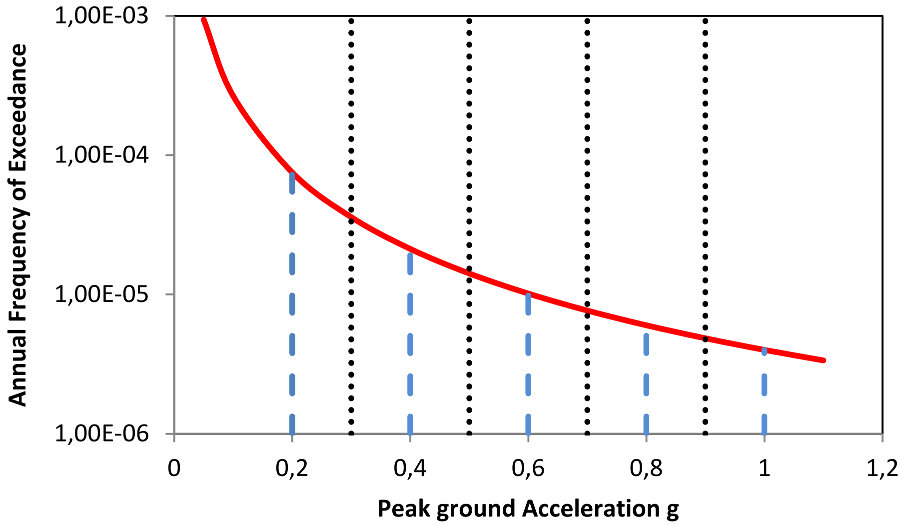
[16] Based on Figure 2-3 and 2-8 of [12].

The simulation approach generally consists in two basic steps:

1. Assembling representative MCSs or functions characterizing the plant state and
2. Random sampling from a number of continuous probability functions, leading to an estimate of the probability of core damage / fuel damage. Execution of these steps is supported by specific software packages.

In the discretization approach, a continuous function is approximated by a finite number of {<pi, xi>} doublets. The quantification steps then proceed along the given intervals of the hazard curve to determine the plant fragility curves and finally the CDF. The functions representing the frequency of occurrence and probability of failure must be combined just two at a time in this approach and the process is repeated for each discrete interval.

Fig. 4-14 Example of hazard curve discretization



Several approaches can be used to implement discrete probability distribution process. The most complex ones use simulation for each of the subintervals. As one example the software HazardLite can be mentioned [32].

The simplest way is based on using mean values. Mean values of hazard curve (dashed lines in Fig. 4-14) are combined with mean values of the composite fragility curves, as described in chapter 4.6. On one hand such approach is convenient to transfer PSA level 1 into PSA level 2. On the other hand this simple approach does not allow to perform uncertainty analysis.

Based on the work performed within steps 1 to 7 quantification of seismic PSA is a standard (mainly software based) activity like in PSA for internal events, see. [19] for further details. However, this is only the case for seismic risk quantification on mean values. If the seismic PSA quantification is to account for uncertainty, then it must be supported by specific software, for further details regarding the principles of suitable methods see Appendix C of [10].

An integral part of the quantification process is sensitivity (and importance) analysis. Besides the obvious evaluation of the importance of basic events (components, systems etc.), which is based on the Fussel-Vessely importance, risk achievement worth factors and sensitivity of used parameters, the effect of simplifying assumptions should be evaluated, see [21] . For example, the conclusion of sections 4.1.4 states that systematic work within step 1 can require a certain level of simplification which typically leads to conservative assumptions and consequently to risk overestimation. Importance analysis (even if it does not evaluate the interaction of factors) represents a handy tool to estimate the contribution of induced events to the overall results in this case. If this analysis reveals some contributors are out of balance, then the relevant cases should be reviewed in order to avoid adopting ineffective corrective measures.

Another controversial situation can be caused by double counted basic events, see section 4.7.2. Such a potential double counting should be checked by a detailed analysis of the minimal cutsets.

4.9 REPORTING

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

Final report of extended PSA should take care of identification of significant beyond design scenarios caused by combination of seismically induced events.

It should be noted that integral part of PSA reports is also discussion of results as well as suggestion of further provisions. However, determination of provisions to improve seismic resistance for cases considering peak ground acceleration far beyond design basis values can be a tricky task.

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 [37]. The general discussion on definition of PDSs and protocols and recommendations for performing PSA are to be found in the ASAMPSA2 guidelines ([38] and [39]).

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.

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 ([38] and [39] 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 accidents 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 ASAMPSA_E (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 PSA level 1 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. All these components can be subjected to a fragility analysis as described above. There is no difference in the methodology except for containment tightness failure which requires specific failure criteria.

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

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) and later to its drying after water boiling.

4.10.5 MULTI-UNIT EFFECTS (OTHER NUCLEAR FACILITIES)

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[17] (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.).

4.10.6 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. [10].

Exhausting examples to evaluate seismic failure correlation are presented in [25]. Table 3.1 of [25] presents rules for assigning response correlation as follows:

1. Components on the same floor slab, and sensitive to the same spectral frequency range (i.e., ZPA, 5-10 Hz, or 10-15 Hz) will be assigned response correlation - 1.0.
2. Components on the same floor slab, sensitive to different ranges of spectral acceleration will be assigned response correlation - 0.5.
3. Components on different floor slabs (but in the same building) and sensitive to the same spectral frequency range (ZPA, 5-10 Hz or 10-15 Hz) will be assigned response correlation - 0.75.

[17] For example paper SAFETY ASSESSMENT OF MULTIUNIT NPP SITES SUBJECT TO EXTERNAL EVENTS in [23] states in page 92: *In summary, it can be said that the site safety assessment for a multiunit site will be quite complex and need to start with individual unit risk assessments, these need to be combined considering the interactions between units and their responses, and the fragilities of the installations established considering the combined demands from all interactions*

4. Components on the ground surface (outside tanks, etc.) shall be treated as if they were on the grade floor of an adjacent building.
5. "Ganged" valve configurations (either parallel or series) will have response correlation - 1.0.
6. All other configurations will have response correlation equal to zero.

See also [23][18] which discuses approach presented in [25]. If such correlation is assumed then it requires extra work to implemented correlated failures into fault trees. However; in general there is not common agreement how such correlation effect should be 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. 4-7) 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,

[18] Paper LEVEL-1 SEISMIC PROBABILISTIC RISK ASSESSMENT FOR A PWR PLANT.

  - 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:

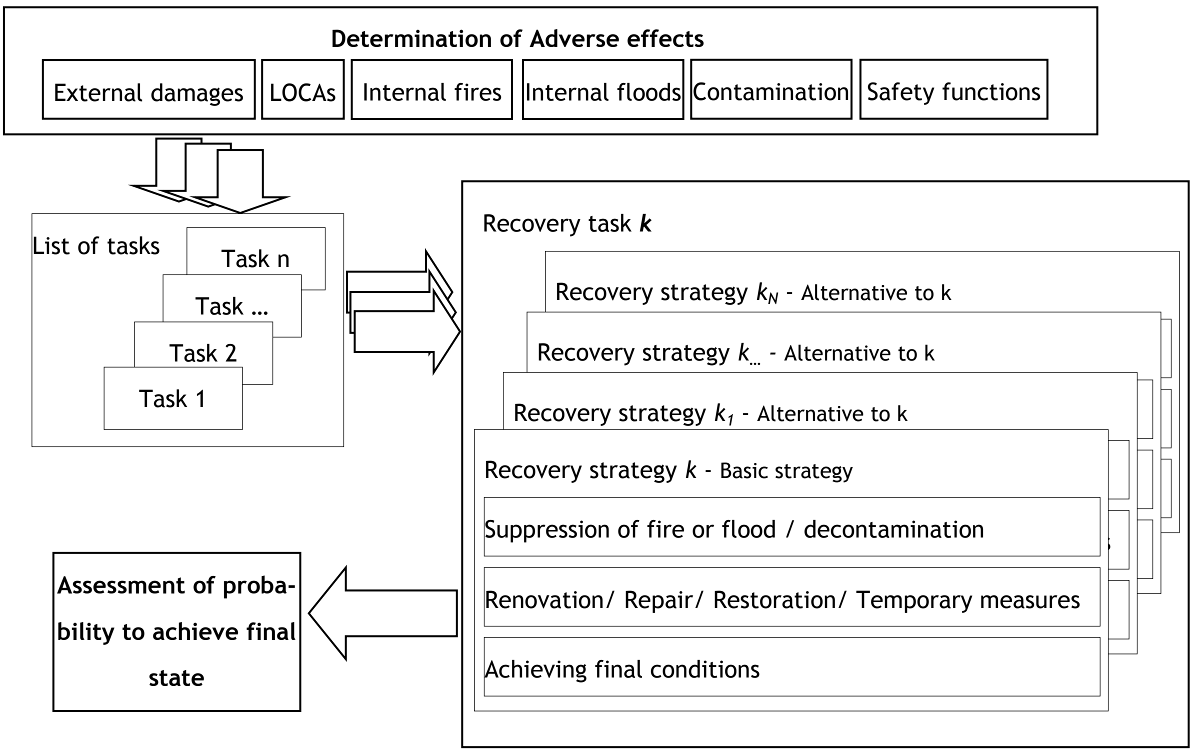
- evaluation of initial conditions including expected scope of damages and determination of all significant adverse effects,
- definition of final (safety) state,
- determination of a list of recovery tasks to mitigate adverse effects and restore desired state,
- definition of implementation strategy 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 [19]:

- 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).

General outline of post-seismic PSA is introduced in the next figure.

Fig. 5-1 Outline of post-seismic PSA



However, credit taken for operator recovery actions and accident management for the recovery of the plant from a degraded state or core damage condition shall be carefully evaluated. As demonstrated in the Fukushima accident these activities can be severely restricted by releases at other installations. The human reliability analysis for single units does not take such a scenario into consideration. For multiunit site the human reliability analysis needs to account for condition where the site is contaminated with radioactive material and accident management action need to be executed in this environment, adding another level of complexity to the safety assessment of multiunit sites, [23][19].

Multi-unit aspect can issue in situation where several task should be performed simultaneously in heavy working conditions (radiation in site, large scale damage, damaged access routes, escalation progress of accidents etc.). Under such conditions also correctness of decision of emergency center should be erroneous and several recovery tasks can be affected by success of some other tasks. These factors can cause difficulty to perform creditable analysis and may that classic PSA based on fault trees and event trees will be not capable to take into account complexity of post-seismic scenarios.

[19] SAFETY ASSESSMENT OF MULTIUNIT NPP SITES SUBJECT TO EXTERNAL EVENTS, page 89

6 CONCLUSION, RECOMMENDATIONS AND OPEN ISSUES

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, multi-units and mobile equipment, inaccessibility of location after a seismic event etc., which is covered by post-seismic analyses. Such introduced 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 lacks 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 explosions. In general preparation of report as well as several user meetings highlighted following points that form further areas of research and development:

- A long-term issue is formed by uncertainty which follows from data and method used in seismic hazard analysis as well as from fragility analysis. Both cases hazard and fragility analyses require more time to unify and precise method to reach common understanding and reduce aleatory and epistemic uncertainty. Uncertainty directly determines reasonability of provisions to improve seismic resistance for cases considering peak ground acceleration far beyond design basis values,
- Mentioned uncertainty can be multiplied by lack of specific methods to assess conditional probabilities of some induced events, e.g. internal fires,
- Similar topic is formed by screening criteria. It looks that application of screening based on contribution to risk can be quite demanding (such screening requires approximately the same scope of analysis as seismic PSA) so common handy screening methods based on seismic capacity should be developed.

Further important points from methodological and applicability of PSA results are:

- Harmonization between deterministic standards and PSA requirements regarding mission time is required. Many deterministic standards require work of plant in isolated regime after seismic event. This requirement has direct impact on considered mission time.

The same importance has also benchmarking between seismic PSA. Even if any seismic PSA is location and plant specific and benchmarking as such will be not straightforward activity initiating of such process can help to harmonize PSA methods as well as to reduce a generality of current standards.

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