ASAMPSA_E SEVENTH FRAMEWORK PROGRAMME	Advanced Safety Assessment Methodologies: extended PSA	EURATOM

"NUCLEAR FISSION "

Safety of Existing Nuclear Installations

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Report 4: Guidance document
Implementation of BIOLOGICAL INFESTATION hazards in extended PSA

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

Reference ASAMPSA_E
Technical report ASAMPSA_E /WP21&22/D21.3&D22.2-3 report4/ 2016-22
Reference IRSN PSN-RES/SAG/2016-00226

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Summary :

This report is a joint deliverable of WP21 (Initiating events modelling) and WP22 (How to introduce hazards in L1 PSA and all possibilities of events combinations).

The report introduces feasible approach based on already existing guidelines dealing with the implementation of external hazards in L1 PSA. It summarizes the lessons learnt from existing standards, existing gaps and possibility for future development and is focused on implementation of biological infestation hazards in extended PSA.

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EXECUTIVE SUMMARY

This report covers the assessment of biological hazards. It provides an overview of the available data and available practices in modelling this type of hazard.

First researches in the national and international literature regarding PSA for external and internal hazards shows that probabilistic analyse were very rarely carried out in order to quantify the risk induced by biological hazards. Nevertheless, Section 3 provides some data from some countries. History has shown that this hazard can happened and can be highly safety significant. Screening out this event must be done with great care.

The overall analysis approach for Level 1 PSA for internal events can be used for the biological hazards with some care to take into impact the nature of the hazard as it impacts many systems at different times and duration. A proposed detailed methodology is described in Section 4.

Still some open issues remain: The methodology must also consider event combination of biological infestation with other external hazards wind or flooding or rainfall and multi units impact. These aspects present still a lot of challenges to PSA developers.

ASAMPSA_E group recommends that further emphasis to be put on these two aspects of PSA modelling: Multi-site units impact and hazards combinations.

ASAMPSA_E PARTNERS

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

1	Institute for Radiological Protection and Nuclear Safety	IRSN	France
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5	Lloyd's Register Consulting	LRC	Sweden
15	Forsmark kraftgrupp AB	FKA	Sweden
16	AREVA NP SAS France	AREVA NP SAS	France
28	AREXIS S.A.R.L.	AREXIS	France

CONTENT

GLOSSARY

CCF	Common Cause Failure
CDF	Core Damage Frequency
CCWS	Component Cooling Water System
EOP	Emergency Operating Procedure
EPRI	Electric Power Research Institute
EPZ	Emergency Planning Zones
ESWS	Essential Service Water System
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IRS	IAEA International Reporting System
LOCA	Loss of Coolant Accidents
LOOP	Loss of Off-Site Power
LUHS	Loss of Ultimate Heat Sink
MCS	Monte Carlo Simulation
MIC	Microbiologically Influenced Corrosion
NPP	Nuclear Power Plant
OL	Olkiluoto NPP Unit 1, 2 and 3 (Finland)
PDF	Probability Density Functions
ppm	part per million
POS	Plant Operational State
PSA	Probabilistic Safety Assessment
PSHA	Probabilistic Seismic Hazard Analysis
PSR	Periodic Safety Review
PWR	Pressurized Water Reactor
SAM	Severe Accident Management
SBO	Station Black Out
SMA	Seismic Margin Assessment
SOER	Significant Operating Experience Report
SPRA	Seismic Probabilistic Risk Assessment
SSC	Structure System and Component
WANO	World Association of Nuclear Operators
WP	Work Package

DEFINITION

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

Bounding Analysis	Analysis that uses assumptions such that assessed outcome will meet or exceed the maximum severity of all credible outcomes.
Event Tree Analysis	An inductive technique that starts by hypothesizing the occurrence of basic initiating events and proceeds through their logical propagation to system failure events. • The event tree is the diagrammatic illustration of alternative outcomes of specified initiating events. • Fault tree analysis considers similar chains of events, but starts at the other end (i.e. with the 'results' rather than the 'causes'). The completed event trees and fault trees for a given set of events would be similar to one another.
Fault Tree Analysis	A deductive technique that starts by hypothesizing and defining *failure events* and systematically deduces the *events* or combinations of *events* that caused the *failure events* to occur. • The fault tree is the diagrammatic illustration of the *events*. • *Event tree analysis* considers similar chains of *events*, but starts at the other end (i.e. with the 'causes' rather than the 'results'). The completed *event* trees and fault trees for a given set of *events* would be similar to one another.
Cliff Edge Effect	In a nuclear power plant, an instance of severely abnormal plant behaviour caused by an abrupt transition from one plant status to another following a small *deviation* in a plant parameter, and thus a sudden large variation in plant conditions in response to a small variation in an input.
Design Basis	The range of conditions and *events* taken explicitly into account in the *design* of a *facility*, according to established criteria, such that the *facility* can withstand them without exceeding *authorized limits* by the planned *operation* of *safety systems*.
Design Basis External Events	The *external event(s)* or combination(s) of *external events* considered in the *design basis* of all or any part of a *facility*.
External Event	An event originated outside a nuclear power plant that directly or indirectly causes an initiating event and may cause safety system failures or operator errors that may lead to core damage or large early release. Events such as earthquakes, tornadoes, and floods from sources outside the plant and fires from sources inside or outside the plant are considered external events. By historical convention, LOOP not caused by another external event is considered to be an internal event. According to NUREG 2122, the term external event is no longer used and has been replaced by the term external hazard.
External Hazard Analysis	The objective is to evaluate the frequency of occurrence of different severities or intensities of external events or natural phenomena (e.g., external floods or high winds).
Fragility	The fragility of a structure, system or component (SSC) is the conditional probability of its failure at a given hazard input level. The input could be earthquake motion, wind speed, or flood level.
Fragility Analysis	Estimation of the likelihood that a given component, system, or structure will cease to function given the occurrence of a hazard event of a certain intensity. • In a PRA, fragility analysis identifies the components, systems, and structures susceptible to the effects of an external hazard and estimates their fragility parameters. Those parameters are then used to calculate fragility (conditional probability of failure) of the component, system, or structure at a certain intensity level of the hazard event. • Fragility analysis considers all failure mechanisms due to the occurrence of an external hazard event and calculates fragility parameters for each mechanism. This is true whether the fragility analysis is used for an external flood hazard, fire hazard, high wind hazard, seismic hazard, or other external hazards. For example, for seismic events, anchor failure, structural failure, and systems interactions are some of the failure mechanisms that would be considered.
Fragility Curve	A graph that plots the likelihood that a component, system, or structure will fail versus the increasing intensity of a hazard event. • In a PRA, fragility curves generally are used in seismic analyses and provide the conditional frequency of failure for structures, systems, or components as a function of an earthquake-intensity parameter, such as peak ground acceleration. • Fragility curves also can be used in PRAs examining other hazards, such as high

	winds or external floods.
Hazard	The ASME/ANS PRA Standard defines a hazard as "an event or a natural phenomenon that poses some risk to a facility. • Internal hazards include events such as equipment failures, human failures, and flooding and fires internal to the plant. • External hazards include events such as flooding and fires external to the plant, tornadoes, earthquakes, and aircraft crashes."
Hazard Analysis	The process to determine an estimate of the expected frequency of exceedance (over some specified time interval) of various levels of some characteristic measure of the intensity of a hazard (e.g., peak ground acceleration to characterize ground shaking from an earthquake). The time period of interest is often taken as 1 year, in which case the estimate is called the annual frequency of exceedance.
Human Reliability Analysis	A structured approach used to identify potential human failure events and to systematically estimate the probability of those events using data, models, or expert judgment.
Initiating Event	An identified *event* that leads to *anticipated operational occurrences* or *accident conditions*. • This term (often shortened to *initiator*) is used in relation to *event* reporting and *analysis*, i.e. when such *events* have occurred. For the consideration of hypothetical *events* considered at the *design* stage, the term *postulated initiating event* is used.
Loss of Offsite Power (LOOP)	The loss of all power from the electrical grid to the plant. In a PSA/PRA, loss of offsite power (LOOP) is referred to as both an initiating event and an accident sequence class. As an initiating event, LOOP to the plant can be a result of a weather-related fault, a grid-centered fault, or a plant-centered fault. During an accident sequence, LOOP can be a random failure. Generally, LOOP is considered to be a transient initiating event.
Structures, Systems And Components (SSCs)	A general term encompassing all of the elements (items) of a *facility* or *activity* which contribute to *protection and safety*, except *human factors*. • *Structures* are the passive elements: buildings, vessels, shielding, etc. • A *system* comprises several *components*, assembled in such a way as to perform a specific (active) function. • A *component* is a discrete element of a *system*. Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.
Severe accident	A type of accident that may challenge safety systems at a level much higher than expected.
Screening	A process that distinguishes items that should be included or excluded from an analysis based on defined criteria.
Screening criteria	The values and conditions used to determine whether an item is a negligible contributor to the probability of an accident sequence or its consequences.
Sensitivity Analysis	A quantitative examination of how the behaviour of a *system* varies with change, usually in the values of the governing parameters. • A common approach is parameter variation, in which the variation of results is investigated for changes in the value of one or more input parameters within a reasonable range around selected reference or mean values, and perturbation *analysis*, in which the variations of results with respect to changes in the values of all the input
Uncertainty	A representation of the confidence in the state of knowledge about the parameter values and models used in constructing the PRA. OR Variability in an estimate because of the randomness of the data or the lack of knowledge.
Uncertainty Analysis	An *analysis* to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem.

1 INTRODUCTION

1.1 Objective/Scope of Biological Infestation PSA

This report covers the assessment of biological infestation hazards. It provides an overview of the best practices in modelling this type of hazard. This report makes a link between the exhaustive bibliographic review performed in ASAMPSA_E D21.1 [28] regarding the modelling of all extended hazards, the combination of these hazards (D21.2) and level 1 PSA modelling aspects as covered in WP22.

The scope of the report is to present a summary of the existing literature regarding the PSA modelling of biological hazards, an overview of the approaches to assess these hazards and their combination and identify best practices.

1.2 Potential Impacts on the Plant

Biological infestation hazards may lead to a wide range of potential safety issues.

In general these hazards can be classified into:

- Infestation by water, as for example:
    - biological flotsam,
    - jellyfish,
    - algae,
    - fish, etc.[1]
- Infestation by air, as for example
    - swarms of insects,
    - swarms of birds.
- Infestation by ground, as for example
    - bug,
    - mice,
    - rats,
    - rabbits, etc.

Biological phenomena mainly affect cooling water system and the ultimate heat sink, due to excessive growth of algae, mussels and clams, or clogging due to fish or jellyfish. Ventilation systems have become clogged by leaves or insects in the filters. Cases of rats and bacteria attacking Instrumentation and Control (I&C) cables have been recorded. Corrosion effects and accelerated ageing of steel structures exposed to the marine environment can be induced by sulphate-reducing bacteria [1].

1.3 Lessons Learned from Past Events

Past experience related to biological hazards is scarse. Some of it is presented in Section 3 mainly.

ASAMPSA_E, D10.3 report [20] presents the collected data provided by PSA End-users in response to a questionnaire launched by the ASAMPSA_E project about external hazards that have affected nuclear power plant (NPP) or other facilities. The information has been completed by the authors based on publicly available

[1] Oil slippage related hazards are not included in the scope of ASAMPSA_E project.

information and complemented from the IAEA IRS database. Table 4 of this report presents biological infestation and their consequences.

Twelve “real” events on NPP caused by biological or geological phenomena have been described: 5 in Europe, 4 in USA, 3 in Asia. Three of them are considered as safety significant. The following phenomena have been observed [20]:

- biofouling,
- jellyfish and tunicates invasion,
- reeds intrusion,
- sand deposit,
- silting,
- small fishes invasion,
- vegetable material in the heat sink,
- rats intrusion.

Many of them might occur in combination with storms/high winds or after hydrological events (e.g. floods) and they might cause a total loss of the heat sink or heat exchangers blocking or inadequate heat removal [20].

2 PSA GUIDANCE DOCUMENTS

From ASAMPSA_E D21.1 [28], the following table lists some of the references that provide some guidance on the assessment of biological hazards. Even they are not specific for biological hazards they can be used as a reference for the PSA treating this type of external hazards.

Table 1: Guidance documents - Implementation of Biological Infestation Hazards in Extended PSA

Ref	WA1	WA2	WA3	WA4	Remarks
IAEA SSG-3	x	x	x		General and does not differentiate between external hazards with however a focus on (Section 8): (a) Seismic hazards; (b) High winds; (c) External floods; (d) Human-induced hazards. Remains still a good reference.
IAEA SSG-4				x	General does not differentiate between external hazards.
IAEA 50-P-7	x	x			Guidance on conducting a PSA for external hazards, with application to four of the most frequently analysed: earthquakes, high winds, floods and man induced events. The methodology itself is general and can be applied equally well to other types of hazard. Information is provided on the inclusion of external hazards in a Level 1 or Level 2 PSA. This guide has been however superseded.
WENRA Issue O	x	x			All External Events
NEA/CSNI/R(2009)4	x		x		Non-Seismic Hazard including biological
SKI, Report 02:27	x	x			Non-Seismic External Events including some biological hazards identified as solid impurities and water contamination
EUR 2001 “Volume 2 Generic Nuclear Island Requirements. 2.1 Safety requirements. 2.17 PSA Methodology. Revision D”	x	x			General, covers assessment of external hazards even though biological hazards are not included.
WENRA RHWG, Safety of New NPP Designs - March 2013		x			General principles. Covers external hazards including biological hazards.
WENRA "Position paper on Periodic Safety Reviews (PSRs) taking into account the lessons learnt from the TEPCO Fukushima Dai-ichi NPP accident", March 2013			x		General nothing specific on biological hazards

Ref	WA1	WA2	WA3	WA4	Remarks
HSE "Safety Assessment Principles for Nuclear Facilities", 2014, Revision 0			x	x	General principles. Covers external hazards however nothing specific on biological hazards. See ONR reference below.
EPRI 1022997			x		Good reference that covers external hazards including biological. Provides a review of many of the documents listed in this table as IAEA 50-P-7, SKI 02:27.
ONR Technical Assessment Guide - External Hazards. NS-TAST-GD-013 – Rev. 5, September 2014				x	General principles. Covers biological hazards. No specific PSA guidance.

Notes:
WA1 – IMPACT ON THE STRUCTURE SYSTEM AND COMPONENT (SSC'S) MODELED IN L1 PSA EVENT TREES
WA2 – IMPACT ON HUMAN RELIABILITY ASSESSMENT MODELLING IN L1 PSA
WA3 – SITE IMPACT MODELLING IN L1 PSA EVENT TREES
WA4 – SITE IMPACT MODELLING IN L2 PSA EVENT TREES

3 DATABASE

This section presents some information that would be helpful to assess biological hazards. Some examples of available data for the PSA are presented.

In general the following information is needed to perform a Biological hazard PSA:

- **List of data required for hazard assessment.** (Type of data describing natural phenomena, site-specific data, etc.)
- **Data sources** (links to find data such as natural event catalogues, data series, etc.; for many hazards it will be necessary to distinguish between instrumental, historical, and pre-historical data; if no or insufficient site-specific data are available: discuss workaround by using data from comparable sites or regions)
  - Generic/regioinal data
  - Site-specific data including data from site-specific observation networks
- **Operational event database of plants** (links to find plant-specific data connected to external events and their root cause analysis; events that led to reactor shut down)
- **Numerical simulation data** such as for meteorological events

Note that the data completeness and quality (completeness and accuracy of measurements) need to be assessed, by specific methods for assessing key input parameters (statistical or expert methods).

3.1 Finland

Finland Stress Test report [2] discusses biological hazards. However, it gives quite limited information looking on data sources for organic material in the water even though it shows that frequencies have been estimated from operating experience, see e.g. on page 197.

The following is extracted from Reference [2]:

Intake water blockage: blockage of cooling water intakes by ice, frazil ice, debris, seaweed, and marine life, e.g. bivalves, jellyfish or fish

Reduced flow due to algae and marine growth (e.g. bivalves):

The Olkiluoto units 1 and 2 (OL1&2) experience on mussels, living and dying in the seawater tunnels have been considered in the design of Olkiluoto unit 3 (OL3). **Frequency of large amount of algae is 0.02/year based on OL1&2 experience**. Algae can cause an initiating event only if precautionary actions such observation of the phenomena and algae nets fail or the band screens are blocked.

The precautionary actions to prevent a final Loss of Ultimate Heat Sink (LUHS) event mentioned above have been evaluated probabilistically and considered for the further PSA modelling.

Prevention of oil slicks from entering cooling water intake:

The determination of a frequency of oil spills entering the Essential Service Water System (ESWS) inlet channel has been estimated by the Finnish Technical Research Centre VTT (Note: It is not available in reference [2]). The calculation is based on an Event Tree taking into account the frequency of a tanker accident in the Gulf Bothnia and three countermeasures:

- surrounding of the oil before the islands separating the Olkiluoto bay from the Gulf,
- installation of a temporary oil boom in the inlet channel,

- manual switchover of the ESWS pumps suction towards the outlet channel

Under-water landslide[2]:

This event has been screened out using the severity and applicability criteria. An under-water landslide may result in deteriorated quality of the intake water, which is assumed not to threaten the plant. Furthermore, any plant effects from bad intake water quality will be gradual. If any countermeasures are required, then licensee will plan and implement them accordingly. The design of the intake water structures is such that no credible landslide can occur, resulting in loss of the ultimate heat sink.

Surface ice[3]

This event has been screened out using the severity and warning criteria.

Ice barriers[3]

This event has been screened out using the severity, warning and applicability criteria.

Corrosion (from salt water)

This event has been screened out using the severity criterion.

Chemical release to water[4]

This event has been screened out using the severity criterion. The event is defined as impact due to chemical releases to water. The focus is on reduction of water quality. The releases may be due to a ship accident, but may also originate from land. No credible effect can be defined, as plant is assumed to be non-sensitive to credible scenarios.

Consideration of potential combination of weather conditions

Strong wind (affecting external power supply) and organic material in water (affecting UHS): Organic material in seawater will be quantified as a single event. The multiple external events will not be quantified, as presumed that organic material already alone has caused the loss of ultimate heat sink.

3.2 France

On 1st December 2009 a massive amount of vegetable materials blocked the entrance to the pumping station of the units 3 & 4 of the Cruas site[5]. Following this event the train A of the ESWS unit 4 was unavailable. The operator EDF stopped the reactor 4 by dropping the control rods and switched the ESWS onto the train B that was also unavailable. The event derived into a total loss of the heat sink at Unit 4. The Emergency Operating Procedures (EOP) and the French National Crisis Organization was activated. The duration of the total loss of the heat sink was about 10 hours. The event was mitigated by using a specific procedure introduced due to PSA development in the past (using of the refuelling tank water thermal inertia). The total loss of heat sink at unit 4 was simultaneous with partial loss of heat sink on units 2 and 3 (one ESWS train unavailable for 14h / 18h). The event represented also a

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[2] Under-water landslide is classified under the external hazards group Geological events under ASAMPSA_E WP 21 [28].
[3] Surface ice is classified under the external hazards group Meteorological events under ASAMPSA_E WP 21 [28].
[4] Chemical releases are classified under the external hazards group External Man-Made events under ASAMPSA_E WP 21 [28].
[5] P. Brac, “Session 2 – Lessons of past real events / hazards for PSA”, ASAMPSA_E, End users workshop – Uppsala – Sweden, May 2014 [15].

precursor of a multi-units loss of the heat sink. However, in France following the Periodic Safety Reviews (PSR), deterministic analysis and safety enhancements to deal with multi-units loss of the heat sink + loss of off-site power (LOOP) induced by a natural hazard were already implemented, such as:

- stronger requirements on the water inventory in the tanks necessary to fill-up the water tanks of the auxiliary feed water system;
- some adaptation of the accident procedures in order to deal with multi-units loss of the heat sink and of the external electrical supplies;
- improvement of the on-site emergency planning to deal with multi-units accidents, in particular in case of external hazards (access difficulties etc.).

Additional improvements (design, organizational) resulting from the post-Fukushima “stress tests analyses” are also under implementation: “Hardened safety core” - Fixed on-site additional SSCs and special nuclear rapid response force (off-site support).

3.3 Germany

3.3.1 Current Situation

Preliminary research on the national and international literature regarding PSA for external and internal hazards show that probabilistic analyse were very rarely carried out in order to quantify the risk induced by biological hazards.

The technical document on PSA methods ([3]; FAK 05) of the German PSA Guideline ([4]; BMU 05) mention biological infestation as hazard that need to be investigated probabilistically. However, no methodical guidelines are given.

The following statements are identified in the German framework for the performance of a periodic safety review (PSR)[6]:

- Evaluation of operating experience
  Biological hazards, which could impact the safety of the NPP, are not known in the operating experience (of the plant)
- Prevention measures
  Particular emphasis on control measures of slow deterioration by visual examination. Concerning biological products on the surface of the water, deflectors (baffles) should be installed. Cleaning systems (e.g. bar and fine screens) or screening systems, which are connected with the emergency power system exist already and are partly redundant.
- Assessment of possible damages
  Blocking of water intake structures or cooling water channels by organic material (especially mussels, fishes, algae, seaweed); detritus deposition leading to lower heat exchange performance

The blocking of water intake structures or cooling water channels leads to the loss of main heat sink (condenser cooling) and to the loss of the ultimate heat sink, in case of NPPs taking the cooling water from a river. In order to cope with this event, an alternative heat sink exists in German NPPs, which consists of permanently installed equipment (e.g. water well) or emergency measures.

In case of complete loss of the ultimate heat sink, the residual heat removal is possible by discharge of main

[6] Based on the German framework for the performance of a periodic safety review (PSR), it can be concluded that biological hazards (from water) do not need to be considered in probabilistic analyses.

stream over roof.

The plant is protected against big mammalians by a fence. Small animals as birds, rodents and insects are assumed as irrelevant.

Site Assessment

Site inspections are important in order to establish a list of hazards for a site. While searching relevant biological hazards, for instance cases are found as:

- flooding after breach in a dyke that drifts big amounts of organic material,
- uncoordinated opening of water gateways with a sweeping of organic material,
- decrease of flow velocity due to heavy rain and entrainment of biological material,
- movement of biological material in the direction of the water intake structure or air intake due to windstorm or tornados (e.g. leaves in autumn).

The site assessment is also to carry out in order to screen out unusual circumstance of biological hazards (e.g. infestation of rodents, termites, blocking of air intake by bird nests).

After a site inspection and site assessment, a list of biological hazards - called $L_{total,Bio}$ - should be available. This list includes all biological hazards that might occur at the site and that must be assessed. The list $L_{total,Bio}$ should also include combinations of different hazards and it should be used to estimate the quantitative contribution of each hazard $L_{total,Bio}$ to the risk. An estimation of the frequency of the damage states is the product (and sum) of the following parameters:

a) Occurrence frequency of the hazard (in different levels of its strength),
b) Conditional probability(s) of the initiating events that are caused by the hazard,
c) Unavailability of the system functions for every single initiating event, which are necessary for the control of design-basis accidents.

Indeed, potential dependencies have to be considered for such estimations. A detailed quantitative evaluation will be very difficult in many cases. However, all possible dependencies should be discussed at least, in order to determine an appropriate risk increase.

For instance, “strong algae infestation” might be a result from the site assessment. Thus, “strong algae infestation” can be an element of the list $L_{total,Bio}$. For the risk calculation, the following parameters are necessary:

a) Occurrence frequency of “strong algae infestation”

The evaluation of historical sources leads e.g. to the result, that “strong algae infestation” occurs averagely all 100 years. Of course, “strong algae infestation” has to be defined in detail. It might be the amount of biomass, which leads to blocking of all cooling water channels regarding the current design. This amount of biomass is called critical.

b) What is the probability, that in case of critical algae infestation blocking the cooling water intake, it leads to an initiating event?

For instance, an assumption might be that the probability for blocking of cooling water intake and systems is 1 for a specific critical amount of biomass. Appropriate increments of the conditional blocking probability can be estimated for lower amounts of biomass. Plant specificity need to be investigated, and if one or several initiating events (e.g. loss of main heat sink) can result from the blocking of the cooling water intake and systems. Corresponding conditional probabilities have to be determined.

c) Unavailability of the safety functions for every single initiating event, which are necessary for the control of design-basis accidents

These unavailabilities can be taken from level 1 PSA but before, it is needed to examine, whether the plant model has to be modified due to additional failures or losses.

3.3.2 Germany Historical Data

The following tables provide an overview of biological events that have happened in Germany[7].

Most of the identified biological events are Microbiologically Influenced Corrosion (MIC) (six events over a total of twelve). MIC affects the ESWS but the impact on the NPPs is considered low. One event required a manual shutdown because of the accumulation of foliage and gas in the intake structure with the loss of circulating water pumps. One event tripped the turbine because of martens in the outdoor portion of the generator bus duct (stator ground fault monitor tripped).

Table 2: Germany Historical Biological Events

#	Short description	Cause	Affected systems	Conse-quences
1.	Leakage from vent line of the motor air cooler of secured service water pump	MIC	ESWS	Low
2.	Drip leaks from the drain line of the essential service water system	MIC	ESWS	Low
3.	Leakage from the drainage pipe of the essential service water system	MIC	ESWS	Low
4.	Leakage from the pipe nozzles of the essential service water system	MIC	ESWS	Low
5.	Leakage from the sampling line of the essential service water system	MIC	ESWS	Low
6.	Microbiological influenced corrosion of the threated fasteners of the service water pump	MIC	ESWS	Low
7.	Mussels clogging an CCWS HX; erosion corrosion of CCWS HX; leakage; drop in level of expansion tank	Mussels	Component cooling water system	Low
8.	Martens in the outdoor portion of the generator bus duct; stator ground fault monitor tripped	Martens	Generator	Turbine trip
9.	Accumulation of foliage; opening of overflow hatch; ingress of foliage into service water system; reduced service water flow	Flooding, foliage	ESWS	Low
10.	Algae in charge air cooler of an emergency diesel engine reduced; cooling water flow; abnormal heating in coolant supply	Algae	Emergency diesel	Low
11.	Accumulation of foliage and gas in intake structure, loss of circulating water pumps	Rainfall, foliage	Circulating water system	Manual shutdown

[7] List of events extracted from the restricted VERA database of GRS, which contains reportable events that occurred in German NPPs.

12.	Accumulation of foliage; opening of overflow hatch; blockage of CCWS HX; reduction in service water flow	Rainfall, foliage	Component cooling water system	Low

Table 3: Compilation of Germany Biological Events, and their Effects

Biological influence		Number of events
Microbiological influenced corrosion		6
Foliage		3
Mussels		1
Marten		1
Algae		1
	Sum:	12
Effects		**Number of events**
Low		10
Turbine trip		1
Manual shutdown		1
	Sum:	12
Affected Systems		**Number of events**
Residual heat removal chain		9
Service water system		7
Closed cooling water system		2
Circulating water system		1
Generator		1
Emergency diesel		1
	Sum:	21

Table 4 lists Germany biological events with a combination of other events (not necessarily biological). Two events required a manual shutdown because of the loss of service water system.

Table 4: Germany Historical Combined Events

#	Short Description	Causes	Affected systems	Consequences
1.	Ingress of rain water into the reactor building and turbine building; subsurface erosion with subsidence	Rainfall, shifting substrate	Rainwater drainage system	Minor contamination in controlled area
2.	Fouling; shutdown of 3 of 6 circulating water pumps	Low water, driftwood	Circulating water system	Power reduction
3.	Ingress of foliage, opening of an overflow hatch, Ingress into essential service water system, reduction of service water flow	Flooding, biological impacts	ESWS	Minor
4.	Fouling of pump bearings, loss of lubricant supply to essential service water pumps	Flooding, driftwood	ESWS	Minor
5.	Ingress of foliage and gas into the intake structure, loss of circulating water pumps	Precipitation, biological impacts	Circulating water system	Manual shutdown
6.	Ingress of foliage, opening of an overflow hatch, clogging of an CCWS HX, reduction in service water flow	Precipitation, biological impacts	Component cooling water system	Minor
7.	Fouling; reduction of water levels in the intake structure, loss of essential service water pumps	Rainfall, driftwood	ESWS	Manual shutdown

3.4 Sweden

In Sweden only biological hazard associated with seawater cooling are considered. Biological clogging of air-cooled system and failure of safety system due to rodents are screened out.

Data needed to assess the clogging of the seawater inlet is the concentration of the biomass with an associated probability. The biomass can be grouped, for example: fish, jellyfish, seaweed etc.

To make the hazard assessment, the environmental assessment of the plant is used supported by experience feedback from the operation and assessment of invasive species. To assess the risk of invasive species seawater flow, temperature, salinity, pH, oxygen level and Secchi depth can be used together with open literature and the experience feedback from the power plant and nearby industries and fishermen.

Site-specific data is needed to assess the biomass of the most common species in the seawater and biofouling of heat exchangers and seawater channels. Assessment of invasive species can use open literature and regional data (example Baltic Sea).

The Swedish Agency for Marine and Water Management is responsible for the administrative and coordinative work around invasive species in aquatic environments. There is no established collaboration information system to alert the nuclear power sites about new invasive species.

Example of site-specific Hazard assessment:

Biological hazard assessment in seawater is usually performed during the design of the seawater. The plants and animals are converted to volume biomass per volume seawater (expressed as part per million (ppm)). Jellyfish is not a common species in Forsmark NPP. Assessment of the biomass is done by assessment of sea water flow, temperature, salinity, pH, oxygen level and Secchi depth.

Table 5 Hazard Assessment

Biomass	Yearly [ppm]	Anticipated [ppm]	Improbable [ppm]
Phytoplankton	1	1	10
Aquatic plants	0,1	1	150
Jellyfish	0,001	0,01	28
Fish	0,5	4	10

Marine Biologist and other experts are needed to assure the completeness and quality of the data and the assessment. The PSA team or the power plant is not usually equipped with these types of competences and it can be hard to find. Therefore it could be enough with a re-assessment of the hazard every 10 years or when a new invasive species is found in the sea water inlet waste.

3.5 Canada

REGDOC-2.5.2, Design of Reactor Facilities: Nuclear Power Plants requires that natural external hazards considered in the design process should include biological phenomena and collision of floating debris (e.g., ice, logs) with accessible safety-related structures, such as water intakes and ultimate heat sink components.

REGDOC-2.4.1, Deterministic Safety Analysis, requires that common cause events induced by external hazards be analyzed. Biological hazards (for instance, mussels or seaweed affecting cooling water flow and/or temperature) are such external hazards. However, REGDOC-2.4.2, Probabilistic Safety Assessment, does not identify biological hazards as events that need to be assessed.

Gentilly-2 NPP Experience[8]:

Numerous incidents of biological interference have occurred at the Gentilly-2 pump house rotating sieve and mechanical rake. Many of the incidents of degraded water intake conditions are due to large influx of algae, fish or oil entering the rotating sieves. Proliferation of zebra mussels had also become an operational issue at Gentilly-2 due to clogging of heat exchanger piping and growth on water intake wells. Significant measures have been undertaken at Gentilly-2 to respond to biological phenomena entering the cooling water intakes, specifically, five key topics were addressed in their response to WANO SOER 2007-2:

- assessing changing environmental conditions,
- surveillance techniques, early warning and predictive methods,
- design and modification,
- maintenance programs,
- training.

On the basis of this approach, it has been judged that biological issues are unlikely to cause core damage and that the operational procedures should be adequate to prevent core damage; this event has been screened out. No information is available on the frequency of the events.

[8] This plant was shutdown for decommissioning in 2012.

3.6 Generic

Table 6 is a compilation of worldwide biological events. They are extracted from the IRS database (INTERNATIONAL REPORTING SYSTEM FOR OPERATING EXPERIENCE) of IAEA (http://www-ns.iaea.org/reviews/op-safety-reviews.asp?s=7&l=49#irs).

Twenty-two biological events have been identified with the following remarks (see Table 7):

- fish, sea grass and mussels are the most frequent biological infestation,
- four events tripped the reactor and sixteen events required a power reduction or a manual trip,
- service water systems are the most effected systems.

Table 6: List of Worldwide Biological Events

#	Brief description	Cause	Affected System	Effect
1.	Jellyfish ingress into circulating water cleaning system; reduction in circulating water flow	Jellyfish	Circulating water system	Manual shutdown
2.	Ingress of debris into circulating water intake; loss of drum screen	Precipitation, seagrass	Circulating water system	Power reduction
3.	ingress of seagrass, loss of two redundancies of the circulating water supply	Wind, seagrass	Circulating water system	Power reduction
4.	Clogging of traveling screen; reduction of circulating water flow; loss of a feed water pump	Wind, algae, driftwood		Power reduction
5.	Accumulation of plant parts and sediments at the drum screens; degradation of circulating water supply	Flooding, plants	ESWS	Reactor trip
6.	Seaweed: degradation of circulating water supply to service water system	Wind, seaweed	ESWS	Manual shutdown
7.	Plants in the circulating water intake; loss of both trains of nuclear service water system	Flooding, plants	ESWS	INES 2
8.	Birds nest in the switchgear; loss of electrical components	Birds	Switchgear	Power reduction
9.	Algae; clogging of traveling screens, loss of circulating water pumps	Algae	ESWS	Power reduction
10.	Ingress of mussels; degradation of CCWS, cooling of emergency power diesel sets and condenser	Mussels	Component cooling system, emergency diesel	Power reduction
11.	Crustaceans; loss of two circulating water pumps and two feed water pumps	Crustaceans	Circulating water system	Reactor trip
12.	Fish; clogging of traveling screens of circulating water system , loss of main condensate flow	Fish	Circulating water system	Manual shutdown
13.	Jellyfish intake structure; loss of circulating water pumps	Jellyfish	Circulating water system	Manual shutdown
14.	Crustaceans; corrosion and leakage in nuclear service water system	Crustaceans	ESWS	Manual shutdown
15.	Seagrass in condenser inlet boxes	Wind, rain, seagrass		Reactor trip
16.	Control valve of steam generator blocked with mussels; waste DE- level	Mussels	Feed water system	Reactor trip
17.	Mussels in the heat exchanger of the cooling system of the diesel engine	Mussels	Diesel	Low
18.	Fish in intake structure	Fish	Circulating water system	Manual shutdown
19.	Fish in the intake structure, shutdown of 2 of 6 circulating water pumps	Fish	Circulating water system	Manual shutdown

20.	Service pumps intake piping uncovered; loss of service pumps	Low tide, fish	ESWS	Power reduction
21.	Fish clogging with ice formation in circulating water intake; loss of auxiliary power transformer	Fish	Switchgear	Power reduction
22.	Mussels in essential service water system; clogging of residual heat removal system heat exchangers	Mussels	Residual heat removal system	Low

Table 7: Compilation of Worldwide Events, and their Effects

Biological Influences		Number of Events
Fish		5
Seagrass		4
Mussels		4
Crustaceans		2
Jellyfish		2
Algae		2
Plants		2
Birds		1
	sum:	22
Effects		**Number of Events**
Manual shutdown		8
Power reduction		8
Reactor trip		4
Low		3
	sum:	23
Affected Systems		**Number of Events**
Residual heat removal chain		8
Essential service water system		6
Component cooling water system		1
Residual heat removal system		1
Circulating water system		8
Feed water system		3
Switchgear		2
Diesel generator		2
	sum:	31

Table 8 provides a list of combined events that happened worldwide and compiled in the IAEA IRS database. Most of them are not biological related events. The most common combination of biological events is wind or flooding or rainfall with biological influences (see Table 9).

Table 8: List of Worldwide Combined Events

#	Short description	Causes	Affected systems	Effects
1.	Malfunction of a screen unit; damage to an essential service water pump; low auxiliary service water flow	Rainfall, driftwood	Essential service water system	Low
2.	Ingress of rain water into the reactor building and turbine building, partial subsurface erosion and subsidence	Rainfall, substrate shifting	Rain water drainage system	Minor contamination in controlled area

#	Short description	Causes	Affected systems	Effects
3.	Flooding und inoperability of the CCWS	Earthquake, flooding	Component cooling water system	Reactor trip, loss of offsite power, start of emergency power diesel
4.	Destruction of a heavy oil tank of auxiliary steam generator	Earthquake, flooding	Service Auxiliary System	Reactor trip
5.	Flooding of battery room. Release of a small amount of radioactivity outside of the control room	Earthquake, flooding		Reactor trip, loss of offsite power, start of emergency power diesel
6.	Flooding of an essential service water pump	Earthquake, flooding		Reactor trip, loss of offsite power, start of emergency power diesel
7.	Investigation into the effects of the earthquake. Risk of building subsidence	Earthquake, substrate shifting		Integrity of pipeline of both trains of essential service water system jeopardized
8.	Ingress of debris into circulating water intake, loss of drum screen	Rainfall, debris, seagrass		Power reduction
9.	Entry of seagrass, inoperability of two redundancies of the circulating water supply	Wind, seagrass		Power reduction
10.	Clogging of traveling screen; reduction of circulating water flow; loss of a feed water pump	Wind, algae, driftwood		Power reduction
11.	Accumulation of plant parts and sediments in to the drum screen; degradation of the circulating water supply	Flooding, plants		Reactor trip
12.	degradation of circulating water supply through ingress of debris and sediment into the filter and screen unit	Rainfall, wind, driftwood		
13.	Seaweed: degradation of the circulating water supply to the essential service water system	Wind, seaweed		Manual shutdown
14.	Plants in the coolant inlet; loss of both trains of the nuclear service water system	Flooding, plants		Manual shutdown
15.	Fire in house transformer	Earthquake, flooding		
16.	Loss of the main transmission lines from the four units during freezing rain; Loss of off-site power supplies	Rainfall, low temperatures, wind		Reactor trip
17.	actuation of hi-hi steam drum level protection	Rainfall, flooding		Reactor trip
18.	Safe shutdown following tsunami strike	Earthquake, flooding		Reactor trip
19.	Partial flooding of the plant, due to sudden clogging of the outlet of the cooling tower, induced by concrete beam rupture	Driftwood, flooding		Power reduction
20.	*Loss of service water system*	Wind, driftwood		
21.	Seagrass in condenser inlet boxes	Wind, snow storm, seaweed		Reactor trip
22.	Total loss of offsite power	Wind, rainfall		Start of EDG´s. Loss of all off-site power supplies

#	Short description	Causes	Affected systems	Effects
23.	Total loss of AC power	Wind, rainfall		Start of an EDG. Loss of all off-site power supplies
24.	Power failure on transmission grid	Driftwood, low temperatures		Power failure on transmission grid
25.	Fish; uncovery of essential service water pump suction line; loss of essential service water pump	Low tide, wind, biological impacts		Power reduction
26.	Flooding of the pump house. Loss of essential service water pump.	Rainfall, flooding		Manual shutdown
27.	Rainfall, flooding, potential damage to essential service water pump	Rainfall, flooding		Manual shutdown
28.	Fish clogging with ice formation in the circulating water intake; loss of house transformer	Low temperatures, biological impacts		Start of an EDG. Power reduction
29.	Clogging of coolant supply	Low temperatures, wind		Power reduction
30.	Water infiltration into underground rooms housing spent resin storage vessels	Rainfall, flooding		Minor release of radioactivity

Table 9: Compilation of Worldwide Combined Events

Hazard Combinations		Number of Events
Earthquake, flooding		6
Rainfall, flooding		4
Wind, biological influences		3
Flooding, biological influences		2
Rainfall, driftwood		1
Rainfall, biological influences		1
Rainfall, soil changes		1
Rainfall, low temperatures, wind		1
Wind, rainfall		3
Wind, driftwood		1
Wind, rainfall, biological influences		1
Driftwood, flooding		1
Driftwood, low temperatures		1
Low temperatures, biological influences		1
Low temperatures, Wind		1
Earthquake, soil changes		1
Low tide, wind, biological influences		1
	Sum:	30
Effects		**Number of Events**
Manual shutdown		4
Power reduction		6
Emergency shutdown		9
Release of radioactivity		2
Loss of power supply		5
Low		1
	Sum:	27
Affected systems		**Number of Events**
Essential service water system		1
Rainwater drainage system		1
Component cooling water system		1
Service auxiliary system		1
	Sum:	4

4 HAZARDS ASSESSMENT METHODOLOGIES

4.1 Introduction

The overall analysis approach for Level 1 PSA for internal and external hazards depicted by IAEA SSG-3 can be used for the biological hazards. The following figure summarizes this approach.

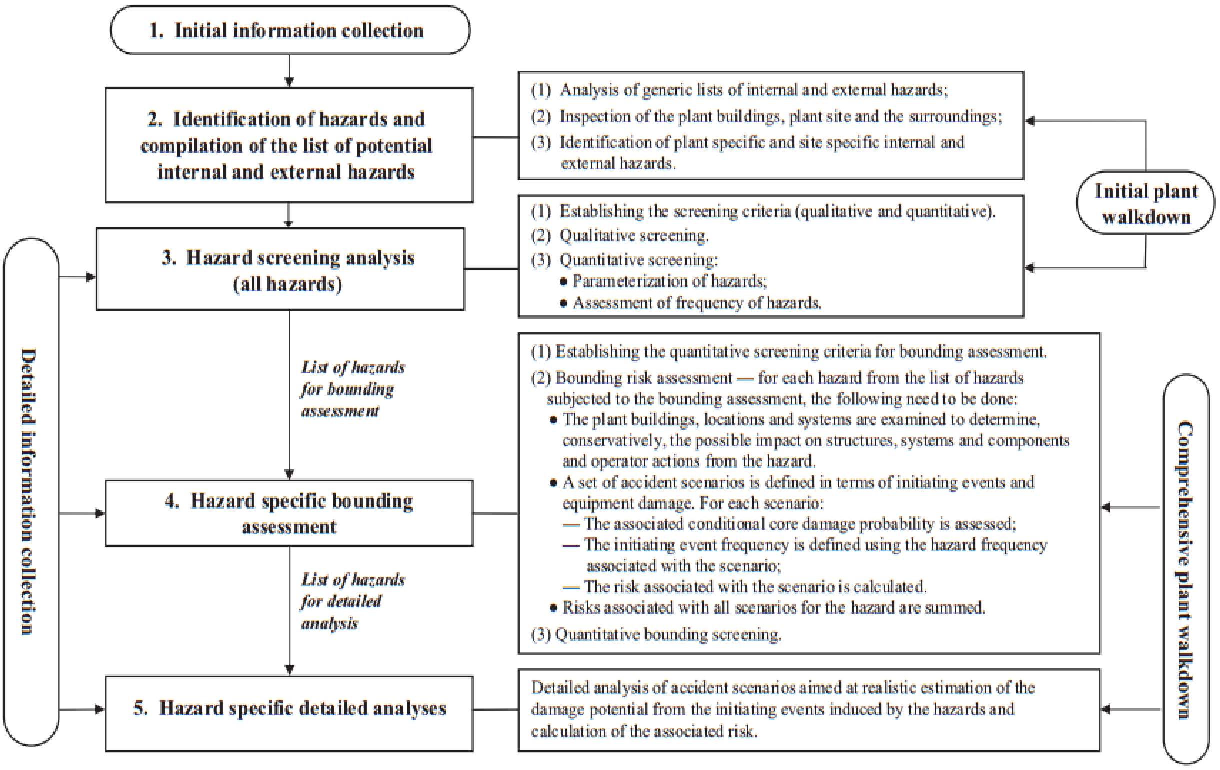

Figure 1: IAEA SSG-3 Overall Approach for Level 1 PSA for Internal and External Hazards

4.2 List of Potential Hazards

Technical report ASAMPSA_E/WP21/D21.1 [28] provides an exhaustive list of biological hazards.

The following is the list of potential biological hazards identified in ASAMPSA_E WP21 [28]:

Water Based:

- N 53 – Marine/river/lake growth (seaweed, algae), biological fouling:
    - The hazard is defined by excessive growth of algae, seaweed, bacteria or else affecting the availability of cooling water from the UHS.
- N 54 – Crustacean or mollusk growth (shrimps, clams, mussels, shells):
    - The hazard is defined in terms of clogging of water intake or outlet by encrusting organisms effecting on the availability of cooling water from the UHS.
- N 55 – Fish, Jellyfish:

- The hazard is defined by the unavailability of the UHS due to clogging of water intake by exceptional quantities of fish/jellyfish or abnormal fish population in the cooling pond.

- N 58 – Biological Flotsam:
  - The hazard is defined in terms of the damage or clogging of cooling water intake or outlet affecting the availability of the UHS by the accumulation of large quantities of flotsam.
- N 59 – Microbiological corrosion:
  - The hazard is defined in terms of damage to the plant by microbiological corrosion.
- Air Based:
- N 56 – Airborne swarms (insects, birds) or leaves:
  - The hazard is defined in terms of damage to the plant due to blockage of air intake by birds or blockage of ventilation systems by leaves or insects in the filters.
- Ground Based:
- N 57 – Infestation by rodents and other animals:
  - The hazard is defined by damage of cables or wires attacked by rodents (rats, mice), and by undermining of structures by burrowing mammals.

Appendix A (Section 11) compares this list of biological hazards (from the technical Report ASAMPSA_E/ WP21/ D21.1) [28] with the biological hazards identified by AREVA.

4.3 Screening

The screening analysis is plant and site-specific. As a result no general result can be brought. Nevertheless, the following section summarizes the most expected results of screening analysis for biological hazards. A specific example is provided in Appendix B, Section 12.

Infestation by water:

Biological infestation by water hazards are in general frequent hazards. They affect mainly the plant intake water systems (pumping station, raw water systems, condenser cooling water system etc.). A number of events of nuclear power plants water intakes plugin or flow reduction by biological materials already occurred. As for example, on 01/12/2009 a massive amount of vegetable materials blocked the entrance to the pumping station of the units 3 & 4 of the Cruas site (See Section 3.2).

The massive biological infestation by water hazard is in general included in the PSA for internal events as part of the loss of last heat sink initiating event. However the initiating event is generally modelled using the internal events PSA basic assumptions (24 hours sequence time, one unit, potential combination of hazards not considered, interaction between reactor and spent fuel pool not considered). Nevertheless the PSA could provide interesting insights on the mitigation strategies of such events induced by external hazards, affecting one plant or the whole site and to evaluate the benefits gained by the safety improvements (especially the modifications implemented in the post Fukushima context).

In general, following the screening analysis for the PSA scope extension, the biological infestation by water hazards cannot be screened out and need to be analysed in detail. Additionally, combinations of hazards involving biological infestation by water need also to be analysed in detail taking into account the possible dependencies (as for example high wind phenomena which may lead to loss of electrical grid and to massive arrival of biological materials into the pumping station intake). Nevertheless, in general, the level 1 PSA related to internal event (as performed in France for example) may be able, with minimum of adaptation, to deal with these kinds of hazards.

Infestation by air and infestation by ground

The swarms of insects or birds can affect the air intakes of ventilation systems or of the Diesels (blocking or reducing the air flow). In general, this kind of hazard is not considered in the existing PSA and is screened out from the external hazards PSA. The hazard screening out is based generally on the absence of the threat at the given site or on the design provisions which allow maintaining a minimum airflow in case of event.

Also, the biological infestation by ground is not treated in the existing PSA and is in general screened out form the external hazard PSA. The screening out is generally based on the operational measures and on the low safety threat of this kind of hazard (based on expert opinion or bounding assessment).

However for the screening out of theses hazards the comprehensive list of potential natural hazards should be considered for the given site. Bounding analysis may be also performed as applicable. The combination of these hazards with other hazard phenomena should be considered, taking into account the possible dependencies (severe weather conditions, high winds, heat wave, drought, etc.; See Section 5)

In the next sub-sections only the biological infestation by water hazards are treated. The methods to evaluate the associated risk with the biological infestation by air or by ground are similar with the methods described in the ASAMPSA_E topical reports.

4.4 Hazard Frequency Assessment for PSA

The frequency of each event, which has been screened-in, needs to be evaluated.

The frequency estimation of biological infestation by water hazards should be based on the operating experience (national or/and international). In this respect, a comprehensive database should be developed and used to support the frequency assessment for these hazards. The database should include all relevant information necessary to support realistic and valid estimations of hazard curves. Historical information on the occurrence of hazards in the vicinity of the site and in the region should be included in the database. The frequency of specific natural hazards should be estimated using both site specific and regional data. When, neither site specific nor regional data are available, worldwide data could be used or phenomenological models (or a mixture of two). In using the worldwide data, the applicability of these data to the site under consideration should be investigated.

In general, for this hazard several cases should be considered, by taking in account the "extent" of the event as for example:

- partial plugging of the intake (or of the raw water systems) of one unit,
- total loss of heat sink of one unit,
- extended events affecting more than one site unit,
- more extended events affecting area sites (nuclear or industrial).

The duration of events of biological infestation by water is one of the most important input data which need to be evaluated. It will depend also on the possibilities to repair and clean-up the pumping station(s).

Also the combinations with other hazards (external flooding, high winds etc.), which can affect the plant or more than one plant (site events, multi-site events, extended area events) should be investigated.

The extended PSA should analyse all the identified cases by appropriate methods (bounding analysis, detailed single unit PSA, detailed multi-facilities PSA).

Section 3 provides some worldwide data that can be used for the assessment of the hazard frequency.

4.5 Bounding Analysis

As stated in SSG-3 [18], bounding analysis may be performed with the aim of reducing the list of external hazards subject to detailed analysis; thereby focusing on the most significant accident scenarios. The bounding analysis should be performed in such a way that it provides assurance that the core damage associated with the specific external hazard is insignificant compared with other hazard sources.

In the bounding analysis, all potential impacts of each non-screened external hazard on the nuclear power plant should be considered.

The cumulative contribution of the external hazards subject to the bounding analysis should be calculated and retained in the final results of the Level 1 PSA.

A set of scenarios for the specific hazard should be developed unless all the impacts of the hazard on the plant can be bounded by a single scenario, which is typically not the case.

In the bounding analysis, combinations of external hazards should also be considered.

The bounding estimations should be based on models and data that are either realistic or demonstratively conservative. Such models and data include:

(a) Assessment of the frequency of hazards (i.e. estimations of the frequency of exceedance of particular intensities);

(b) Analysis of the impact of hazards on the plant (i.e. loads associated with the hazard);

(c) Analysis of the plant response (i.e. fragilities);

(d) Level 1 PSA models and data, etc., for the plant.

For the situations which associated risk cannot be estimated by bounding assessments (results too conservative or method not appropriated) a detailed analysis need to be performed. However the results of bounding analysis need to be counted in the global risk.

4.6 Detailed Analysis

4.6.1 Consequences on the Installation

The impact on a nuclear power plant from either a single biological external event or a combined external event including a biological hazard generally falls within the following categories:

- damage on the plant structures,
- loss of the offsite power,
- loss of the ultimate heat sink,

- impact on HVAC system.

The objective of the analysis is to identify those structures, systems, and components that are susceptible to be affected by the external hazard.

The analysis should not be limited to on-site structures but should include off-site structures, which may have an impact on the installation safety.

An example of analysis provided by AREVA is presented in Appendix C (Section 13).

4.6.2 Fragility Analysis (Plant Response)

The objective of the fragility analysis is to determine the plant-specific failure probabilities of the structures, systems, and components that are affected by the external hazard as a function of the intensity of the hazard.

The fragility of structures and components should be evaluated using plant specific information to the extent necessary for the purpose of the analysis (bounding analysis or detailed analysis).

The fragility analyses should be supported by a plant walk down.

All realistic failure modes of structures and components that interfere with the operability of the equipment should be identified through a review of the plant design documents and a plant walk down.

Fragilities should be evaluated for all relevant failure modes of structures (as for example for the water screening systems: plugging, overturning, drift).

The fragility analysis should also treat the potential additional effects of the biological infestation by water hazards, like internal flooding, heavy equipment drifts. In general for this type of hazards, the evaluation of fragility of SSC (failure probability in given conditions) can be performed by using simple and conservatives approaches.

4.7 Integration in the Level 1 PSA Model

4.7.1 General Approach

The Level 1 PSA model for internal initiating events is practically always used as a basis for the Level 1 PSA model for external hazards. The Level 1 PSA model should be adapted from the Level 1 PSA model for internal initiating events in order to incorporate aspects that are specific for the biological infestation by water hazards.

The impacts of the hazard that could lead to different classes of internal initiating should be assessed in the selection of the appropriate event tree from the PSA model for internal initiating events, which have to be adapted in order to incorporate the hazard specific aspects. If the specific initiator was not developed in the internal events PSA a specific event tree should be developed.

The appropriate hazard curves, and fragilities of, structures, systems and components involved in the mitigation (or support) should be incorporated in the Level 1 PSA model for external hazards. All important dependencies, correlations and uncertainties associated with the specific hazard should be accounted for in the Level 1 PSA model for external hazards.

The internal events PSA should be completed with aspects which, possibility, were considered negligible for the internal events, but which may be important in case of loss of heat sink such as:

- ventilation systems,
- I&C and control room conditioning systems,
- interaction between the reactor and spent fuel pool,
- water reserves.

The possible induced effects of the hazard, like internal flooding or drift of heavy components should also be analysed and incorporated in the PSA model. It is important that the analysis capture the important dependencies among external hazard caused failures (e.g., spatial or environmental dependencies).

The accident sequence times should also be adapted in order to cope with long lasting events and to take into account the inevitable operations (like refilling of water reserves or resupplying with diesels fuel).

The modelling of post-accident human errors should be revised in order to assess the impact of the hazards on the management of the situation (specific procedures, impact on the site infrastructures and the on-site emergency management) as well on the operator actions modelled in the Level 1 PSA for internal initiating events.

Warning time available to take mitigating steps should be analysed and taken into account (plant initial stated, human actions, preventive means reliability).

Also the credited recoveries and repairing actions should be analysed and adapted. The possible offsite support may be also analysed and integrated in the PSA.

The Level 1 PSA model for the biological infestation by water hazards should reflect the as built and as operated plant conditions.

4.7.2 Example of Methodology (Germany)

For the most cases, a compilation of the equipment list B-EL and dependency list B-DL (B means biological hazard) will probably be necessary. B-EL contains the equipment that is affected by the biological hazard B_i. In other words, all SSCs that can fail or are not anymore available due to the biological hazard and thus give a contribution to the damage frequency. B-EL is established by means of a comprehensive selection process while using plant walk down. The dependency list for each biological hazard B-DL contains the corresponding dependency that have to be considered. B-DL is established by means of a comprehensive selection process while using plant walk down.

Ideally, the occurrence frequency of the initiating event under consideration is already modelled in the plan model by means of a fault tree. Hence, all cooling water pumps could be added in the list B-EL for the occurrence of the biological hazard, e.g. critical algae infestation. This would be done while assuming the blocking of a cooling water circuit leads to failure of the related cooling water pump, and dependencies could be added. E.g. the related groups of circulating water pumps and auxiliary service water pumps could be added in B-DL. Thus, the initiating fault tree could be modified by means of the information of B-EL and B-DL. Finally, the conditional probability of occurrence of the initiating event (here loss of heat sink) caused by the biological hazard algae infestation can be calculated.

In Figure 2, the approach to determine the core damage frequency (or other risk metrics) due to biological hazards is presented. Abbreviations used are explained in Table 10.

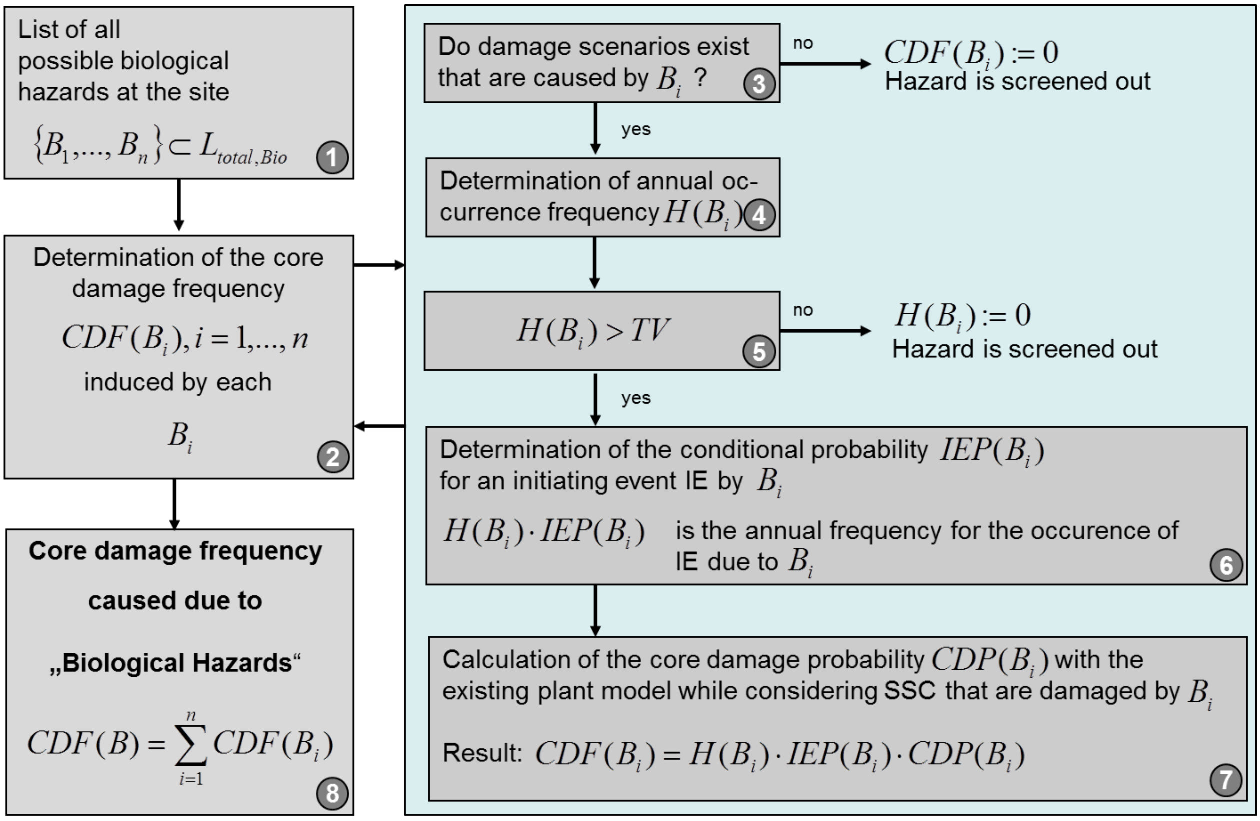

Figure 2: Determination of the Core Damage Frequency Caused by Biological Hazards

Table 10: Abbreviations

Abbreviation	Explanation
B_i	i[th] biological hazard at the site, i = 1, …,n
$H(B_i)$	annual occurrence frequency of B_i (actual curve of exceedance frequency depending on the B_i-intensity levels)
TV	threshold value
$CDP(B_i)$	conditional core damage probability depending on B_i
IE	initiating event
$IEP(B_i)$	conditional probability that the initiating event is caused by B_i
$CDF(B_i)$	annual core damage frequency caused by B_i
CDF(B)	annual core damage frequency caused by the biological hazards occurring on the site
EL	equipment list
DL	dependency list
SSC	systems, structures and components

Step 1:

- In the 1st step of the accomplishment of a site specific Extended PSA, a list L_{total} of all site specific hazards has to be established. This list includes also the biological hazards that can occur at the site. It should be noted that in existing German or international PSA – regarding first researches – up to now not more than two biological hazards ($n \leq 2$) have been considered.

Step 2:

- The conditional core damage frequency has to be determined for all biological hazards of step 1. In the most cases this will be a rough estimation. The determination of the core damage frequency itself and the answering of the question, what is level of details for the analysis, is described in the next steps 3 to 7.

Step 3:

- In this step, the question is asked, whether SSC can be damaged due to the biological hazard under consideration B_i, which could consequently contribute to the risk of the investigated risk metric (here core damage frequency). It is assumed that the biological hazard leads to failure or loss of SSCs. Thereafter, it is to investigate whether this failures or losses can result in initiating events. If this is not the case, the biological hazard under consideration B_i is not relevant and can be screened out (or the induced core damage frequency is zero.) Otherwise, the biological hazard is to be investigated more in depth → step 4

Step 4:

- The annual occurrence frequency of the biological hazard is to be determined, which is a difficult task. A decision for the appropriate intensity level of the hazard has to be taken. The occurrence frequency is to be estimated for every intensity level of the hazard.

Step 5:

- Depending on the overall goal of the analysis, a threshold value *TV* has to be defined. If the occurrence frequency of the biological hazard is less than *TV*, further analysis can be neglected. Otherwise, the biological hazard is investigated → step 6.

Step 6:

- For every intensity level of the biological hazard B_i, the conditional probabilities $IEP(B_i)$ have to be determined for the initiating events IE caused by B_i. Therefore, initiating fault trees can be used. Intensity depended failure probabilities are necessary for the failures of the SSCs of the basic events caused by the biological hazard.

Step 7:

- The calculation of the induced core damage probability for the biological hazard under consideration is carried out with the extended plant model of level 1 PSA. It is required to verify, if SSCs of the plant model can fail due to the biological hazard, and if failure dependencies exist. The examination corresponds to the compilation of the lists *B*-EL and *B*-DL.
  For biological hazards, the lists *B*-EL and *B*-DL will be empty for the most cases. SSC that could fail due to biological hazards are often not included in the PSA plant model, since they mostly cause the failure of SSCs used in operational systems, which are usually not modelled in PSA of level 1. For biological hazards, they are considered in the initiating fault trees.
  For practicability regarding biological hazards and simplification, it is assumed in the formula of step 7 in figure 1 that per each biological hazard B_i only one initiating event occurs. Thus the sum of $IEP(B_i)$ does not have to be considered.

Step 8:

- The core damage frequency caused by all biological hazards is the result of the sum of each analysed biological hazard B_i of the list $L_{total,Bio}$ of site hazards.

4.8 Methods for the Assessment of Hazards Combinations

In terms of hazard combination frequency evaluation, the nature of combination has to be taken into account. As it was derived in [26]: "Hazard *correlations discriminate between: (1) Causally connected hazards (cause-effect relation) where one hazard may cause another hazard; or where one hazard is a prerequisite for a correlated hazard. (2) Associated hazards which are probable to occur at the same time due to a common root cause*" and in additional, hazard combinations of independent phenomena have been denoted".

IAEA Fault Sequence Analysis (FSA) Methodology

IAEA developed a complementary safety analysis FSA methodology and supporting tool to assist in evaluation of the impact of extreme events on NPPs [21] [22]. 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 [22].

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 [22].

Extreme Event Analyzer (EEA) Methodology

Lloyd's Register Consulting (LRC), in cooperation with IAEA, has further developed the FSA method [23]. LRC developed a value added tool (ExtremeEventAnalyzer (EEA)) to systematically analyze the accident scenarios not explicitly addressed in the design extension conditions using integrated deterministic and probabilistic approaches. The tool has incorporated lesson learned from FSA methodology developed by IAEA, which has been verified by application on Goesgen-Daeniken NPP (Switzerland) and Medzamor NPP (Armenia).

This method utilise an internal initiating events PSA model for assessing the impact of extreme events, including the consideration of hazard susceptibility limits of SSCs and impact of extreme external hazards. In EEA method, a number of extreme events (including credible combinations) can be postulated, for example seismic, water levels, extreme temperature, weather conditions etc. The extreme event analysis is linked directly to the PSA model (in RiskSpectrum) to ensure that the whole PSA model is included in the evaluation of the impact of the event or combinations of events. The EEA perform re-quantification of the PSA model including the hazard susceptibility limits of the SSCs. The outcome of the analysis is to [23] [24]:

- Identify sensitive scenarios for extreme events;
- Analyse simultaneous extreme events;
- Prove robustness of plant design, for individual components and for buildings.

Below is a list of sequential steps to perform while using the EEA method to identify scenarios sensitive for extreme events [23]:

1. Determine what hazards to include. This will be site specific and screening criteria may be applied.
2. Determine the components, buildings that can be susceptible to the hazards. Plant data collection and plant walk downs 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" that 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.

4.9 Integration in the Level 2 PSA

From Reference [19] (IAEA SSG-4), the interface between Level 1 PSA and Level 2 PSA is where the accident sequences leading to core damage are grouped into plant damage states based on similarities in the plant conditions that determine the further accident progression. If the status of containment systems was not addressed in the Level 1 PSA, it needs to be considered by means of so-called 'bridge trees' of the interface between Level 1 PSA and Level 2 PSA or as the first step of the Level 2 PSA.

In order to extend the scope of the Level 2 PSA to include internal and external hazards, their impact on systems necessary for mitigation of severe accidents, including systems that support operator actions, as well as the impact on containment integrity, should be taken into account. This could lead in some cases to the specification of a new set of distinct plant damage states, for example, for the case of earthquakes with the potential to induce containment failure. The system analyst should consider the need to introduce new plant damage states and possibilities for assimilating new plant damage states into existing ones; for instance some containment failures could be assimilated into containment isolation failures [19].

Appendix D (Section 14) provides a discussion and recommendations regarding the definition of Plant Damage States (PDSs), which should be used as boundary conditions in the Level 2 analyses for the biological infestation hazards.

4.10 Solution to Model – Multi-Units for the Biological Infestation PSA

One of the major challenges to model in PSA the biological infestation by water hazards is the modelling of multi-unit, multi-installation, effects of the hazard. Indeed, if the loss of heat sink is caused by a natural hazard, all the site units may be affected (in particular the units with common pumping station or with neighbouring water intakes).

As for example, for the previous described Cruas event, it must be noted while the cooling by the ESWS at Cruas was totally lost at only one unit, 2 of the 3 other units were also challenged (with partial loss of the ESWS).

The modelling of the impact on multi-units leads to consider in the PSA mainly the following aspects (the example presented here is based on PWR French design):

- the limited availability of water reserves for the secondary cooling, due to common reserves for several units and designed to cope with a loss of the ultimate heat sink at only one unit;

- the impossibility to use the common means on site (as the ultimate site diesel generator or other ultimate devices) by more than one unit at the same time;
- the impact on the human factor, and on the site accident management,
- the impossibility to use back-up by other site units.

The simultaneously impact on the reactor and on the spent fuel pool has also to be considered.

However, the development of the PSA which could take into account the multi-unit, multi-installation aspects is challenged by several issues which need further methodological and guidance developments as well as additional support studies. The analysis of the international operating experience for lessons to be learned from significant events and accidents may be useful in this context. Some examples of the issues, taken from [5], are:

- lack of deterministic safety analyses of multi-unit accidents,
- modelling of single and multi-unit accident sequences,
- consideration of multi-unit common cause and causal dependencies, including functional, human and spatial dependencies,
- consideration of adverse impacts of single reactor/facility accident on other units, thus creating additional multi-unit accident scenarios,
- consideration of operator actions which may be adversely affected by multi-unit interactions,
- consideration of the timing of releases from different units,
- consideration of the radiological contamination of the site which may inhibit operator actions and accident management measures,
- consideration of new end states involving multi-unit accidents and interactions,
- the static PSA modelling approaches may require a re-evaluation of dynamic PSA approaches,
- CCF models and supporting data analysis need to address inter-unit and intra-unit CCFs,
- the human reliability models and analyses need to be improved to address performance-shaping factors unique to multi-unit accidents,
- extension of mission times beyond 24 hours.

4.11 Hazard Assessment Tools

Some tools can be used for hazard assessment. RiskSpectrum® HazardLite [25] (hereafter called ***HazardLite***) is one of them. It is a light tool for assessing hazard risks, e.g. earthquake, tsunami, extreme weather etc. The input to ***HazardLite*** includes definition of initiating events ranges, hazard curves and fragilities. The output is an excel workbook containing the results in form of Basic Events. This excel file can be imported into RiskSpectrum® PSA for further analysis. In addition, if the Monte Carlo method is selected in the analysis, a series of text files will also be generated for uncertainty analysis in RiskSpectrum® PSA.

Appendix E (Section 15) provides more details on this tool.

5 HAZARDS COMBINATIONS

Biological phenomena mainly affect the availability of cooling water from the UHS and the service water system as consequence of excessive growth of algae, mussels or clams, or clogging by exceptional quantities of fish or jellyfish. Very often malfunctions have also been recorded in ventilation systems because of clogging by leaves or insects in the filters. Such scenarios have usually been found to be combined with flooding, which can cause the sudden removal of marine growth (deposited in different areas) and clogging into the water intake, and strong winds which can cause the clogging of air intakes by leaves or insects in unusual seasonal conditions [6].

The most significant risks related to external hazards combination is the combination of strong wind with a high concentration of organic material in the water intake.

A hard stormy wind may lead to a loss of off-site power and remove bottom sediments and debris from the seawater. This phenomenon is especially challenging for the operation of the intake channels, and it may deteriorate the functioning of the residual heat removal systems.

An exhaustive review of biological hazard combination with other external hazards is provided in ASAMPSA_E WP D21.2. Table 11 [28], next page, is extracted from this later reference.

Table 11: Correlation Between Biological Hazards and Other External Hazards

	ASAMPSA_E		N7	N8	N9	N10	N12	N13	N14	N18	N19	N20		N28a	N31	N40	N41	N46		N53	N55
	D21.2 **External Hazard Correlation Chart** **K. Decker & H. Brinkman** **2014-12-15**	**Flooding and hydrological hazards**	Tsunami	Flash flood	Floods from snow melt	Flooding by water routed to the site	Obstruction of a river channel	Canging river channel	Waves in inland waters	Sea: high tide, spring tide	Wind generated waves	Sea: storm surge	**Meteorological events**	High cooling water temperature	Drought	High wind	Tornado	Wind blown debris	**Biological / Infestation**	Marine/river/lake growth	Fish, jellyfish
Biological / Infestation																					
N53	Marine/river/lake growth													↙	?						
N54	Crustacean/mollusk growth													↙							
N55	Fish, jellyfish													↙							
N56	Airborne swarms, leaves															↙	↙				
N57	Infestation																				
N58	Biological flotsam		↙	↙	↙	↙	↗	↙	↙	↙	↙	↙									
N59	Microbiological corrosion													?						↙	

Legend:

A ↗ B	A is prerequisite for B
A ↙ B	B is prerequisite for A
A ↗ B	A may cause B
A ↙ B	B may cause A
A B	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 occurrence are not identified.

6 OPEN ISSUES

One of the major challenges to model in PSA the biological infestation by water hazards is the modelling of multi-unit, multi-installation effects of the hazard which need further methodological and guidance developments as well as additional support studies. Following a biological infestation, all the site units may be affected (in particular the units with common pumping station or with neighbouring water intakes). As for example, for the previous described Cruas event, it must be noted while the cooling by the ESWS at Cruas was totally lost at only one unit, 2 of the 3 other units were also challenged (with partial loss of the ESWS).

Also the methodology for the combination of biological infestation with other hazards (external flooding, high winds etc.), which can affect the plant or more than one plant (site events, multi-site events, extended area events) need to be developed.

7 CONCLUSIONS AND RECOMMENDATIONS

This report covers the assessment of biological hazards. It provides an overview of the available data and available practices in modelling this type of hazard.

First researches in the national and international literature regarding PSA for external and internal hazards shows that probabilistic analyse were very rarely carried out in order to quantify the risk induced by biological hazards even though history has shown that this hazard can happened and can be highly safety significant. Screening out this event must be done with great care.

The overall analysis approach for Level 1 PSA for internal events can be used for the biological hazards with some care to take into impact the nature of the hazard as it impacts many systems at different times and duration. A proposed detailed methodology is described in Section 4.

Nevertheless, there are still some challenges in PSA development and usage for biological infestation, mainly multi-units' impact and hazards combination modelling. Severe biological infestations may impact all the units of a same site at different times and degrees and may happen in combination with other hazards as flooding or strong winds. For instance, combination and correlation of wind and biological infestation could lead to loss of ultimate heat sink and loss of offsite power which need to be considered in PSA modelling.

ASAMPSA_E group recommends that further emphasis be put on these two aspects of PSA modelling: Multi –units' impact and hazards combinations.

Biological phenomena in water and air, including biological contamination should be considered in regulatory requirements on external hazards PSA. Also, slow occurring biological phenomenon required to take appropriate protective action plans with time. Expert judgement is also used if a specific input data is insufficient [27], or when there are no continuous variables to describe the phenomenon (e.g. biological blockage).

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11 APPENDIX A – EXAMPLE OF BIOLOGICAL HAZARDS IDENTIFIED IN WP21 AND BY AREVA

TABLE 1 – List of Potential Single Biological External Events

<table>
<tr><th></th><th>Biological hazards identified in WP21</th><th>Biological hazards identified by AREVA</th></tr>
<tr><td rowspan="5">Water based</td><td>N 53 - Marine/river/lake growth (seaweed, algae), biological fouling.
The hazard is defined by excessive growth of algae, seaweed, bacteria or else affecting the availability of cooling water from the UHS.</td><td rowspan="2">W15 - Growth of organic material in the cooling water system
The event is defined as plant impact due to the growth of organic material in the cooling water system.</td></tr>
<tr><td>N 54 - Crustacean or mollusk growth (shrimps, clams, mussels, shells)
The hazard is defined in terms of clogging of water intake or outlet by encrusting organisms effecting on the availability of cooling water from the UHS.</td></tr>
<tr><td>N 55 - Fish, Jellyfish
The hazard is defined by the unavailability of the UHS due to clogging of water intake by exceptional quantities of fish/jellyfish or abnormal fish population in the cooling pond.</td><td rowspan="2">W 10 - Invasion of organic material in the intake water (fish, jellyfish, biological flotsam…)
The event is defined as plant impact due to organic material in intake water.
The following sources of blocking material are considered in the quantitative model:
- Algae
- Other organic or inorganic material in sea bottom that can loosen in a e.g. Typhoon or Tsunami (sea garbage)
- Fish, Jellyfish</td></tr>
<tr><td>N 58 - Biological Flotsam
The hazard is defined in terms of the damage or clogging of cooling water intake or outlet affecting the availability of the UHS by the accumulation of large quantities of flotsam.</td></tr>
<tr><td>N 59 - Microbiological corrosion
The hazard is defined in terms of damage to the plant by microbiological corrosion.</td><td>W11 - Microbiological corrosion
The event is defined as an impact on the integrity of the plant due to corrosion and accelerated ageing of steel structures which have no imaginable impact on the power plant.</td></tr>
<tr><td rowspan="2">Air based</td><td>N 56 - Airborne swarms (insects, birds) or leaves
The hazard is defined in terms of damage to the plant due to blockage of air intake by birds or blockage of ventilation systems by leaves or insects in the filters.</td><td>A27 - Invasion of leaves or insect in the filters of the ventilation system
The event is defined as plant impact due to the invasion of organic material on the ventilation system of the plant. The material may be leaves or insects.</td></tr>
<tr><td></td><td>A26 - Massive fall of birds or insects on the grid
The event is defined as plant impact due to the crash of organic material on the external power supply. The material may be birds or insects.</td></tr>
<tr><td>Ground based</td><td>N 57 - Infestation by rodents and other animals
The hazard is defined by damage of cables or wires attacked by rodents (rats, mice), and by undermining of structures by burrowing mammals.</td><td>G3 - Cutting of grid components or I&C cables by rodents or other animals
The event is defined as plant impact due to the attack of I&C cables. The material may be rodents or bacteria.</td></tr>
</table>

12 APPENDIX B – EXAMPLE OF SCREENING ANALYIS

In the frame of a PSA, AREVA consider biological hazards together with all the other external events. The same methodology is applied regardless of the event´s category.

This methodology is based on the reference [7] and involves the two following main steps:

- the identification of a complete list of single and combined biological external events and
- the screening process of these events based on screening specific criteria.

During the deterministic screening, the single and combined potential external events, which do not cause any initiating event in the frame of a Probabilistic Safety Analysis, are screened-out. Only the events having an impact on the plant leading to a transient or a plant shut-down remain.

12.1 Screening Criteria for Single External Events

The screening criteria for single external events can be separated in two distinct categories:

The relevancy screening, which allows screening out the potential external events which are not relevant to the site, which means that they cannot occur at the site or in its relevant surroundings or that their strength is evidently too low. The events screened-in during this step are considered to be "site-relevant".

The impact screening, which allows screening out the potential external events which do not have a possible impact on the plant. The events screened-in during this step are considered to be "plant relevant".

The following criteria in Table 2 from the reference [1] are considered at AREVA:

Table 12: Screening Criteria for Single External Events

C1/Severity *Site-related screening criteria*	C2/Frequency *Site-related screening criteria*	C3/Distance *Site-related screening criteria*	C4/Inclusion *Impact screening criteria*	C5/Warning *Impact screening criteria*	C6/ Applicability
Screened-out if: The event has a damage potential that is less or equal to another event that the plant is already dimensioned for.	Screened-out if: The event has a considerably lower frequency of occurrence than events with similar uncertainties and cannot result in worse consequences.	Screened-out if: The event cannot occur close enough to the plant to affect it.	Screened-out if: The event can be included in the definition of another event.	Screened-out if: The event develops in such a slow rate that there is enough time to initiate counteractions.	Screened-out if: The event is not applicable to the site because of other reasons.

12.2 Screening Criteria for Combined External Events

The number of possible combinations is too high to allow an analysis of every combination. Therefore, there is a need for an initial relevance screening before doing it. Thus, a suggested set of selection criteria must be defined to identify the single events which are relevant candidates to be considered as part of events combinations.

The following criteria to identify relevant combination of external events based on the single external event screening results are usually considered at AREVA:

Table 13: Pre-screening Criteria for Combined External Events Considered at AREVA

Can be consider as potential initiator in event combinations	Can be consider as potential subsequent events in event combinations	Can be considered as not relevant for a combination
Those single events which have been screened-in in the single events screening analysis **OR**	Those single events which have been screened-in in the single events screening analysis **OR**	Those single events which have been screened-out using the criteria“C3/Distance” or “C6/Applicability”
Those single events which have been screened-out in the single events screening analysis using the screening criteria “C1/Severity” or “C4/Inclusion”.	Those single events which have been screened-out in the single events screening analysis using the screening criteria “C1/Severity”, “C2/Frequency” and “C4/Inclusion	

After identifying the single events which can be considered as candidates for events combinations and the impact resulting from these combinations a summary table can be established to gather the potential combinations of external events.

Then the following criteria can be applied for the screening analysis of the combinations pre-selected.

Table 14: Screening Criteria for Combined External Events

M1 / Definition	M2 / Independence	M3 / Impact	C1 – C6
Screened-out if: The multiple events are included in the definition of a single event, which is already analyzed for the plant	Screened-out if: The events occur independently of each other in time **AND** The probability of simultaneous occurrence is low, i.e., below single event frequency screening criteria C2	Screened-out if: The events do not occur independently in time (see criterion M2) **AND** The events affect the same plant safety function **AND** The combined effect on the safety function is not greater than the effect from the most severe of the single events involved	Screened-out if: Any of the single external events criteria apply to the potential multiple events

12.3 Expected Results on Biological Hazards

The screening analysis is plant and site-specific. As a result none general result can be brought. Nevertheless, the following section summarizes the most expected results of screening analysis for biological hazards.

The C2/Frequency criterion is not considered as an exclusion criterion in this section because it can only be performed after estimation of the event frequency which is out of scope of this report.

The following sub-section provides an example of screening used by AREVA. The equivalent biological hazard number used in ASAMPSA_E WP21 is provided when applicable, e.g. A27 (AREVA) and N56 (WP21).

12.3.1 A26 – Massive Fall of Birds or Insects on the Grid

The loss of offsite power due to birds impact has usually an extremely low frequency of occurrence and is covered by the frequency of the initiating event (LOOP) considered in the internal events level 1 PSA.

Excluded	C1/Severity	C2/Frequency	C3/Distance	C4/Inclusion	C5/Warning	C6/Applicability
☒	☒	☐	☐	☐	☐	☐

The event “Massive fall of birds or insects on the grid” can usually be excluded because its impact on the plant is covered by the events ”strong wind” which usually has a higher frequency of occurrence.

12.3.2 A27 – Invasion of Leaves or Insect in the Filters of the Ventilation System (N56)

The ventilation of the safety-relevant systems is usually designed in such way that in case that such an event impacts the HVAC system, these can be switched over into a recirculation mode. For this reason, the impact on HVAC systems is not considered explicitly as a real impact to most plant.

Excluded	C1/Severity	C2/Frequency	C3/Distance	C4/Inclusion	C5/Warning	C6/Applicability
☒	☒	☐	☐	☐	☐	☐

Usually this event is screened-out using the C1/Severity criterion.

12.3.3 G3 – Cutting of I&C Cables or Grid Components by Rodents (N57)

A threat on the safety of the power plant through animals is considered as negligible.

Effects on the plant caused by animals are considered to be covered by transient initiators (e.g., LOOP) and component failures modelled in the internal events PSA (level 1).

Excluded	C1/Severity	C2/Frequency	C3/Distance	C4/Inclusion	C5/Warning	C6/Applicability
☒	☒	☐	☐	☒	☐	☐

This event can usually screened-out with the C1/Severity criterion considering that first of all the access into electrical equipment rooms by rodents or other animals endangering cables and electrical equipment is reliably prevented in the nuclear power plant and second the strict redundancy separation ensures that only one redundancy is affected in such a case. Consequential failures of electrical equipment may lead to partial loss of electrical power supply in the plant and are therefore covered by consideration of a total Loss of offsite power, thus C4/Inclusion criterion applies as well. As a result, there is no potentially safety-relevant impact on the plant.

12.3.4 W10 – Invasion of Organic Material in the Intake Water (N55 & 58)

Excluded	C1/Severity	C2/Frequency	C3/Distance	C4/Inclusion	C5/Warning	C6/Applicability
☐	☐	☐	☐	☐	☐	☐

The relevancy of this biological hazard cannot be generally excluded because of its significant potential impact on the safety of the nuclear power plant. Screening need to be performed based on site specific data on amount and frequency of organic material in the water and the capacity of the water cleaning equipment.

According to NS-G-1.5 [6], the blockage of intake structures and the related system components with foreign matter is the most common cause of impairment of the ultimate heat sink.

12.3.5 W11 – Microbiological Corrosion (N59)

Excluded	C1/Severity	C2/Frequency	C3/Distance	C4/Inclusion	C5/Warning	C6/Applicability
☒	☒	☐	☐	☒	☐	☐

The event "Corrosion effects and accelerated ageing of steel structures exposed to the marine environment by sulphate reducing bacteria" can usually be screened-out using the C1/Severity criterion because the use of sea water as ultimate heat sink is considered in the design of the power plant and thus the piping of the sea water carrying systems is considered as adequately protected against corrosion. Additionally in-service inspections are performed periodically to exclude pipe failures due to corrosion.

Pipe failures are dealt with by internal flooding analyses. Thus, C4/ Inclusion criterion applies additionally.

12.3.6 W15 – Growth of Organic Material in the Cooling System (N53 & 54)

Excluded	C1/Severity	C2/Frequency	C3/Distance	C4/Inclusion	C5/Warning	C6/Applicability
☒	☐	☐	☐	☒	☒	☐

If the plant is equipped with an alert system the event "growth of organic material in the cooling system" can be excluded regarding the Warning criteria (the event develops in such a slow rate that there is enough time to initiate counteractions). The event can also be screened-out with the Inclusion Criteria regarding the fact that its impact on the plant is covered by the impact of W10 "Invasion of organic material in the receiving water".

13 APPENDIX C – EXAMPLE OF INSTALLATION CONSEQUENCES ANALYIS (OLKILUOTO NPP IN FINLAND)

This section presents an example of consequence assessment for OL1, OL2 and OL3 (Olkiluoto NPP in Finland).

13.1 Event Consequences

The impact on a nuclear power plant from either a single biological external event or a combined external event including a biological hazard generally falls within the following categories:

- STRU Damage on the plant structures
- LOOP Loss of the offsite power
- LUHS Loss of the ultimate heat sink
- HVAC Impact on HVAC system
- NONE No actual impact

The following table gathers the possible effects of the biological hazards listed above:

Table 2 - Potential impacts of biological hazards

EE	Name	STRU	LOOP	LUHS	HVAC	NONE
Air-based						
A26	**Massive fall of birds or insects on the grid** The event may impact the off-site power by damaging the switchyard and leading to a LOOP.		X			
A27 (*N56*)	**Invasion of leaves or insect in the filters of the ventilation system** The event may impact the HVAC system by clogging the filters of the system.				X	
Ground-based						
G3 (*N57*)	**Cutting of I&C cables or grid components by rodents** Rodents can trip the electrical system and cause failures of short-circuits by chewing on electrical cables or by getting into equip-ment.		X			
Water-based						
W10 (*N55 & N58*)	**Invasion of organic material in the intake water** The impact may be due to clogging of the intake strainers, or to clogging of heat exchangers in intermediate cooling systems. In the latter case, the material causing the heat exchanger clogging has passed the intake strainers.			X		
W11 (*N59*)	**Corrosion effects and accelerated ageing of steel structures ex-posed to the marine environment** The event may impact the UHS by its potential to deteriorate the			X		

	heat exchanger surface and impair its effectiveness					
W15 *(N53 & N54)*	**Growth of organic material in the cooling system** The organic material formation can block the cooling water intake and lead to a LUHS. The screens do not hold back mussel larvae and the larvae grow - often in considerable amounts - in the piping systems. These mussels can enter the coolers of the plant and reduce their cooling capacity or block the coolers.			X		

13.2 Design Basis

13.2.1 N56 – Invasion of Leaves or Insect in the Filters of the Ventilation System

The filtration capability of the supply air filters will ensure that supply air is filtered to prevent the build up of dust and airborne biological agents (such as pollen).

Furthermore, the ventilation of the safety-relevant systems is usually designed in such way that in case that such an event impacts the HVAC system, these can be switched over into a recirculation mode.

13.2.2 N57 – Cutting of I&C Cables or Grid Components by Rodents

The plant is protected against larger animals by fences. It is assumed that the NPP are not vulnerable to impact from smaller animals, e.g., rodents.

13.2.3 N59 - Microbiological Corrosion

The heat exchangers are adequately protected against corrosion from salt and microbiological organisms.

Furthermore, the plant design considered the effects of corrosion and its pollution, thus by providing of cool water to the several components of the plant and the turbine condenser the direct cooling by the Service Water System is avoided.

13.2.4 N53 54 55 & 58 – Biological Growth or Invasion in the Cooling Water

In the case of loss of normal ultimate heat sink, all plant units have some possibilities to remove the residual heat. Especially precautions have been taken against the cooling water intake blockage due to different impurities in sea water.

The following sub-sections present the impact on OL1, OL2 and OL3 (Olkiluoto NPP in Finland) based on Reference [2].

13.2.4.1 OL1&2 Design

Phenomena leading to seawater channel blockage have been taken into account in the design of nuclear power plants by installing a seawater screening system that mechanically removes impurities before seawater is routed into the cooling water channel.

To prevent the collapse of the cooling water channel, structural requirements of the cooling water channel have been defined based on land use at ground level.

On OL1&2 the sea water inlet is equipped with coarse and fine intake screens as well as travelling basket filters that will prevent fish and other foreign matter from being sucked into the water pumps and heat exchangers.

13.2.4.2 OL3 Design

On OL3 the cooling water intake is protected against floating objects by the trash racks in the intake structure, and additional mechanical cleaning equipment in the inlet of the circulating water pump building.

OL3 will be provided against seaweed, jellyfish and algae in seawater:

- Manual cleaning of the intake screens in the circulating water intake structure
- Monitoring of circulating water screening plant equipment by differential pressure measurement
- Automatic cleaning of the screening plant in circulating water pump building; additional manual cleaning can be performed.

If the cleaning of the screens cannot ensure sufficient water supply for normal operation, the plant will be shut down in accordance with the operating manual. Consequential loss of offsite power in conjunction with marine life is not assumed because marine life has no effect on the offsite grid.

13.3 Estimation of Safety Margin for OL1, Ol2 and OL3

13.3.1 N53 54 55 & 58

Presuming that all countermeasures against biological impurities above have failed, the following features are considered.

13.3.1.1 OL3:

If the sufficient water supply during normal plant operation cannot be ensured, the circulating water pumps will be switched off. After the trip of the circulating water pumps, a sufficient water supply for the ESWS pumps will remain. The required flow rate for all trains of the essential service water is lower than 8% of the required flow rate for all cooling water systems. The flow rate for all cooling water systems is even ensured in case of operation of 3 active cleaning lines (preventive maintenance of one screening plant). Due to this low required flow rate for essential service water, a sufficient free screen surface will be available for this water demand, even in case of the loss of the active cleaning function of the whole screening plant.

If the entire cooling water inlet is unavailable due to blocking, the ESWS pumps can be supplied with cooling water through the connection from the circulating water seal pit to the circulating water pump building supplying the essential service water pump buildings. The flow direction is reversed, from the circulating water outfall rock tunnel for at least two redundancies of service water. This connection needs to be opened manually.

The ESWS outlet lines will be switched over to the intake channel via an alternative outlet line (anti-icing line). This is established for all ESWS trains. The switchover can only be carried out when the anti-icing pumps are not in operation. The anti-icing line is designed for a flow of approx. 3000 kg/s (2 of 3 pumps in operation). According to the safety requirement only two lines are needed.

13.3.1.2 OL1&2:

If the cooling water channel intake side is blocked, the water level decreases in the channel between the blockage and the cooling water pumps. This creates an alarm in the cooling water screening plant, which trips the cooling water pumps of the turbine condenser. At the same time, hatches will open in the cooling water channels causing a recirculation of water for the service water system pumps. Due to the rather small volume of recirculated water, the temperature of the water increases. Within one hour, the cooling water intake must be switched to the outlet channel.

During the recirculation with the intake blocked, water surface in the screening plant will rise, and the difference in level will work to remove the impurities that caused the blockage. If the impurities cannot be removed, water level will rise to a level of +3.5 m. This may cause flooding in the cooling water screening plant building, and further, in the auxiliary cooling water pump rooms. From here, the water can be discharged through the doors to the yard outside the plant unit. This will not damage the shut-down service water system pumps.

The water level will lower back to normal, and the normal flow direction in the channels can be restored after the blockage has been removed. After this, the operating state of the cooling water system is restored.

If the water rises to the pump rooms in the auxiliary system building, the water may spread elsewhere in the plant unit. The underground levels may be flooded. There is a small possibility that some water spreads into the diesel generator rooms, either from the inside or outside.

If the inlet tunnel is blocked, it is possible to switch the water intake to the outlet side. In this case the water going to the auxiliary buildings is taken from the water outlet. This provides a sufficient water flow for the safety systems.

13.3.2 N53 – Biological Fouling

13.3.2.1 <u>OL3</u>

Due to the slow flow velocity in circulating water intake rock tunnel, the loose shells from bivalves will mainly sink and accumulated in the rock tunnel. The larvae of the mussels will be transported. The cleaning plant in circulating water pump building will remove loose shells via the coarse and band screens. The larvae can pass through the cleaning plant. The cleaning of the circulating water pump building and its facilities with respect to mussels will be done depending on the amount of mussels.

Each of the four ducts from the UQA building to the service water pump buildings UQB can be isolated separately and manually cleaned.

The ESWS trains are protected against bio-fouling with the following countermeasures:

- Selection of piping material which provide the smoothest surface roughness in order to reduce the attachment of mussels;
- Selection of piping diameter in order to achieve a flow velocity of nearly 2.9 m/s which entrains the mussels and avoids attachment;
- Upstream of the ESWS-CCWS heat exchanger a Taprogge debris filter is installed. The filtered mussels are back flashed to the downstream side of heat exchanger, and further transported to the outlet; and
- Differential pressure measurements are provided for the pumps and the heat ex-changers.

The dedicated ESWS trains are closed during normal plant operation, the part of the system including the heat exchanger and the debris filter are filled with demineralised water, which prevents organic (mussel) growth due to oxygen deficit and the smooth rubber surface in the pipes. The debris filter back flushing sequence will simultaneously be initiated when the pumps will function, thus preventing the clogging the filter.

13.4 Measures which can be Envisaged to Increase Robustness of the Plant Against Extreme Weather Conditions

If the Probabilistic Safety Analysis leads to an unacceptable risk from a biological hazard some plant modifications or improvements may have to be planned to mitigate the risk or reduce its impact.

Regarding the previous analysis, it mainly concerns the potential for blockage of cooling water supply due to organic material in the receiving water or slowly developing effects.

Appropriate site-specifically measures are to be provided to prevent the loss of the ultimate heat sink provided.

Possible failure of filtering or screening devices (e.g. screen damage or opening of by-pass gates) leading to sudden and massive entry of dirt into the cooling systems, particularly in connection with high pollution loads of the receiving water, must also be reliably prevented by taking appropriate measures, e.g. by shutdown of the main cooling water pumps at high differential pressure at the screening devices. If, due to the systems technology installed, a simultaneous failure of more than one cooling train (redundancies) caused by the sudden entry of large pollution loads can no longer be excluded, effective remedial measures are to be provided.

The following measures from the reference [13] and [9] are shown as examples of what it could be done to improve the reliability of the Ultimate Heat Sink regarding these risks:

- it must be possible to monitor the operability of the safety-relevant heat exchangers by an appropriate instrumentation. This also includes the timely detectability of influences which inadmissibly impair the heat transfer of the heat exchangers, e.g. due to fouling, sudden or gradual blocking of the heat exchanger tubes, shell deposits, etc,
- it is important to be aware, through an early warning system, of an impending potential influx of seaweed into the Cooling Water System (CWS) system (based for instance on tidal, wind direction and wind speed indicators) and the need to be clear on the actions to be taken should a large ingress of seaweed occur. The same holds true for the case of water release from upstream dams,
- massive and sudden arrivals of materials at the water intake entrance should be taken into account to define periodicity of the inspection and cleaning of coarse screens or rotating drum screens,
- monitoring maintenance operations, especially analysing the results of de-silting operations (nature, granularity, amount of removed sediment…) should be implemented,
- periodicity and methodology of bathymetry measurements should be able to detect a slow silting-up kinetic,
- regular dredging operations on the intake channel entrance reduce the probability of a total heat-sink loss,
- sufficient protection measures should be in place to avoid ESWS/CCWS heat exchanger clogging and fouling,
- further actions are needed to secure the long term supply of raw water for residual heat removal taking also into account the possibility of an accident affecting more than one unit on the site.

Reference [12] provides guidance on how to deal with biological hazards in the design of specific safety related systems.

14 APPENDIX D - WP40 – LEVEL 2 PSA CONTRIBUTION: INTER-FACE LEVEL 1 – LEVEL 2)

14.1 Foreword

This appendix provides recommendations regarding the definition of Plant Damage States (PDSs), which are used as boundary conditions in the Level 2 analyses, for the biological infestation 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 [15]. The general discussion on definition of PDSs and protocols and recommendations for performing PSA are to be found in the ASAMPSA2 guidelines ([16] and [17]) 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. The only exception is for the “biological infestation” group, for which to our knowledge no specific analysis has been performed or reported to date. For this group, guesses are given, on the basis of potential (or known) infestation incidents.

14.2 Definition of Plant Damage States (PDS) for Biological Hazards Initiating Events

It is assumed in this section that potential biological hazards will have “localized” consequences which propagate plant-wide as is the case of accidents initiated by internal fires hence the discussion is valid also for these initiators.

Since the definition of, and collection of data for the PDSs are tasks that may fall upon different teams that perform the analyses (Level 1 and Level 2 teams), this section is intended primarily for Level 2 experts.

It must be stressed, as was done for analyses of internal events, 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 fuel 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 biological hazards events, 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, 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. The danger is that these systems 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 biological hazards events. The combination of dependent and independent systems failures due to biological hazards events-induced sequences may require the definition of additional PDSs that were not considered possible for internal events. 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.

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

15 APPENDIX E - RISKSPECTRUM® HAZARDLITE

A probabilistic safety assessment of an external hazard is different from analysis of internal events e.g. seismic hazards. The differences are mainly that:

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

HazardLite is applied in seismic hazard and could be applied to other external hazards in similar manner. An example from HazardLite methodology and its application in seismic fragility analysis and PSA is discussed below:

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

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

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

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

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

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

The quantification algorithm is described by following:

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

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

Quantification of hazard, initiating events, point estimate calculation

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

Fragility

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

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

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

Where:

- (Φ) is the standard Gaussian cumulative distribution
- a is the PGA
- A_m is the median capacity of the component
- β_R is the random variability (the randomness w.r.t. the earthquake)
- β_u is the state of knowledge uncertainty (uncertainty of fragility curve shape)
- Q is the confidence that the conditional probability of failure, f, is less than f´ for a given peak acceleration a.

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

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

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

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

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

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

Assume following cut set

H_1, F_1, B

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

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

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

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

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

$$F_{i,h_k} = \frac{\sum_{j=1}^{100}(h_{ij} \cdot f_{ij})}{\sum_{j=1}^{100} h_{ij}} \qquad (5)$$

Where:

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

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

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

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

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

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

Where:

W_{hk} is the weight of hazard curve k

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

Component groups and combinations

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

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

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

Combination

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

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

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

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

Uncertainty calculation

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

The method is:

- randomly select one of the hazard curves (according to its weight),
- randomly select one of the fragility curves in the group of fragility curves (for each component),
- calculate the hazard frequencies for all defined intervals,
- calculate the fragilities for all intervals, under the condition of the selected hazard curve (convolute with the selected hazard curve only),
- calculate Component groups and combinations,
- perform next sampling.