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Abstract

This report is the deliverable of the Task 2.4, "Identification of general risk-significance thresholds of external hazards". Within the scope of the BESEP project, the task focuses on the topics related to probabilistic safety assessment and plant level risk targets connected to the external hazards. Based on the information collected from all BESEP partners, the general risk-significance thresholds of the most important external hazards are identified. Since the spectrum of BESEP partners represent various NPP site conditions (seaside versus inland, warm climate in France versus low temperature weather conditions in Finland and Sweden), the collected information enables an interesting comparison and provides reasonably good coverage of the status-quo in different geographical locations over Europe.

The report consists of two main parts. In the first part (Chapter 2) following the Introduction, risk-significance thresholds are discussed from theoretical point of view with the focus put on the fact, that the new NPPs, sometimes operated on lower level of risk than the older ones, may need to involve and use new risk-significance metrics. Chapters 3 and 4 are devoted to the specific questionnaire survey developed, filled-in and analysed for the purposes of BESEP Task 2.4. Final conclusions are made in Chapter 5, followed by references in Chapter 6.

The collected information described and analysed in this report will be utilised in the specification of case study groups in BESEP Task 3.2 and in the definition of comparison criteria for the cross-group comparison in Task 4.1. It will also provide basic features of the context of NPP operation from the point of view of external hazards impact, which will be used in comparison of case studies performed in Task 4.2, evaluation of balance in verification of safety margins between different external hazards in Task 4.3, selection and evaluation of the best practices in HFE area in Task 4.4 and making recommendations on deployment of more sophisticated safety analyses in Task 4.5.

The report is based on the questionnaire developed for the purposes of this BESEP Task, agreed and filled in by all BESEP partners. The blank questionnaire is described and commented in the report, including the ways it is expected to help the analysis in next BESEP Tasks.

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LIST OF ABBREVIATIONS

BESEP	Benchmarking Exercise on Safety Engineering Practices
CDF	core damage frequency
CCDF	conditional core damage frequency
CCFP	conditional containment failure probability
CLRF	conditional large release frequency
DBA	design basis accident
DEC	design extension conditions
FDF	fuel damage frequency
FV (F-V)	Fussel-Vesely (measure)
HRA	human reliability analysis
IAEA	International Atomic Energy Agency
I&C	instrumentation and control
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LERF	large early release frequency
LRF	large release frequency
NPP	nuclear power plant
PSA	probabilistic safety/risk assessment
PSAR	Preliminary Safety Analysis Report
PSHA	Probabilistic Safety Hazard Analysis
PWR	pressurized water reactor
RAW	risk achievement worth
RG	regulatory guide
RIR	risk increase ratio
RRW	risk reduction worth
SC	safety class
SE	systems engineering
SSC	structure, system, component
NRC	Nuclear Regulatory Commission
WP	work package

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1 Introduction

This report is the deliverable of BESEP Task 2.4, "*Identification of general risk-significance thresholds of external hazards*". Within the scope of the BESEP project, this task focuses on the topics related to probabilistic safety assessment and plant level risk targets primarily connected to the external hazards.

The topic of risk significance is in the focus of the report. Although risk significance has been one of the key aspects in the history of development of plant PSA models and PSA applications in the process of increasing safety of NPP operation (see [1], for example), there are still subjects to be discussed related to the measures of importance. Such discussion is presented in Chapter 2 of this report, mostly based on the conclusions made for NuScale design [2] but considered valid also for some new and even older NPPs in Europe, where the level of risk represented by CDF/LERF dropped down due to new design features or due to numerous measures taken with the aim to increase safety of operating plants. The basic point of the discussion, where the ideas from [1] are used as the basis for possible new approaches to the risk-significance measures, is that the traditional metrics may not fit to the purposes of the processes developed for keeping plant safety at the high level and using the resources for that in an efficient manner.

The conclusions made in Chapter 2 are generally valid, but there are specific features of plant operation typical to the countries and companies of the individual BESEP partners. With the aim of making the collection of this plant/country specific information efficient, a questionnaire was developed within Task 2.4 by the coordination of UJV and in cooperation with all BESEP partners, which was later filled in by all partners. The process of developing and filling in the questionnaire, as well as the scope and structure of the questionnaire itself, are described in Chapter 3 of the report. Since the spectrum of BESEP partners represent various NPP site conditions (seaside versus inland, warm climate in France versus colder temperature conditions in Finland and Sweden), the collected information and the subsequent application in the process of analysis and comparison of selected case studies oriented to risk engineering enables interesting comparison and provides a reasonably good coverage of status-quo in different geographical locations over Europe.

The information given in response to the questionnaire by BESEP partners was studied, compared, and analysed. The results of the analysis are summarized in Chapter 4 of the report, including recommendations how to utilize the analysis results in the next tasks of BESEP.

2 Considerations to redefining traditional risk significance threshold

This part of the report contains an overview of the current status of the concept of risk-significance thresholds as applied in PSA studies and applications. The focus is on the background and goals of the BESEP project.

In Section 2.1, an overview is made regarding risk-significance thresholds in their traditional form and a discussion is given whether these traditional thresholds are supposed to be always suitable for future applications or they need to be modified to better fit the new NPP designs operating on a significantly lower risk level than the NPPs of older design. This discussion is important from the point of view of the BESEP project, where several partners representing different NPPs across Europe provide information for case studies representing possibly different levels of risk of plant operation.

Section 2.2 focuses on risk-significance thresholds related to external hazards risk, one of the main subjects of the BESEP project. The aim of the section and later described data is to link them with the residual risk originating from the extreme values of natural and human induced hazards in order to better understand and characterize the role of such extremes in plant safety.

In Section 2.3, the approach used for collection of information about risk-significance thresholds in BESEP is described. The collected information covers not only the threshold related facts, but also primarily the connection of risk-significance thresholds with extreme values of natural phenomena representing risk-significance levels of external hazards impact. This connection is very important for the future tasks of BESEP, where the risk impact of external hazards is going to be studied.

2.1 Risk-significance thresholds in PSA studies

In the Benchmark Exercise on Safety Engineering Practices (BESEP) project, the safety engineering processes running in several countries are benchmarked in support of assessing safety margins and verifying safety requirements. Since the levels of operational risk may differ from country to country due to differences in plant design and the way, the plants are operated, there is a question, whether the traditional risk-significance levels are flexible enough to cover these differences.

The purpose of this chapter is to describe an approach for determining risk significance in the context of the PSA and to provide the basis for the approach and relevant criteria. It includes:

- a discussion of the current risk-significance criteria and why they may be inappropriate for broader comparison of various NPP designs;
- an example of how alternative criteria may be used for:
    - criteria based on an absolute evaluation of the RAW importance measure;
    - criteria based on the FV importance measure;
- the basis for the alternative criteria, including a comparison to safety goals, for new reactors with lower level of risk in particular.

The points of view presented here relate to the methodology for identifying the elements in the PSA model as candidates for risk-significance. They may be applied also to the PSA for internal hazards and external hazards. They address all plant operating modes, including low-power and shutdown. They cover the background of the analysis of both CDF (i.e., Level 1 PSA) and LRF (i.e., Level 2 PSA).

The following equations (1) and (2) provide details on how the traditional risk-significance measures RAW (or the risk increase ratio RIR) and FV importance are calculated

$$RAW = R_1 / R_b, \quad (1)$$

where R_1 is probability of top event if a certain element of the PSA model (e.g. a basic event) is set true (i.e. failure probability equals 1), or conditional CDF (CCDF), or conditional LRF (CLRF)); R_b is baseline PSA risk metric (i.e., CDF or LRF).

$$FV = 1 – R_0 / R_b, \quad (2)$$

where R_0 is decreased risk with basic event or some other suitable element of the PSA model set false (i.e., 0.0, perfectly reliable), R_b is baseline PSA risk metric (i.e., CDF or LRF).

The criteria and the terms used in the equations in this chapter are consistent with the definition of significance in [8].

2.1.1 Thresholds based on absolute risk metrics

The current designs, significantly employing passive systems, diversity principles etc., result in risk estimates that are significantly lower than those related to the plants operated for decades. In order to reflect the benefits of global improvements in safety in risk significance determination, including those following evaluation of risk contributions of external hazards, new thresholds may be needed, which may be based on an absolute risk metric.

The existing thresholds for identifying risk significance, measured as a ratio to the total CDF or LERF, while appropriate for the fleet of large operating NPPs built some time ago, may not be appropriate for new designs. For the current fleet of NPPs operated over Europe, CDFs are typically in the order of 1×10^{-5} per reactor year. With a baseline CDF of 1×10^{-5} per reactor year, using the relative risk metric of a RAW = 2 implies a change in CDF of 1×10^{-5} per year; and a component is risk-significant if its CCDF is equal to or greater than 2×10^{-5} per year.

It may be in contrast to new designs, where a CDF of the order 1×10^{-6}/ year (or even 1×10^{-7}/year) may be the target and RAW=2 means that the CDF increases by only 1×10^{-6}/year (or 1×10^{-7}/year). In such case, the component is considered as risk significant if CCDF related to it is only 2×10^{-6} or 2×10^{-7} /year, values that are much lower than those for the operating fleet. Consequently, when using a relative risk metric such as RAW, a plant with a baseline CDF of 1 x 10^{-5}/year would allow an increase in CDF of 1 x 10^{-5} per year, whereas a much safer plant with a baseline CDF of 1 x 10^{-6} (or even 1 x 10^{-7}) per year would only allow an increase of 1 x 10^{-6} per year (or even 1 x 10^{-7} per year) after which the item would already become risk significant.

As the frequencies of core damage (and large release) become smaller and smaller, the uncertainties associated with those frequency estimates become relatively larger. Assuring completeness in the PSA becomes more challenging when dealing with such low frequency events. At the relatively high frequencies associated with the older generation of plants, there can be reasonable confidence that the dominant contributors and the drivers of the risk profile (i.e., those events that influence the risk the most) have been reasonably identified and accounted for. For the low event frequencies associated with new designs, assuring complete accounting of all the significant contributors has become more problematic.

At such low frequencies (i.e., less than one-in-a-million-years events), relevant external hazards are much more difficult to be identified (including both natural hazards and man-made hazards). At these low frequencies, natural disasters that have potentially global consequences such as asteroid impact and super-volcanoes, and inherently unpredictable human errors of commission (both intentional and unintentional), could well become the important or even dominant risk contributors. The consequence of this fact is that, while there can be reasonable confidence that the risk of plant operation is very low, there should be more scepticism in identifying the dominant contributors to that very low risk, since the subtle changes in assumptions, conservatisms or including/excluding selected very rare events, external hazards related in particular, can significantly change the plant risk profile. Relying on this risk profile by using relative importance measures to guide the expenditure of resources may not be a particularly effective or efficient strategy.

With the uncertainties associated with such small risk estimates, using absolute metrics would provide assurance that the risk (albeit uncertain with respect to the dominant contributors) will remain low. Specifically, when assessing changes to an already very low CDF, the use of absolute metrics provides confidence that any “non-significant” change in risk will result in the risk remaining very low.

Although the criteria based on relative metrics are broadly used in the current risk-oriented decision making, the use of absolute metrics is not new. For example, in NUREG/CR-3385, “Measures of Risk Importance and their Applications” [3], RAW values and risk reduction worth (RRW) intervals were used to evaluate the importance of safety functions and containment for four NPPs. The Birnbaum importance measure, which was defined several decades ago, is also an absolute risk measure. The following formula (3) provides details of how the $RAW_{interval}$, also called the risk increase interval (RII), is calculated

$$RAW_{interval} = R_1 - R_b, \quad (3)$$

where R_1 is increased risk with basic event set to true (i.e., 1.0, failed), or CCDF, or CLRF, R_b is baseline PSA risk metric (i.e., CDF or LRF).

While the ratio and interval definitions generally give the same risk rankings for plant SSCs, the interval definition is more appropriate for cost-benefit evaluations, or when different plants are compared. The use of an interval measure of importance will also address some of the limitations of ratio-based importance measures since these traditional importance measures may be insensitive to global improvements in safety. If the results of using universally fixed FV and RAW criteria were compared in the case studies made in past; even though several protection systems were added, thereby reducing reliance of plant operation safety on the original system, and reducing overall risk, the importance measures did not really change very much.

It can be generally seen that the absolute value of risk may be also critical for the decision-making acts, opposed to the importance measures that are based on the relative risk value only. It seems that in reducing the frequency of accident sequences that dominate new plant designs, the traditional FV and RAW based criteria artificially raise the importance of traditionally less important SSCs. Therefore, it may be appropriate to use the $RAW_{interval}$ as an absolute measure in the determination of risk significance. The point is that for some relatively large CDF, the analysis and consequent measures taken (investment into the design etc.) to decrease the risk may have a significant impact on the total risk (what is the goal). However, as soon as sufficiently low total risk has been reached, the parameters/measures/criteria based on relative risk may still provide candidates for further investment into risk reduction, which is going to be relatively low taking absolute values into consideration. This may be an interesting topic for the discussion within BESEP project later.

In general, one of the goals of the risk informed decision-making community should be that the criteria used to determine risk significance should be consistent and suitable for broad spectrum of designs and should address real absolute levels of overall plant risk. In the new plant designs, with very low estimated frequencies of core damage and large releases, a large number of SSCs may be identified as risk-significant using the criteria based on relative values and an inappropriately large population of SSCs may be gathered that are suggested as a subject to enhanced availability and reliability controls, with commensurate undue burden for both the licensee and regulatory staff.

The traditional criteria artificially raised the relative importance of SSCs in the NuScale plant [2]. As an illustrative example, roughly half of the systems modeled there in the PSA were flagged as risk significant utilizing these criteria in a preliminary NuScale PSA model. Including roughly half of the PSA systems in a special reliability assurance program would direct resources on the SSCs that do not control risk, at the expense of SSCs that are really important for maintaining safety. It should be noted, however, that this illustrative example focused on system level importance. To maximize the benefit of the reliability assurance program, SSCs should be identified that focus resources on design and operational issues commensurate with, providing reasonable assurance of adequate protection of the environment and public health and safety.

Alternative thresholds were proposed and approved for other new light water reactor designs. As discussed in NUREG-1966, Volume 4 [4], the following thresholds for identifying potentially risk-significant basic events in the Economic Simplified Boiling-Water Reactor (ESBWR) design were approved:

RAW > 5 for individual events;
FV > 0.01 for individual events;
RAW > 50 for common-cause failure events.

The basic events that do not meet the threshold values are considered not risk-significant in the context of the ESBWR PSA.

2.1.2 Definition of risk-significance thresholds

The optimum approach to the risk importance thresholds should focus on identifying SSCs whose reliability and availability are important in ensuring that the margins to the safety goals are maintained, while **also** maintaining the low risk profile. It should depict the changes in CDF and LERF that are considered as being acceptable when making permanent changes to a plant's licensing basis. For those cases where the baseline CDF and LERF are small, larger risk increases may be accepted by the approach and consequent risk-oriented decision making.

The guidance in RG 1.174 [5] supports decisions for making plant changes based on small changes in risk while meeting current regulations and safety goals and maintaining sufficient defence-in-depth and safety margins. These guidelines are also consistent with the view that the existing safety goals, safety performance expectations, subsidiary risk goals and associated risk guidance key principles, and quantitative metrics for implementing risk-informed decision making, are sufficient for the new plants.

2.1.3 Risk-significance criteria/thresholds for core damage frequency

The current industry practice for judging component-level risk significance associated with equipment failure uses mostly the RAW importance measure. The RAW measure estimates the increase in risk that would result without the component (i.e., if the component failed 100 percent of the time). The RAW is especially informative and useful for high reliability components because it shows increases in risk when the reliability of the component is considerably reduced.

Following on the discussions provided in Chapter 2.1.1, it is re-emphasized that the current criteria use a threshold value for RAW of greater than 2 for components. If, when failing a component-level basic event, risk increases by a factor of 2, the component is considered risk-significant. However, because the current criteria were developed for operating plants that typically have a CDF for internal events on the order of 1×10^{-5} per year, a RAW = 2 for a failed component would result in an increase in CDF by a factor of 2. For a baseline CDF of 1×10^{-5} per reactor year, an increase in CDF by a factor of 2 represents a significant loss in safety margin with respect to the possible safety goal of 1×10^{-4} per reactor year. However, if the baseline CDF is lower, of the order of 1×10^{-6} or even 1×10^{-7} per reactor year, an increase in CDF by a factor of 2 is not significant in view of the markedly lower level of baseline risk. Maintaining an expectation for risk significance based on a RAW = 2 may effectively result in a new safety goal for the designs that are demonstrably safer than the fleet operated for some time. It is supposed that the point of suitability of the criteria used for older plants in case of new designs will be discussed later in the BESEP project. Following on the discussions provided in Chapter 2.1.1, it is re-emphasized that the current criteria use a threshold value for RAW of greater than 2 for components.

For such case, the approach employing an absolute evaluation of the RAW importance measure with the criteria consisting of the component-level CCDF value greater than or equal to 3 x 10^{-6} per year can be recommended. Basically, if the failure of any component results in a CCDF of 3 x 10^{-6} per year or higher, it would be considered a risk-significant candidate by this approach.

For a system-level threshold, the criteria from NEI 00-04 [6], as endorsed in Regulatory Guide 1.201, [7] may be considered; specifically, the importance measure criteria for common cause events based on a RAW=20. This value reflects that common cause is usually measuring the failure of two or more redundant trains of a safety system. As such, this common cause criterion applies to system-level events. Most systems expected to provide important safety missions in NPP designs typically include some intra-system redundancy. As such, current industry practice commonly uses about one order of magnitude increase for system-level metrics compared to component-level metrics.

Therefore, as soon as system-level PSA events are evaluated, the NuScale criteria [2] use a threshold of 1 x 10^{-5} per year, i.e., about a half order of magnitude above the component-level threshold of 3 x 10^{-6} but below the threshold level in RG 1.174 [5]. If the failure of any system results in a CCDF of 1 x 10^{-5} per year or higher, the system is considered a risk-significance candidate.

These thresholds, applied at a single module level, could be applicable to all initiating events collectively, that is aggregated across all events and hazards, i.e. internal events, low-power and shutdown conditions, internal flooding, internal fires, other internal hazards, and external hazards, both natural and human induced. Still, the risk-significance thresholds could be also partitioned based on expectations regarding the contribution to risk taken from each event category listed above. For example, if only an internal events PSA model is available, and internal events are expected to contribute roughly ten percent of total plant risk, the risk-significance thresholds could be reduced to ten percent of the component-level and system-level thresholds discussed above.

From the point of view of BESEP, where external hazards are in the focus, similar reduction can be carried out after the relative contribution of external hazards to the total CDF level is estimated. The same rule is valid for specific single external hazards, where some concrete hazard may clearly dominate the external hazards risk. If, for example, extreme wind contributes to roughly 50 % of total risk caused by external hazards, the risk-significance threshold can be reduced to a half of the risk summarized for all external hazards.

In the United States, using the range between 1 x 10^{-5} and 1 x 10^{-6} as the threshold for determining risk significance is further supported by guidance from RG 1.174 [5], which addresses permanent changes to a plant's licensing basis the following way: *"When the calculated increase in CDF is within the range of 1 x 10^{-6} per reactor year to 1 x 10^{-5} per reactor year, applications with possible impact on safety will be considered only if it can be reasonably shown that the total CDF value is less than 1 x 10^{-4} per reactor year."* Here, the component-level threshold of 3 x 10^{-6} represents approximately the midpoint (on a log scale) of the interval for changes acceptance in RG 1.174, and the total CDF may remain significantly below the 10^{-4} per year value with very high probability. Furthermore, the proposal is to use this threshold to simply identify risk significance on a component level, and it does not imply that these evaluations constitute permanent changes to the design.

The system-level value of 1 x 10^{-5} represents the upper end of the interval range for CDF identified in RG 1.174 for making permanent changes to a plant's licensing basis. It provides an order of magnitude margin to the safety goal of 1 x 10^{-4} per year for CDF.

2.1.4 Risk-significance criteria/thresholds for large release frequency

In the process of risk-oriented decision making SSCs are evaluated also for risk significance against LRF, by the PSA Level 2 criteria, in addition to core damage. The recommended approach may be similar to that for CDF. The criteria consider an absolute evaluation of RAW measure and consider both component and system-level thresholds. The thresholds for LRF are suggested as being numerically an order of magnitude below those for CDF. If the failure of any component (i.e., setting the failure probability to true) results in a CLRF of 3×10^{-7} per year or higher, it is considered a risk-significant candidate. If the failure of any system results in a CLRF of 1×10^{-6} per year or higher, it is considered a risk-significant candidate.

These thresholds, applied at a single module level, are applicable to all initiating events collectively, what means aggregated across all categories of elements of PSA model (i.e., internal events, low-power and shutdown conditions, internal flooding, internal fires, other internal hazards, and both natural and man-caused external hazards). Similarly to the CDF metrics, the LRF risk-significance thresholds could be partitioned based on expectations regarding the contribution to risk from each single hazard or broader hazard category.

The component-level value of the 3×10^{-7} was chosen for several reasons. First, it is an order of magnitude below the criteria for CCDF, which is consistent with the CCFP goal of 0.1 for newly constructed plants. In addition, it is below the goal of less than 1×10^{-6} per year for LRF for new reactor designs. Looking at the practice typical for large NPPs fleet at United States, for example, this threshold fits the RG 1.174 criteria in the range between 1×10^{-6} and 1×10^{-7} per year (a midpoint on a logarithmic scale), where making permanent changes to a plant's licensing basis is allowed.

The system-level value of 1×10^{-6} per year represents the upper limit for the LERF identified in RG 1.174 for making permanent changes to a plant's licensing basis and, at the same time, it meets the safety goal of 1×10^{-6} per year for large release. It is also an order of magnitude lower than the guideline of 1×10^{-5} per year for LERF for the plants of older design.

2.1.5 Risk-significance criteria based on fractional contribution

To supplement the absolute RAW metrics, an additional metrics can be employed to identify those SSCs that have the largest fractional contribution to risk, regardless of CDF or LRF. The focus of this criteria is on identifying SSCs for which the reliability and availability have the greatest influence on the risk profile.

This kind of a metric represents a contribution threshold and proposes that any SSC modeled in the PSA that contributes 20 percent or more to risk be considered a risk-significant candidate (i.e., FV greater than or equal to 0.20). Such criterion ensures that any SSC that has an unusually large contribution to risk is identified and the reasons for that contribution are examined, regardless of CDF or LRF and regardless whether it is classified as risk significant by means of the criteria based on absolute values or not.

The current industry practice for judging risk significance based on contribution also makes use of the FV importance measure. The FV importance measure allows events to be ranked according to their contribution to overall risk. It measures the overall percent contribution of cut sets containing a basic event of interest to the total risk. This criterion is used to identify SSCs that represent a significant fraction of a risk even with very low risk. In addition to equipment unavailability and human failures, this metric also may include initiating event contributors.

The contribution related threshold could be also applied individually to each category of risk inputs (internal events, hazards, and mode of plant operation). For example, SSCs may be identified as candidates for risk significance if they contribute 20 percent or more (i.e., FV > 0.20) to internal events risk, or seismic risk, or external flood risk, etc. It may also be applied individually to CDF, and LRF.

Based on the risk of operating NPPs and the current typical FV importance thresholds, a reasonable measure of significance can be rationalized based on the significantly lower CDFs typical for new plants. For a typical older operating plant with a CDF of 1×10^{-5} per year, the current FV threshold (i.e., 0.005 or 0.5 percent) translates to a CDF of 5×10^{-8} per year. For the plant designs with an expected CDF of the order of 1×10^{-6} per year, a CDF of 5×10^{-8} per year corresponds to an FV of 0.05, or 5 percent. However, setting a threshold for FV at 0.05 does not fully reflect the intent behind the use of FV for identifying all those components that contribute by a significant portion to the risk. To be more consistent with this intention, a higher value of FV may be proposed. In [2], for example, the proposed limited FV value is as high as FV = 0.2, but this value seems to represent another (opposite) extreme leading to very limited number of risk significant components and, as a consequence, possible underestimation of the contributors to the risk portfolio. The point of optimum set up of the limiting values for the criteria based on the FV measure can be a very interesting topic for the discussions in later BESEP WPs.

This way, the FV metric may identify additional events, including those related to external hazards, that represent a significant fraction of a hazard with very low risk.

2.1.6 Implementation and use of risk-significance thresholds

The current utilities typically have chosen to utilize risk information in many of the decision-making processes employed to develop a safe, economical, and efficient design. To do that, the selection of risk important SSCs or other elements of PSA model has to be balanced from the point of view of positive impact on increasing safety on one side and reasonable allocation of resources on the other hand. If the selected thresholds produce a very limited number of safety important SSCs, there is a feeling that it has not been made enough for keeping plant operation safe. If the thresholds are too conservative, the number of safety important SSCs may be too large to specify priorities for treatment of them in a reasonable manner.

It seems that applying the existing criteria to the PSA models of new designs, even roughly half of the systems may be identified as risk significant. With absolute RAW and FV thresholds, the number of risk-significant systems is reduced by approximately 25 percent for the new designs. Identifying such portion of the systems modeled in PSA systems as candidates for risk significance may better focus resources on design and operational issues commensurate with their importance to safety.

Consistently with the principles of risk-informed decision-making, PSA results and importance measures are used to identify candidate risk-significant SSCs. However, the ultimate determination of risk significance has to be also based on appropriate consideration of uncertainties, sensitivities, traditional engineering evaluations and regulations, and maintaining sufficient defence-in-depth and safety margins. As such, PSA risk insights have to be considered along with deterministic approaches and defence-in-depth concepts so that the approach to NPP safety is a “risk-informed” rather than a solely “risk-based”.

2.1.7 Summary and conclusions on the subject of risk-significance criteria

The outputs of the BESEP project are going to cover themes and topics related to a variety of NPP designs across Europe. Some of the plants under concern have been operating for decades and were constructed following the safety requirements valid that time, but some others are newer and have from the beginning followed new requirements representing increasing safety. The conclusions and outputs developed in the BESEP project should be devoted to all these subjects.

New reactor designs have an enhanced level of severe accident prevention and mitigation capability. As a result, new designs have achieved a higher standard of severe accident safety performance than prior designs and provide an enhanced margin of safety in preventing core damage, containment failure, and a release. The traditional risk-significance criteria utilized by the fleet operating for decades are overly conservative for newer plant designs with one or two orders of magnitude lower CDF/LERF values. Therefore, alternative risk-significance criteria and thresholds to identify risk-significant candidate SSCs or other elements of PSA model, including those related to external hazards, may be suitable. These criteria may include an absolute evaluation of the RAW importance measure and using the FV importance measure.

The criteria suggested for new design should directly address the ratio limitations of traditional importance measures thereby identifying SSCs whose reliability and availability are important in maintaining safety margins for the relatively low risk profile. This focuses the resources spent of further increasing of NPP safety or keeping the safety level still high after plant modifications made with the goal to increase efficiency of operation, on the SSCs whose design and operation provides reasonable assurance of maintaining adequate protection of the environment and public health and safety. While importance measures do not directly relate to changes in risk, the risk impact is indirectly reflected in the values used to determine whether or not the SSC is risk significant. Such guidelines are based on the principles and expectations for risk-informed regulation and support licensing basis changes to NPPs.

In general, the methodology suitable for new designs involves calculating importance measures for basic events or broader segments of PSA model and identifying those that meet the criteria outlined in the table below, which are discussed in [3]. The criteria are intended to apply to the full-scope PSA, including all hazards and operating modes, and both CDF and LRF. The criteria apply to all PSA basic events, including those representing operator actions and initiating events. The thresholds are applied at a single module level; the absolute RAW thresholds apply to the aggregated risk across all categories of risk contributors, and the FV thresholds apply individually to each category of risk contributors and mode of plant operation, and individually to CDF and LRF.

Table 1. Criteria for risk significance of new NPP designs.

Parameter	Criteria for Risk Significance
Component-level basic event	CCDF > 3 x 10^{-6}/ year
System-level basic event	CCDF > 1 x 10^{-5}/ year
Component-level basic event	CLRF > 3 x 10^{-7}/ year
System-level basic event	CLRF > 1 x 10^{-6}/ year
Basic event/contributor	Total FV > 0.20

Within the context of BESEP project, the criteria presented in the table can be seen as an example of a recently emerged approach and trend internationally. Further discussion of risk-significance criteria is expected in the continuation of the BESEP project during presentation, discussion and analysis of case studies provided by the BESEP partners. These criteria (or some alternative criteria discussed later in relation to case studies selected in Task 3.2 of BESEP) may be used to examine events considered in the PSA models and identify candidates for risk significance. The results may be used to support the design reliability assurance program and many other applications that consider risk importance. These applications may use the PSA risk-significant insights; however, the process is seen as risk-informed rather than risk-based, that's why it should be supplemented with appropriate consideration of uncertainties, sensitivity analyses, traditional engineering evaluations and regulations, and maintaining sufficient defence-in-depth and safety margins. All these aspects will be discussed in consequent tasks of BESEP, as well.

PSA can be used to evaluate the risk profile of a plant to ensure that the design and operating practices satisfy the safety goals. In addition, PSA can be used to identify cases where human or component failure, or exceeding design values as a result of external hazard impact, could potentially lead to core damage and a release to the environment. Providing risk-informed insights helps operators and regulators to ensure that the risks resulting from changes in reliability or availability are maintained acceptably low. Risk significance is measured with respect to the contribution to the total CDF or LERF, or with respect to the contribution to the CDF or LERF for a specific category of risk contributors, including external hazards in categories.

The term "significant", within the traditional context of PSA results and insights can be defined in terms of absolute or relative risk criteria. CDF or LERF values related to the NPP under concern can be used for employing of absolute risk criteria. For the relative risk criteria, parameters based on importance measures can be used. The typical values used in case of relative measures applied define PSA basic event or another type of contributor based on the PSA model as significant if its risk achievement worth is greater than 2.0 or its Fussell-Vesely importance is greater than 0.005. This is a relatively new approach to determining risk significance, which is needed because the traditional relative importance measures may be insensitive to the global improvements in NPP safety associated with the lower absolute values documenting risk level of NPP operation. These values may artificially raise the relative importance of some SSC that do not drive the risk objectively, eventually leading to needless spending of resources.

The recommendation is to consider an absolute evaluation of the RAW importance measure for the newer NPP designs and to discuss it in later BESEP WPs in connection with the case studies. The approach directly addresses the ratio limitations of traditional importance measures. It also includes the FV importance measure, which capture measurable contributors to risk regardless of the overall level of core damage frequency or large release frequency. For the operating NPPs, the full-power internal events mean core damage frequency is, in Czech Republic, for example, in the order of 1 - 1.1 x 10^{-5} per year. This may be in contrast to newer plants where the full-power internal events CDF may be by one or even two orders of magnitude lower. With a baseline CDF of 1 x 10^{-5} per year, using the relative risk metric of risk achievement worth (RAW=2) implies a change in CDF of 1 x 10^{-5} per year, whereas, in contrast, a CDF on the order of 1 x 10^{-6} per year and a RAW=2 means that the CDF increases by only 1 x 10^{-6} per year.

Consequently, when using a relative risk metric such as RAW for criteria supporting decision making process regarding adoption of proposed change in plant design or operation, a plant with a baseline CDF of 1 x 10^{-5} per year would be allowed an increase in CDF of 1 x 10^{-5} per year, whereas a safer plant with a baseline CDF of 1 x 10^{-6} would only be allowed an increase of 1 x 10^{-6} per year before an item becomes risk significant. Using the current relative risk criteria would result in categorizing a majority of changes in advanced PSA systems as risk significant.

In summary, it may be recommended to use the criteria for determining SSC risk significance, which include an absolute evaluation of the RAW importance measure, and a backstop using the Fussell-Vesely (FV) importance measure. Such approach directly addresses the ratio limitations of traditional importance measures and can be implemented in a manner consistent with meeting regulatory body safety goals. It is also consistent with the goals of the BESEP project, where risk-significance criteria should be consistent for broader spectrum of designs and absolute levels of overall plant risk. The methodology discussed in BESEP should include evaluation of all SSCs considered in the PSA against CDF and large release frequency (LRF) with the focus on internal and external hazards, for broad scope of operating modes

2.2 Considerations to external hazards from the perspectives of BESEP

The specific focus of BESEP is the area of external hazards. To some difference from the more traditional parts of a PSA model that is oriented to internal events, i.e. failures of plant equipment with a failure potential quantified by single failure probability, the term (external) hazard represents a phenomenon of various intensity where the relationship between intensity (and risk impact) and probability (or frequency) is described by a continuous curve.

As soon as the relationship between event frequency and hazard intensity is defined and studied in the risk engineering related project, it makes sense to search for connection between risk importance thresholds and the values of hazards intensities (extremes), which correspond to them. That was the reason, why the discussion among the BESEP partners and the information collected by means of the questionnaire has not been limited just to the basic (probabilistic) thresholds pointing out to risk significance, but some information about extreme intensity values representing probabilistic limits (design basis related etc.) were also included into the scope of work.

Collecting information about the external hazard extremes defined by the individual BESEP partners could be used for useful comparison of the approaches applied in Europe. It may also provide a basis for comparison and explanation of specific features of the individual case studies provided by BESEP partners and studied in later tasks of BESEP.

2.3 Approach used for collection of information related to external hazards related risk-significance thresholds

The partners in the BESEP project represent different countries, geographical conditions, and plant designs. That was the reason why it was decided to start the discussion of risk significance matters related to external hazards and some other hazards related information by development of a questionnaire, where the information from each partner is collected. The plan is to use this information, as soon as needed, during the discussions within next Tasks of the BESEP project, when the individual case studies provided by BESEP partners will be studied and compared and lessons will be learnt about the current status of external hazards related risk engineering activities in Europe.

The quantification of the parameters of external hazard extremes is generally known as a very challenging task, because a relatively “very short” data samples covering plant site characteristics documented over several decades of plant operation have to be extrapolated to estimate the intensity of hazards representing (beyond) design basis limits. To a big difference from derivation of component failure rates in PSA, for example, the derived extreme values are very significantly based on the methodology used for that purpose (choice of probability distribution, scope of data included into the sample, interpretation of historical records) and the choice of the approach and interpretation of results may be fairly subjective. That was the reason why also some additional information about the way, the extreme values have been derived, was asked to be filled in the questionnaire by the BESEP partners.

3 Description of a questionnaire survey developed for collecting information in Task 2.4

3.1 Development of questionnaire

The questionnaire for BESEP Task 2.4 was developed in UJV in cooperation with the other BESEP partners. It was carried out in several iterations separated by internal discussions in UJV and the discussions with BESEP partners, as well. Some BESEP partners (NUBIKI, VTT) carried out informal revision of the questionnaire and provided very valuable inputs into the discussion and consequent modification of it.

The questionnaire was supplemented by a guidance related to the individual items. In addition, a filled in version representing nuclear power plant Dukovany site in Czech Republic was provided together with the blank version of the questionnaire to make the responses easier for the BESEP partners.

3.2 Structure of the questionnaire

The questionnaire starts with an introductory part providing brief general information about the site, the hazard related information is related to. This information includes site identification, country specification and reactor type. The main body of the questionnaire consists of five parts. The main subjects of information collection are gathered in the first part of the questionnaire. The remaining parts provide supplementary information.

3.2.1 Information about risk-significance parameters and risk-significance levels (extremes) related to external hazards

The main (first) part of the questionnaire consists of a table in the MS-Excel format, which was attached in the separate file to be filled in by BESEP partners. The table was developed based on the discussions among all BESEP partners. Fussel-Vesely measure (F-V) was chosen from the widely used risk metrics to characterize the risk contribution attributable to external hazards in the project, as decided during a clarification meeting. The results of importance, or risk-significance analysis based of this measure were expected to be available in the case studies provided by the BESEP partners. Fuel damage and large early release quantified in terms of annual frequency are the primary consequences under concern.

Specific values of extreme intensities of a set of natural external hazards representing the design basis accidents scenarios and the scenarios of design extension conditions were asked to be provided in the table by the BESEP partners. The differentiation of Fussel-Vesely measure to the scenarios based on design basis external event frequencies and those of design extension conditions was optional, but desirable.

The suggested metrics could serve as a basis for grouping of external events into several classes according to their risk significance. Alternate values for threshold levels could be suggested in case studies as an opinion of the BESEP partners. A systematic specification and definition of threshold levels would require consensus of a broader PSA community and is beyond the scope of the project.

In the MS-Excel table forming part of the questionnaire, the plant specific parameters supporting development and analysis of “probabilistic thresholds” are directly present in the columns:

PSA-1 F-V (FDF);
PSA-1 F-V (FDF – DBA);
PSA-1 F-V (FDF – DEC);
PSA-2 F-V (LERF);
PSA-2 F-V (LERF – DBA);
PSA-2 F-V (LERF – DEC).

The extension of collected information by Level-2 PSA data may bring about further views on the risk significance of external events, but it could be left blank by BESEP partners, if such information was missing or Level-2 PSA for the NPP under concern has not been developed enough in this respect.

The information in the other columns of the MS-Excel table, like "*Site design bases/ value*" and "*Practical elimination/ value*", was also postulated as supplementary and possibly collected with the aim to make the risk-significance parameter values, which had been intended to be collected first of all, mutually comparable. The "practical elimination value" was used in the meaning typical for deterministic analysis, i.e. for elimination of the scenarios (severe accidents) of very high consequences, but such low frequency of occurrence that they do not need to be analysed in detail in PSA for the plant under concern.

A full scope PSA covering all plant operation regimes was expected as being the source of information for this questionnaire. It was the general assumption of the coordinator of BESEP 2.4 Task that such plant specific PSAs are available for all BESEP partners.

All BESEP partners were expected to provide country-specific information. Since there were two partners from Finland (VTT and Fortum), these two partners were expected to share the information filled in the document. It was expected that the information collected will consist of six filled in documents (tables and supplementing information segments) representing the following European countries (in alphabetical order): Czech Republic, Finland, France, Hungary, Slovakia, and Sweden.

The set of external hazards addressed in the table represents an output of BESEP Task 2.1, which was somewhat extended to address some other hazards, since they are currently indicated to be possibly addressed in case studies proposed in BESEP Task 3.1. Any BESEP partner, who would like to address some other hazards not presented in the table primarily, could add new rows to present the corresponding information about those hazards. On the other hand, if any BESEP partner did not have any kinds of information available about the hazards required by the table, the corresponding field(s) of the table could be left blank.

If any combination of external hazards is addressed in the studies carried out by some BESEP partner (which may or may not be presented in the questionnaire), the impact of that on the derived (and presented) F-V values for single hazards should be considered adequately. In the analysis represented by the data sample provided by UJV, the frequency of hazards combination "Tornado + Extremely high temperature" was subtracted from frequencies of the single hazards "Tornado" and "Extremely high temperature", respectively.

Since the risk-significance parameter values are site/plant specific, each BESEP partner had to decide, which site/plant will be addressed in the document. In general, it would be useful to cover all sites/plants, which will be later addressed in the case studies provided by the partners to the pool of case studies. To do that, the BESEP partners needed to decide, at least on a preliminary basis, which case studies they intend to put into the pool as a part of Task 3.1, before providing information in this document related to Task 2.4. Another possibility was to provide the information for all sites/plants, which were possible candidates for later case studies selection carried out in Task 3.1.

Fussel-Vesely measure values corresponding to the risk of fuel damage modelled by PSA-1 were asked to be filled into the column "PSA-1/ F-V (FDF)". Fussel-Vesely measure value corresponding to the risk of fuel damage modelled by PSA-1 design basis scenarios could be filled into the column "PSA-1/ F-V (FDF – DBA)", if available. Fussel-Vesely measure value corresponding to the risk of fuel damage modelled by PSA-1 beyond design basis scenarios could be filled into the column "PSA-1/ F-V (FDF – DEC)", if available.

"Truncation value" was defined, for the purposes of the questionnaire, as the value used for elimination of negligible minimum cut sets in the process of PSA model quantification (cut-off). A general experience is that this value may considerably impact the F-V values filled in the table. It is important to know the truncation value later as soon as the F-V values provided by the BESEP partner are going to be compared.

The FDF values represent an aggregated frequency of fuel damage in reactor core and spent fuel pool (for the sake of simplicity, other sources of radionuclides were not considered). In case that the F-V values related to FDF were not available, the values related to CDF could be used in the questionnaire supported by a comment in the column available for that.

The columns in the section "PSA-2 (optional)" were created to contain similar kind of information as the columns in the section "PSA-1". They needed to be filled only in case that the information taken from PSA-2 would differ from the PSA-1 information.

The descriptions/definitions of the load parameters corresponding to the numerical values characterizing extreme intensities of the hazards, which were asked to be are presented in the column “Site design basis/Value”, were specified in the column “Site design basis/Load parameter”. If more than one definition of the load parameter is used in some plant PSA, based on different physical manifestations of the related hazard (e.g. one value for 1s wind gust and another one for 10s wind gust), a new row could be added into the table and the hazard could be split into two mutually connected hazards, e.g. Extreme wind-1 and Extreme wind-2.

Unless stated otherwise, the data in the table are considered to be shared between BESEP partners only. Whenever any data are considered as sensitive by some BESEP partner, only summarized, or anonymized data are supposed to be used in the deliverables of the project

3.2.2 Information about site design basis and “practical elimination” thresholds

The room for additional relevant/important information about the activities related to substantiation of the values presented in “Site design basis” and “Practical elimination” parts of the table in the MS Excel file was provided to the BESEP partners in this part of the questionnaire. The main topics presented in the questionnaire survey were connected with the following questions:

How have the values presented in the table been specified in general?
What have been the challenges in the process of specification of these values?
What could be the challenges expected in future (what challenges have persisted)?

3.2.3 Information about the approach used for analysis of site-specific data

In the optional Part 3 of the questionnaire, each BESEP partner could provide additional information about using available site-specific (and other) data for derivation of extreme values collected for the selected external hazards, corresponding to the design basis frequencies (provided that site specific data were used in the work of the specialists taking part in BESEP). The main topics raised there were connected with the following questions (but the information provided did not need to be necessarily limited to that scope):

How were the “real” values (data) of the extremes already collected (covering several decades probably) used to substantiate the values representing the frequencies separating/limiting DBA, DEC-A or DEC-B, i.e. the annual frequencies of occurrence of 10^{-4} etc. (i.e. representing 10 000 years)? In other words, how a relatively very short history was extrapolated to very long time periods corresponding to the beyond design basis frequency values? Was expert judgment involved? Generic data? Bayesian up-date? Gumbel distribution or other probability distribution recommended in IAEA guides? Another kind of distribution? Something else?

3.2.4 Brief information about the approach and scope of work used for combinations of external hazards

There were no hazards combinations presented in the original main Excel table in the questionnaire because this area of external hazards combinations analysis is quite new. Still, if any BESEP partner wanted to present the data about some combinations of external hazards (which may be later addressed in some case study provided for BESEP), such partner could add additional rows into the main table in MS Excel. Another way to present the information that the analysis of some external hazard combinations has been done, was to add some text in the supplementary Part 4 of the questionnaire specifically devoted to hazards combinations. This part was based on the following table providing combinations on all most important external hazards identified in BESEP Task 2.1.

Table 2. Combinations of external hazards proposed to be addressed in BESEP.

Secondary hazard / Primary hazard	extreme wind	tornado	extreme snow	extreme rain	extreme air temperature	icing (glaze ice and rime)	low water level in river	high sea level	seismic
extreme wind	-								
tornado		-							
extreme snow			-						
extreme rain				-					
extreme air temperature					-				
icing (glaze ice and rime)						-			
low water level in river							-		
high sea level								-	
seismic									-

In some cases, the order, in which the hazards that form together the recorded combination, is important. In the previous table, "primary hazard" is the hazard, which struck the plant as the first, and "secondary hazard" is that one, which was second. So, the table provides room for separating the combinations of hazards on the base of the order of occurrence of the single hazards forming them. As the historical records can show, this possibility may be useful, because the impact on plant caused by combination of hazards A-B (in this order) can be significantly different than the impact of hazard combination B-A (in this order).

It is also important to define and systematically apply a rule specifying the borderline between the occurrence of an event representing a combination of a hazard event and two consecutive occurrences of single hazard events. This rule may have a significant impact on the results of combination of hazards analysis (and, consequently, on the analysis of single hazards, as well).

The BESEP partners could indicate here whether the given combination of external hazards has been addressed in plant PSA. They could also extend the table to indicate combination of already treated natural hazard and a new human induced external hazard. They were also asked to provide additional brief information regarding the basic approaches (rules) used for defining and analysing the combinations of external hazards. The additional topics defined in the questionnaire can be summarized in the following questions, for example:

> *How big is the impact of **order** of hazards in the combination? Do you systematically differentiate between the combinations of the hazards A and B when hazard A starts the event and hazard B impacts the plant as a second one and vice versa?*
>
> *What are the rules applied for differentiation between two occurrences/events of single hazards and (one) occurrence/event of combination of two hazards? In other words, how big time difference (or some other characteristics) has to be to differentiate the event under concern as two independent events and not as a combination of two hazards?*

It was pointed out in the questionnaire that if any combination of external hazards is addressed in the studies carried out by some BESEP partner, the impact of that on the derived (and presented) F-V values for single hazards should be considered adequately. In the analysis represented by the data sample provided by UJV, the frequency of hazards combination "Tornado + Extremely high temperature" was subtracted from the frequencies of the single hazards "Tornado" and "Extremely high temperature" used before the topic of hazard combinations was put into the table

3.2.5 Human induced external hazards

The aim of this part of the questionnaire was to provide brief additional information about the practice, methodology and challenges in specification of parameters related to “risk-significance thresholds” for human induced external hazards. The motivation for having a specific chapter related to human induced hazards were their specific characteristics from the point of view of quantification. Whereas the natural hazards can be described by specific hazard (intensity versus probability) curves providing means for evaluation of extremes and their frequency, such tool is usually not available for human induced hazards and other approaches have to be used to take care of them in risk engineering

3.3 The process of filling in the questionnaire by BESEP partners

To help filling in the table, sample information related to the external hazards identified for NPP Dukovany site was presented in a separate table/attachment. The information in that table was preliminary and was modified and completed in the final version of the questionnaire filled in by UJV.

Some pre-defined choices were given in the questionnaire to make filling in the column “Screening result” and the column “Source of hazard frequency in PSA” easier for BESEP partners.

Unless stated otherwise, the data in the table are considered to be shared between BESEP partners only. Whenever any data are considered as sensitive by some BESEP partner, only summarized, or anonymized data are supposed to be used in the deliverables of the BESEP project.

During the time period allocated for filling in the questionnaire by all BESEP partners, the UJV specialists were ready to help with possible unclear points, questions and challenges. It was found, however, that there was almost no such need and the guidance supplemented with the questionnaire and the previous discussions were sufficient for the partners to provide required information.

4 Interpretation of the information provided in the questionnaire

4.1 General features of the analysis

The way, the analysis was done, the information sorted, filtered, and interpreted, depended on the format of the information provided. There were two basic approaches to filling in the questionnaire.

One partner (EDF) did not fill in the large Excel table, but provided sufficient interesting information in text format, which, in accordance with BESEP aim, was focused rather on the general features of the approach to the hazard analysis and general conclusions regarding the thresholds derived and used than on exact values of hazard intensities and thresholds. The other specific feature of the information provided by EDF was that it covered a large fleet of NPPs (and sites).

The other partners (UJV, RELKO, RISK PILOT, FORTUM+VTT and NUBIKI) directly filled in the Excel table in the questionnaire and supplemented the table by additional comments, typically just for one plant site. Since this information was given in the same format, it was possible to perform some comparison regarding the approaches used for, and values obtained from the base of the analysis. Since the aim of the Task 2.4 was rather to collect more general information regarding the methodology and threshold values, and not to comment, sort or compare the exact numerical values related to the individual hazards, just a summary of information is given in this section, typically in the format of range of the values derived and used by BESEP partners. The exact values collected by the partners in the tables may be used later in the BESEP project as soon as the case studies from the pool are discussed.

Whereas the individual hazards of interest expected in BESEP were mostly predetermined in the table, the partners filling in the questionnaire had got free room for identification and presenting those hazard combinations, they had found most important in their studies. This was done by all partners, including a summary carried out by EDF. A general feature of the hazard combinations identified by BESEP partners is their variety caused by different geographical (climate related) locations of plant sites.

Beside threshold values, the questionnaire asked also, to some extent, about the specific features of the approaches used for data analysis by the BESEP partners, data sources and data extrapolation methodology, in particular. The answers to these points in the questionnaire could enable some comparison of methods used over Europe. It can be concluded here that advanced methods of statistical analysis are used by all partners and that the partners successfully overcame some challenges in their studies

4.2 Evaluation of the questionnaire responses

In this section, some conclusions are drawn on the basis of analysing data provided in the questionnaire by the BESEP partners. The subsections with the conclusions are structured in a similar way as is the questionnaire:

- comparison and interpretation of the information about the hazards selected and treated as potentially significant risk contributors;
- risk-significance parameters for the selected hazards;
- site design basis characteristics related to external hazards;
- practical elimination points related (not only) to external hazards;
- additional information and challenges connected to external hazard analysis;
- site/country specific data – methodology of analysis;
- combinations of external hazards;
- human induced external hazards.

4.2.1 External hazards addressed by BESEP partners

In France, the nuclear safety demonstration shall also include probabilistic analyses of accidents and their consequences, unless the licensee demonstrates that it is irrelevant. The analyses integrate the technical, organisational, and human aspects. In this context, the probabilistic analyses shall also include external hazards, in a specific manner for each nuclear plant, as this kind of analysis should be significantly site-specific. In practice, an external hazards “screening” is expected to be performed by the licensee in France, in order to identify the relevant hazards and combinations of hazards for detailed probabilistic assessment, with the final aim to evaluate the associated risk. EDF had provided an external hazard screening guide for that purpose, which was reviewed by IRSN. EDF already applied this external hazard related screening guide to the 900MWe plant/sites but limited to single hazards.

A related topic opened and discussed in France recently is a “risk aggregation”, a specific point of risk engineering where different types of initiating events are mixed in the same model. The results of analysis by the means of aggregated PSA model should be carefully considered since the level of uncertainties, details of development and maturity of the PSA modelling may be rather different for the individual segments of the aggregated PSA model (internal events, internal hazards, external hazards).

The following hazards have been analysed up to now for the fleet of plants in France:

- *aircraft crash* – all sites, both 900 MW and 1300 MW design, the existing deterministic safety demonstration studies already consider a probabilistic approach; the risk values obtained in these studies are compared to the overall fuel damage risk, where a complete risk portfolio is considered;
- *air pressure wave* – analysed at most 900 MW sites; for two 1300 MW sites the analysis is ongoing;
- *earthquake* – all sites, both 900 MW and 1300 MW design, for 900 MW Tricastin site a simplified and conservative analysis of the hypothetical wave as a consequence of a seismic dyke event has been integrated into the SPSA; a seismic PSA has been developed for each plant/site keeping in mind that the French NPPs are composed of similar reactors on the same site, with the exception of Flamanville 3;
- *riverine flooding* – analysed for most 900 MW sites and two 1300 MW sites as single hazard, the analysis was done for all sites, where this hazard is relevant; the approach used by EDF for external flooding PSAs is a simple one with limited development based on decoupling assumptions that may limit the relevance of insights to be shared; for instance, water propagation inside buildings has not been modelled, but conservatively assumed to result in unacceptable consequences regardless of the water volume on the NPP platform even in case of limited water ingress; such approach with high level of conservatism was not found suitable to study other flood mechanisms such as local rainfalls;

- *water surge* was analysed for two 900 MW sites, a dedicated PSA model has been developed for river flooding and surge; a simplified probabilistic assessment was performed for the consequent intrinsic failures of tanks, systems or components, the analysis only quantified the potential and consequences of occurrence of water ingress, but do quantify fuel meltdown as a consequence;
- *tsunami risk* impact was analysed for two 900 MW plants, and has not been analysed for the 1300 MW plants;
- *fall of meteorite* – this hypothetical event was analysed for all 900 MW sites, but not for the 1300 MW plants;
- *high air/*water *temperature* hazard was found as important for all plant sites in France due to geographical location of the country and analysed for all 900 MW and 1300 MW sites;
- *extreme wind* and *tornado* were analysed for all 900 MW and 1300 MW plants.

Some of the hazards usually considered as important look like not analysed for 1300 MW French plants, but they are represented in the framework of the analysis of hazard combinations, what may be, in fact, a suitable approach for those hazards, which do not represent a serious standalone risk contributor, but may show their strength in combinations with other external hazards.

Information is given in the French survey that meteorite and tsunami hazards are said to be significantly unlikely and no additional PSA development has been engaged. Such conclusion is very well justifiable for meteorite fall. In case of tsunami, that fact does not mean that no new measures have been taken at the plants located at the seaside. Additional equipment has been installed with potential positive impact on tsunami scenarios, such as ultimate diesel generators. It is also supposed, and there is valid argumentation for that, that the tsunami potential in the seas surrounding France is significantly lower than in the case of Japan.

Five BESEP partners (Finland, Hungary, Sweden, Czech Republic, Slovakia) provided information in the table in the developed questionnaire. The conclusions regarding the individual hazards specified in the questionnaire are:

- *extreme wind* was modelled in PSA by most partners, not considered yet just in one PSA study; a typical external hazard, which is modelled as single hazard, but also in combinations with other hazards, the tornado hazard is sometimes separated in the results as a single hazard, sometimes it is modelled together with other cases of extreme wind)
- *tornado, extreme snow*, and *extremely low temperature* were modelled in PSA by most partners, not considered yet in just one PSA study, screened out in another one due to low impact expected
- *extremely high temperature* was modelled in PSA by most partners, not considered yet in just one PSA study, screened out in another one, where the risk impact was evaluated as low on qualitative basis
- *extreme rain* was screened out by most of the partners; it was modelled just in one PSA study, screened out in the Loviisa PSA due to expected low consequences since the water raining, even of extreme volume, would flow out to the sea, this may be the case also for other coastal sites in Europe;
- *icing*, modelled in two PSAs;
- *lighting*, screened out or not modelled by most partners, modelled in one PSA
- *dust storm* – screened out or not modelled by most partners, modelled in one PSA, sometimes this hazard cannot impact the plant site due to site characteristics (site located on a small island surrounded by the sea);
- *earthquake* modelled by all, but one partner, in the Loviisa PSA a significant increase of seismic risk is expected during the ongoing update of seismic hazard assessment and seismic PSA;
- *liquefaction* was found irrelevant (plant site may be located on bedrock) or modelled within the scope of seismic risk assessment;
- *low water level, low water temperature* – screened out due to low risk contribution in all studies, in one case, this conclusion was changed on the base of operational history, it is planned to include this hazard in the PSA in future, in one PSA, an initiating event related to low water level was screened out based on low frequency, but has been still considered in basic events, because additional access to cooling water is unavailable when sea water level is below certain level; frazil ice has been modelled for one site where no other initiating events were recognized from low water temperature above screening criteria;
- *high water level* – depends on relative elevation of the site, evaluated as irrelevant by three partners, modelled by one partner;

- *high water temperature* - screened out or not considered by all partners, for the Loviisa plant, for example, sea water temperatures are regulated, as this NPP is required to reduce power or shutdown if sea water temperature is above predefined limit, but the impact of high sea water temperature is still considered during other initiating events in the Loviisa PSA;
- *geomagnetic hazards* - screened out or not considered by all partners, in case of the Loviisa plant, for example, new studies of solar wind (or geomagnetic storm) are followed, but these studies have shown no need to model solar storms up to now; the main transformers of the Loviisa NPP still have been upgraded to tolerate stronger geomagnetic storms;
- *pandemic* - screened out due to low risk contribution by most partners, planned to be analysed in future in one case;
- *aircraft crash* – screened out due to low contribution (frequency) in most cases, modelled more in detail in one case;
- the impact of *release of chemical substances* outside the plant – screened out in all cases;
- *missiles from rotating equipment* located outside the plant – found totally irrelevant in half of the cases, screened out in the remaining ones;
- *transportation* accidents – screened out, not considered, or found irrelevant by almost all partners, oil slick impact modelled in one PSA for the plant site located at the seaside;
- *electromagnetic interference* – screened out due to low risk contribution in all cases;
- *malicious attacks* – not considered yet, screened out, but mostly found out of the typical scope of PSA;
- *external fire* – added to the list of external hazards having been identified in earlier BESEP tasks, because of indicated as modelled in one PSA.

Specific comments were made on the ranges considered in the PSA studies for the intensities of individual natural external hazards. The complete range of values was usually split into several intervals representing the same plant response model in PSA. These individual ranges are presented in the questionnaire, but only some overall interval values used for hazard intensity values are summarized below:

- for *extreme wind*, the range considered was very broad, starting with 27 - 50 m/s in one PSA (seemingly relatively low value to be treated as upper level, but higher winds are also included in that PSA under hurricane or tornado category), and finishing with 100-120 m/s in another PSA;
- for *tornado*, broad spectrum of strength (F1 - F4) was typically analysed (the upper level had been hypothetical for a long time in Czech Republic, but inclusion of that was finally justified as soon as the tornado in south Moravia occurred in Summer, 2021);
- for *extreme snow*, the typical range was 100 - 260 (360) mm of equivalent water column;
- a broad variety of intervals was identified for extremely *high temperature*, in one PSA, the range was 40 - 58°C, whereas in another PSA (for NPP located in north Europe), just the interval 25 - 30°C was considered, but the definition of the variable was "*mean 24 hours temperature for more than two days*" and the value was based on data recording activities organized since 1850s; another PSA was found as typical with a wide spectrum of hazards intensity considered in general, and the case of high temperature hazard does not represent any exclusion, the interval considered is from 29°C up to 70°C;
- for extremely *low temperature*, the variety is also high, although the total interval of temperatures considered over Europe is not that wide starting with -10°C and finishing with -58°C, an interesting point is that the PSAs from central Europe considers even lower extreme values than the PSA from the north, but this may be connected with the general features of the continent and coastal climate, where the weather extreme values may be larger in inland/continent countries (central Europe) than in low altitude coastal countries, even the ones in the north of Europe since these are more or less on the same elevation as the north and Baltic sea and large water masses stabilize the temperatures there;
- in case of *icing*, different physical quantities were used in the analysis by the partners, in one case, the value of 2183 g/m was used, whereas 50 mm was used in another case;
- for *lightning*, the value of 100 kA was used by one of the partners to measure the strength of electric discharge;
- *earthquake* potential is significantly site specific and one of typical ways how to model earthquake is to discretize the area of all possible values; one partner, for example covered the interval 0.025 g – 1 g and discretized it into ten intervals covering the whole spectrum of possible values

4.2.2 Level-1/2 PSA Risk-significance parameters

In this section, some typical risk-significance values based on F-V importance measure, presented by the partners in the questionnaire, are given:

- *extreme wind* – FV risk-significance measure in the studies is 3 - 4 x 10^{-1} (with one exception of the order of 10^{-3}) – a relatively high risk importance showing that this hazard belongs to the important ones; it seems that extreme wind represents an universally important hazard over European NPPs, provided that the site is not specifically protected against wind by country relief;
- *tornado* – the risk-significance values were usually not specified in the filled in questionnaires among BESEP partners, obviously due to considered relatively low risk potential caused by low frequency of occurrence, the situation has changed recently in Czech Republic when F4 tornado stroke in south Moravia in Summer 2021 just 80 km from NPP Dukovany, an update of tornado hazard analysis was done in response to that; a possibility of presentation of this work as one case study in the BESEP pool of case studies is considered;
- *extreme snow* – FV risk significance in the studies is between 5 x 10^{-2} - 1 x 10^{-1} shows that this hazard is not of negligible importance, this conclusion is valid not just for north of Europe, but also for geographical locations in middle Europe;
- *extremely high temperature* – FV risk significance in the studies is 2 - 7 x 10^{-2}, what represent a pretty big variance, it can be caused by the climate differences among the plant sites considered in BESEP;
- *extremely low temperature* - FV risk significance in the studies represents even bigger differences than in case of extremely high temperature, from 5 x 10^{-4} up to 1.5 x 10^{-2}, the risk significance is generally lower than in case of high temperature;
- *extreme rain* was modelled only in one PSA study and screened out in the others – FV risk significance was very small (1 x 10^{-5}), but this number is related to the complete plant risk, not just to the hazard portion;
- *icing* was modelled in two PSAs with medium/high FV risk significance of 7.5 x 10^{-2} and 4.4 x 10^{-2}, respectively;
- *lighting* was also modelled in two PSAs among BESEP partners, it was included in LOOP and fire events in one PSA, no specific risk-significance value is available there; in the second PSA, the FV measure value for PSA-1 is 1.3 x 10^{-2};
- *dust storm* was modelled in one PSA with FV risk significance of 7.5 x 10^{-2};
- *earthquake* represents “the most traditional” external hazard modelled in PSA by most of BESEP partners, not considered yet in one PSA, FV risk-significance values can be found in a wide range from 8 x 10^{-3} up to 2.7 x 10^{-1}, some FV values are is relatively high (as expected), the hazard characteristics of plant site have got big impact on the FV values;
- *high water level* represents specific hazard, modelled in two PSAs, with FV risk significance relatively small in one PSA – 1 x 10^{-3}, but higher in the second one – 7 x 10^{-2};
- *aircraft crash* was screened out due to low contribution (frequency) in most cases, modelled in one case with medium FV risk significance of 2.6 x 10^{-3};
- *external fire* was also modelled in one PSA study, but included into LOOP and fire events, FV risk significance is not available for this case.

The values set up for truncation of low risk minimum cut sets in the available PSA studies developed by BESEP partners were typically 10 - 12 and lower so that the FV importance values should represent the real risk status adequately. Very low truncation values (the same for PSA-1 and PSA-2) were used for all external initiating events in the Loviisa PSA. These values were changed a bit annually, with an idea to evaluate the risk as accurately as possible, but to have the truncation limits so that the computation process for PSA-1 model of one unit takes not more than 24 hours. The limits in the most recent PSA from 2020 are: 5 x 10^{-16} for minimum cut sets evaluation, 2 x 10^{-15} for calculation of importance measures.

Some additional comments were made in the questionnaire regarding plans to carry out the analysis of those external hazards, which have not been fully analysed yet, to the extent providing specification of risk significance or to increase the scope of the analysis otherwise:

- in one PSA, the risk of damaging fuel stored in the SFP has not yet been assessed for external events endangering water intake from the ultimate heat sink, so the results indicate CDF values rather than FDF values;

- pandemic hazard is planned to be analysed in the near future as part of biological hazards, in other PSA it was is expected that the development of the scenarios from this category is sufficiently slow, making possible timely adoption of adequate preventive measures;
- here was a couple of cases when some hazard was screened out based on low contribution; however, a re-analysis has been started lately in view of recent operating experience;
- in some PSA studies, fragility analysis is ongoing at present and will be finished in near future, also plant response analysis is ongoing in some specific areas found important to assessing plant vulnerability to extremely high temperature.

Very limited information was available from Level-2 PSAs In the Level 2 PSA of the Paks NPP PDSs with a contribution to the overall CDF higher than 1 % were assessed in detail, and PDSs with lower contribution than 1% were assessed conservatively using a bounding PDS

4.2.3 Site design basis aspects

In France the regulation does not define values of probabilistic safety targets or goals. It’s up to the Licensee to define them. However, guidance for the definition of values is provided, based on a recommended value of a FDF below 10^{-5}/year for all events in plant risk portfolio– internal events and internal/external hazards. For example, for the French EPR, CDF is expected to be lower than 10^{-5}/year, including all type of initiating events. The CDF is expected to be lower than 10^{-4}/year for existing plants. The overall results and insights from seismic PSAs, in particular the very low risk contribution and the absence of any cliff edge effects from seismic levels with an intensity up to the post-Fukushima required seismic level, demonstrate the relevance of the modifications implemented by EDF in response to the Fukushima nuclear accident.

In Hungary natural hazards with occurrence frequency of 1×10^{-4}/year or greater and man-made hazards with occurrence frequency of 1×10^{-7} or greater should be considered in the design basis of the operating units of the Paks NPP. For both categories of hazards, the frequency of 1×10^{-7}/year was selected as a screening criterion to exclude hazards from the PSA. This value was established considering the quantitative nuclear safety criteria applied in Hungary.

In the Loviisa PSA model, external event initiating events have not been categorized considering whether the hazard was below or above the design basis limiting value. The conclusion was that most of the external hazards cause initiating events only above the design basis value so that most of the results (portion of risk) belong to the DEC-category.

Additional information was collected regarding values of the individual hazards inside the design basis area of the questionnaire. It was found as important and asked for when BESEP partners filled in the survey, not just to present the numerical value of the design basis limit for a specific hazard, but also the general (physical) definition of the measured variable.

Three BESEP partners (sites) assigned the frequency of 10^{-4}/year as the limit for design basis, one site the frequency value of 10-5/year, producing more extreme values of hazard intensity. Some examples of external hazard design basis limiting values presented by BESEP partners are as follows:

- for extreme wind, the design basis threshold corresponding to the frequency 10^{-4} was 41.5 - 63 m/s depending on the site (country), a quite wide interval of values, but corresponding to different physical definitions, from “one second wind gust” and “three seconds wind gust” up to “ten second wind gust”; the value of 80 m/s corresponding to the frequency of 10^{-5} was related to “five second wind gust at elevation 25 m above sea level”;
- for tornado, the design basis threshold has not been exactly specified for most of sites;
- for extreme snow, the design basis threshold interval was 160 - 190 mm of water column equivalent (impacting plant for 24 hours), in one case a pressure equivalent of 1.6 kPa was used
- for extreme rain, the same water level as snow equivalent, i.e. 190 mm was used in one case (reached for 24 hours), a set of several values (42 mm/10 min, 58.4 mm/20 min, 93.4 mm/60 min, 138 mm/24 hours) was used for another site, a direct comparison can be made for the 24 hour interval only (190 mm versus 138 mm of water column);
- for extremely high temperature, the values from the interval 40ºC - 50ºC are typical for plant sites of BESEP partners, much lower value of 28ºC is used in one case, but this value correspond to the 24 hours average value;

- for extremely low temperature, the temperature around -45ºC is typical for instantaneous values, whereas the values slightly below -30ºC represent 24 hours averages;
- for icing, the design basis values were recorded in two cases in the questionnaire, which are difficult to be compared, because they used different variables, i.e. 2183 g/m, and 50 mm respectively", a similar situation appears for lighting, where the current value of 100 kA was presented in one case, whereas the number of lighting cases characterises the hazard in another case (6.75 per km^2/year);
- for earthquake, a broad spectrum of ground acceleration values from 0.047 g up to 0.25 g form the design basis limits in the individual cases

4.2.4 Practical elimination points

In France, the 1 x 10^{-7}/year screening value may be regarded as a threshold to be used for practical elimination purposes. It is noted, in addition, that if a certain hazard was selected for detailed assessment in the PSA, such truncation was not applied, i.e. risk due to hazards selected for detailed analysis was assessed for occurrence frequencies lower than 1E07/year, as well.

The Loviisa PSA does not consider practical elimination limits. A general screening level for initiating events is 1 x 10^{-8}/year. In some cases, 1 - 2 % share of the total risk has been considered as "practically eliminated". Some external hazards are though in a way practically eliminated if they could not induce initiating events in any thinkable hazard levels.

The same threshold value is typical for the other sites evaluated in BESEP. The information provided in the questionnaire responses implies that where defined, the practical elimination points are connected with the annual frequency value of 1 x 10^{-7}.

4.2.5 Additional information, challenges

In France there is a recent open discussion on "risk aggregation" where different types of initiating events are mixed and the results of analysis of such mix should be carefully considered since the level of uncertainties, details of development and maturity of the PSA modelling may be rather different for internal events PSA, internal or external hazards PSA. In some cases, expert judgment based conservative values instead of realistic hazard curves were used in the hazard probabilistic analysis (as is the case for riverine flooding for instance), which may tend to distort results, their interpretation and practical insights made on the base of that.

For external hazards PSA, in general, it's important to identify the contributions of different scenarios within a PSA. Such hierarchy is strongly dependent on the hazard characterization. The numerical results of external hazard PSAs are therefore (much) less instructive when compared to the numerical results of internal events or internal hazards PSA. Despite these issues, it still has been possible to draw a number of key insights from the EDF flood PSAs. Based on the first river flooding and surge PSAs, EDF concluded that protection enhancements, already implemented following Blayais and Fukushima events, significantly reduce both CDF and FDF.

In addition, no flood scenarios occurred below a 10,000 year flood event except for a few protections' by-pass scenarios which remain low or even negligible in terms of risk, thanks to the alert system triggering a dedicated procedure to anticipate the flood by protective means. Contribution to the risk from a flood scenario that assumes total loss of power supply (normal and emergency generators) with only Post-Fukushima equipment available also remains low in France. A large part of the estimated risk (around 80 %) results from a cliff-edge effect due to overtopping of the highest flood protections; this event can however be considered as a very rare (just hypothetical) event.

The main insights drawn from the Seismic PSA should account for the strength of knowledge in the characterization to the different risk contributions, in particular regarding the uncertainties associated to the seismic hazard, the assumptions introduced for the fragility analysis of certain SSCs and any simplification in the modelling assumptions. As a consequence, the insights from seismic PSA should always be carefully considered and interpreted. In general, a non-negligible part of the quantitative results related to seismic risk spectrum suffer from large uncertainties. The interpretation of results of seismic risk analysis therefore should focus on those seismic levels where uncertainties are still moderate and for which the main seismic failures are established and modelled with sufficient realism.

In general, addressing of the concept of cliff edge effects represents a challenge for risk engineering and this conclusion is particularly valid for risk analysis of external hazards

4.2.6 Approach to employment of site or country specific data

The related point of the questionnaire focuses on the natural hazards data only. It was expected that the partners will detail how they used site specific data assumed that they collected some data directly at the NPP site or in the neighbourhood. The "neighbourhood" was not defined explicitly in the guidance for the questionnaire so that it could cover just some small perimeter around the reactor unit or broader area where several meteo stations are operated. It was expected, however, that the size of region, the data were collected from, and other supporting details will be given in the questionnaire. In Czech Republic, for example, there are seven meteo stations relatively close to NPP Dukovany operated for decades (one located directly at the site) so that the description of the approach in the questionnaire should provide concrete information how the analysts collected, selected and analysed all the data available.

In France one of the main challenges justifying the approach used was about the hazard characterization step, which becomes even more challenging when considering combinations of flood hazards. Indeed, the purpose of probabilistic assessment is to investigate very rare events having return periods in the range from 10 thousand to 100 million years. Unfortunately, only limited observed and historical data are available for flooding events, at best 200 years of data in most cases. Extrapolation of hazard curves parameters over a number of millennia is then needed to reach the required return periods, hence there are large uncertainties around the best-estimate values. Generally speaking, risk calculations of above 10 000 years flood events are therefore considered as producing hypothetical risk parameters.

In Hungary, hazard assessment was generally based on the data collected by the Hungarian Meteorological Service at station Paks during the past few decades (so that the same problems with extrapolation of data to address much longer time period could be expected). The hazard curves were established by fitting Gumbel distribution to the annual extreme values of these measured site specific meteorological data. The formal means of testing of statistical hypotheses were used to justify that the Gumbel distribution fit the data in appropriate manner. Data sets for longer time periods recorded in some other parts of Hungary were also looked at for review and verification purposes (e.g. extreme value distributions were fitted to data collected in the longer run in Budapest and the results were compared to those calculated on the basis of Paks specific data). It may be noted that lightning as an external hazard required a different analysis approach because several physical properties of lightning had to be assessed in order to be able to characterise the vulnerability of plant structures and equipment. In addition to domestic experience, data from countries located up-stream the river Danube as well as non-Danube specific national data were considered during the hazard assessment for external events endangering water intake from the ultimate heat sink. Historical data were utilized in the verification of hazard assessment for hydrological hazards, using expert judgement.

Almost all sources of hazard frequencies in the Loviisa PSA are somehow local and specific data. External hazards depend heavily on site location and it is quite difficult to justify the use of general data.

Overall, there are three categories of data used in estimation of external hazards frequency: expert judgment, generic data and specific data. In the studies performed by BESEP partners, there were few cases of expert judgment, about 10 % of external hazard frequencies was based on generic data and the rest (90 % approximately) on plant specific data. This shows that site specific data is taken very seriously in current hazard analysis, in general.

An interesting subject of discussion is what the category of site specific (hazard) data really means. In the case of internal events represented by component failures, plant specific data are usually based on real plant (site) history (one of the reasons may be that even for the same components, the failure statistics can differ pretty much among the plants, because the values are impacted by the specifics of plant operation, human factor, safety culture etc.). In the case of hazard analysis, however, the data sample available is usually extremely limited in comparison to what would be needed for statistically well elaborated and justified values of (usually low) hazard frequencies. As a consequence, plant specific data can cover broad geographical area in this case, which may differ pretty much among the sites and countries. Thus, the variety of what "plant specific data" category means is much broader than in case of component failures.

Advanced methods of extrapolation of limited data sample were used by all the BESEP partners to derive the hazard intensities for design basis limiting frequencies (10^{-4} or 10^{-5}). Gumbel distribution was used for the individual hazards in 70 % of the studies, a more general GEV distribution in the remaining ones. A couple of intensities were derived by expert judgment. PSHA was mostly used for earthquake hazard.

4.2.7 Approaches and facts related to combinations of hazards

As a minimum, it was expected that the individual BESEP partners will describe the approach to analysis of combinations of external hazards and whether they have considered already some selected hazard combinations or not.

EDF applied French external hazards screening guide to the 900 MWe plant/sites but limited to single hazards (i.e. no combinations so far). The first screening of combinations of hazards is on-going as part of the 4th PSR of 1300 MWe NPPs. The following combinations of hazards are considered:

- wave generated by wind + riverine flooding - three sites located by a river;
- dam failure + riverine flooding – (the same) three sites located by a river;
- riverine flooding + groundwater – (the same) three sites located by a river;
- local intense precipitation + swell - three sites;
- local intense precipitation + tornado – three sites (at the seaside);
- seaside wave (swell + surge + wind) – (the same) three sites at the seaside;
- wind + biological clogging – (the same) three sites at the seaside;
- tornado + hail – all sites;
- tornado + lighting – all sites;
- hail + lighting – all sites (considered, screened out);
- aircraft crash + pressure wave (strongly connected, can be seen as single hazard, as well);
- air pressure wave + gas/liquid releases (toxic, flammable).

In some cases, the approach used for defining combinations of hazards would be probably different in the work of other BESEP partners. Some combinations mentioned above may seem not to be combinations, but the second hazard in the "combination" is rather consequence of the first one than a new, independent hazard. It appears that some partners put emphasis on correlated hazards mostly, while others address combinations of correlated and combinations of independent hazards, as well.

The following combinations of external hazards were selected for detailed assessment in Hungary:

- storm: high wind and extreme precipitation and thunder;
- snowstorm: high wind and extreme snow;
- extremely high temperature conditions: extremely high air temperature and high Danube river temperature;
- extremely low temperature conditions: extremely low air temperature and surface ice on the Danube river (and icing and snow);
- earthquake and soil liquefaction;
- earthquake and extremely high or low air temperature (independent hazards in combination);
- simultaneous accident in nearby industrial facilities that handle dangerous chemical substances (due to a common root cause, e.g. earthquake, high wind or tornado);
- extreme meteorological conditions and handling of dangerous substances (the meteorological conditions can have a significant impact on the dispersion and spreading of dangerous substances).

It should be noted that hazard assessment is ongoing and fragility assessment is going to be started soon for the listed hazard combinations in order to enable detailed PSA modelling thereof.

An example was given in the comment from NUBIKI that in some cases the order of occurrences of the hazards in a combination may be really important. A concrete example was the integrated impact on buildings from snow and wind, which is relevant when there is already accumulated snowpack on (the roof of) safety related buildings and subsequently a wind load also occurs. Another example is seismic event, when the HVAC system may get damaged and subsequently a heat wave occurs. These “primary” and “secondary” hazards should be considered when the relevant hazard combinations are selected and defined. Moreover, this aspect should also be taken into account in the hazard assessment as well as in the plant response and fragility analysis.

The following points can be made regarding considerations to combinations of external hazards in the Loviisa PSA:

- there are many combinations of extreme wind + other hazard(s) modelled;
- a specific approach has been used in Nordic PSAs, where the icing hazard covers also the extreme snow hazard in combination, whereas the extreme snow hazard as a single one is expected to have very low impact, all IEs including icy conditions with high winds are expected blocking e.g. air intakes; some IEs include also external event combinations with frazil ice and / or algae blocking sea water access;
- frazil ice has been typically combined with other external hazards blocking sea water access.

The aggregation (summation) of risk due to different hazards is applicable only if the hazards that are subject to aggregation can be considered as independent, having no dependence at least in terms of occurrence frequencies. The assumption of independence is often applicable to different single hazards; however, this assumption may not be appropriate when modelling combinations of hazards (e.g., a seismic model and a fire model, as opposed to a seismically-induced fire model). The approach to ensuring the independence of a combined hazard model from the single hazard models that are incorporated within the combination is dependent on the hazard assessment method, but it is generally a complex, not straightforward task.

Let us assume that event logic models are developed for high wind, for extreme rainfall, and for the combination of the two. The aggregation of the risk measures from these three initiators would only be adequate if the occurrence frequency of each single hazard is estimated so that the occurrence of another hazard has not been considered (i.e. mutually exclusive initiators). In this example the hazard curve considered in the high wind PSA should reflect the occurrence frequency of high wind events without any rain. Similarly, the PSA on extreme rain should take into account the event frequency of heavy rain without a strong wind, and lastly the model for the combined hazards should cover the frequencies for the occurrence of both hazards simultaneously. Theoretically, use of multivariate hazard functions (hazard surfaces) could yield more detailed results in which marginal distributions for the different hazards would represent single-hazard situations, but the use of such an approach is beyond state-of-the-art at present.

4.2.8 Human induced external hazards

To some difference from previous sections, where the core of natural external hazards expected to be presented in the surveys was given (by the outputs of Task 2.1), there was no concrete expectation regarding human induced external hazards. The idea was to identify human induced hazards selected as important in the individual BESEP countries, in particular those, which are supposed to be addressed later in the case studies. The only exception was aircraft crash, which was supposed to be addressed (as the main and most typical external hazard induced by human) in all countries of BESEP partners.

In France, aircraft crash is considered for all 900 MW and 1300 MW sites and the analysis is ongoing. The existing deterministic safety demonstration studies already consider a probabilistic approach. The risk values obtained from these studies are compared to the overall fuel damage risk with all causes considered.

In Hungary, man-made hazards with occurrence frequency of $1x10^{-7}$/year or greater should be considered in the design basis of the operating units at the Paks NPP, and the same value was selected as screening criterion to exclude hazards from the PSA. Consequently, if the Paks NPP can withstand the design basis loads induced by a man-made external hazard, the risk due to that hazard cannot be significant. Amongst others, this fact led to the exclusion of all man-made external hazards from further detailed assessment in the PSA.

It is also noted that most of the man-made hazards originated from outside of the plant site cannot pose a significant impact on the safety related SSCs of the Paks NPP, hence most of the off-site man-made hazards could be screened out on the basis of impact. Aircraft crash was the only man-made off-site external hazard that required detailed plant response and fragility assessment, including the application of a combination of probabilistic as well as deterministic approaches.

A brief summary of the information presented in the questionnaire by BESEP partners can show that: aircraft crash hazard was screened out due to low contribution (frequency) in most cases, modelled in one case;

- the impact of chemical substances outside the plant was screened out in all cases;
- missiles from rotating equipment outside were found irrelevant in half cases, screened out in the remaining ones;
- transportation accidents were screened out, not considered, or found irrelevant in almost all PSAs; they were modelled to some extent in the Loviisa PSA;
- electromagnetic interference was screened out due to low risk contribution in all cases;
- malicious attacks were not considered yet, screened out, or found out of the scope of PSA mostly.

5 Conclusions of the analysis and recommendations for using the results in the next tasks of BESEP

This document represents deliverable D2.4 of the BESEP project – results of the process of identification and analysis of risk-significance thresholds related to external hazards. Information was collected on the probabilistic safety assessments and plant level risk targets involving external hazards carried out in the countries of BESEP partners. Based on the collected information, the general risk-significance measures related to various external hazards were identified and discussed.

The discussion of risk-significance thresholds was based on an example taken from NuScale technology [1] showing that the traditional metrics used for specification of risk significance may not completely cover the needs of risk engineering applied for new NPPs with expected higher safety level. This is an important conclusion made in the Task 2.4, which will be further analysed and developed in the next Tasks of the BESEP project.

The information collected and evaluated was oriented to four basic areas, which will form important subjects of continuation of BESEP work in the next tasks:

- general risk related thresholds typical for current nuclear power plant risk engineering, and probabilistic safety assessment in particular;
- selected information about risk-significance parameters used and reached in the PSA studies with participation of the BESEP partners for the individual external hazards;
- information about connection between (probabilistic) risk-significance thresholds and extreme values derived for intensities of natural hazards representing design basis limits;
- supplementary information about selected features of the methodologies used for the treatment of external hazards in the individual PSA studies and supporting analyses (plant specific data analysis, for example).

The scope of the work has covered not only individual hazards, but also combinations of hazards, which represent big challenge for current hazard risk analysis (addressed in the activities of OECD NEA WGRISK and WGEV working groups). In addition to the natural hazards, which are in the focus of work, man-caused external hazards have also been included into the scope of the work (aircraft crash, for example).

Thanks to the locations of the NPP sites operated in the countries of the BESEP partners, the analyses carried out in the BESEP project represent big variate of external conditions of NPP operation:

- from the NPPs operated in a relatively cold climate in north Europe up to the mild climate typical for French sites
- from the NPPs operated far away from large water sources in Czech Republic up to the plants located at the seaside
- from the NPPs operated in a geological very stable sires with very low earthquake potential up to the plants with orders of magnitude higher values of seismic hazard parameters.

The collected information described and analysed in this report will be utilised in the specification of case study groups in the BESEP Task 3.2 and in the definition of comparison criteria for the cross-group comparison in Task 4.1. It will also provide basic features of the context of NPP operation from point of view of external hazards impact, which will be used in comparison of case studies performed in Task 4.2, evaluation of balance in verification of safety margins between different external hazards in Task 4.3, selection and evaluation of the best practices in HFE area in Task 4.4 and making recommendations on deployment of more sophisticated safety analysis in Task 4.5.

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