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Report 3: Guidance document on practices to model and

implement EXTREME WEATHER hazards in extended PSA

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The goal of this report is to provide guidance on practices to model EXTREME WEATHER hazards and implement them in extended level 1 PSA. This report is a joint deliverable of work package 21 (WP21) and work package 22 (WP22). The general objective of WP21 is to provide guidance on all of the individual hazards selected at the End Users Workshop. This guidance is focusing on extreme weather hazards, namely: extreme wind, extreme temperature and snow pack. Other hazards, however, are considered in cases where they are correlated/ associated with the hazard under discussion. Guidance developed refers to existing guidance whenever possible. As it was recommended by end users this guidance covers questions of developing integrated and/or separated extreme weathers PSA models.

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EXECUTIVE SUMMARY

The goal of this report is to provide guidance on practices to model EXTREME WEATHER hazards and implement them in extended Level 1 PSA. This report is a joint deliverable of work package 21 (WP21) and work package 22 (WP22). The general objective of WP21 is to provide guidance on all of the individual hazards selected at the End Users Workshop. The objective of WP22 is to provide the solutions for purposes of different parts of EXTREME WEATHER Level 1 PSA fulfilment. This guidance is focusing on extreme weather hazards, namely: extreme wind, extreme temperature and snow pack. Guidance developed refers to existing guidance whenever possible.

The initial part of guidance (WP21 part) reflects current practices to assess the frequencies for each type of hazards or combination of hazards (including correlated hazards) as initiating event for PSAs. The sources and quality of hazard data, the elements of hazard assessment methodologies and relevant examples are discussed. Classification and criteria to properly assess hazard combinations as well as examples and methods for assessment of these combinations are included in this guidance. In appendixes as examples some practices of extreme wind and tornado assessment and specific cases of national experiences on extreme weather assessment are presented.

At all stages of this guidance and especially from an industrial end-user perspective, one must keep in mind that the development of Extreme Weather Hazards probabilistic analysis must be conditioned to the ability to ultimately obtain a representative risk analysis.

As it was recommended by end users (WP10 [1]), this guidance covers questions of developing integrated and/or separated extreme weathers PSA models. Methods to model the combinations/correlations/dependencies of hazards, possible secondary effects, mitigating and aggravating factors are also proposed in the report. This report contains approaches to model mobile equipment but despite this fact, input data related to this (reliability and related human actions, assessment of time for its running) remains a source of significant uncertainty. Approaches for building hazards curves and fragility curves are described in the guidance and presented useful references, as well as approaches for site response analysis (SSCs failure modes, buildings resistance, etc.). A question of how to model an extreme weather hazards to initiating event and specific conditions/factors for Human Reliability Assessment (HRA) is also considered by the report. HRA discussion is based on the identification of personnel actions performed within the accident management strategy and caused by external extreme hazards, and to define human error probability for such actions.

The scope of the guidance is quite wide thus for hazard assessment the general methods were presented with specific focus on the open issues in the existing guidance and current practices. At first, for the hazard assessment in order to reflect the state of the art/science the following issues could be listed:

- limitations in modelling and forecasting the physical phenomena and conditions leading to extreme hazard;
- uncertainties in estimation of the impact of climate change on extreme meteorological events;
- lack of site-specific data and limitations of spatial modelling and downscaling methods;
- practical application of complex probabilistic models, like mixed distributions;
- high uncertainties in tornado data and tornado frequencies estimation;
- validation limitations for tornado physical phenomena and its impact models;
- difficulties in integrated modelling of hazard internal and external impact assessment;
- lack of applicable experiments for the improvement of the extreme wind consequence models.



EURATOM

The main remaining open issues for WP22 part are following:

- limitation in determining the occurrence frequency of extreme weather conditions;
- scope of the fragility curves is limited (especially for extreme temperatures influence);
- adequate and practically applicable methodology for assessing the failure probability of indoor SSCs (taking into account outside temperature and Heating, Ventilation, Air Conditioning (HVAC) capacity);
- correlation among an extreme weather event induced failure modes and on the quantification of correlation coefficients;
- uncertainties in operational strategy under harsh weather conditions;
- winds and tornadoes induced missiles estimation and modelling.

The existing guidance does not cover specially practices to model extreme wind, extreme temperature and snow pack, however dealing with state of the art it is possible to identify practices to analyse this type of hazards or combination of hazards (including correlated hazards). In this guidance, the sources and quality of hazard data as well as elements of hazard assessment methodologies and relevant examples are discussed pointing out how these could be used for hazards assessment and extended PSA. Classification and criteria to properly assess hazard combinations as well as examples and methods for assessment of these combinations are included in this guidance. In appendixes as example the extended practices of extreme wind and tornado assessment and specific cases of national experiences on extreme weather assessment are demonstrated.

The general procedure, modelling principles and major analysis steps in the development of a Level 1 PSA model for extreme weather hazards are in good agreement with that of Level 1 PSA in general. A major limitations and gaps of extreme weather PSA are related to the data availability and its implementation. Main uncertainties appear from the hazard evaluation and NPP response analysis issues (buildings resistance, missile impact, long-term effects, mitigation actions or human errors, etc.). Description of these and other features of extreme weather PSA modelling can be found in the current report.

From an industrial end-user perspective, the PSA methodology must be proportionate to the importance of risks (this can be also required by national laws such as the French Law). The adoption of a graded approach for External Hazards PSA would better focus resources and direct them to identify and address issues that present the highest significance to NPP Risks and Safety. Therefore, there is no relevance to use complex methodologies if a simplified analysis gives sufficient and representative insights.





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ABBREVIATIONS

BWR	Boiling Water Reactor
CCF	Common Cause Failure
CCDF	Conditional Core Damage Frequency
CDF	Core Damage Frequency
CWS	Cooling Water System
DB	Data Base
EOP	Emergency Operating Procedure
ESWD	European Severe Weather Database
ESWS	Essential Service Water System
ET	Event Tree
EVT	Extreme Value Theory
FDF	Fuel Damage Frequency
HEP	Human Error Probability
HRA	Human Reliability Analysis
HVAC	Heating, Ventilation, Air Conditioning
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IRS	Incident Reporting System
LERF	Large Early Release Frequency
LRF	Large Release Frequency
LOCA	Loss of Coolant Accidents
LOOP	Loss of Off-Site Power
MCR	Main Control Room
MCS	Minimal Cut Set
MGL	The multiple Greek letter model
NPP	Nuclear Power Plant
NWS	National Weather Services
PDS	Plant Damage State
РОТ	Peak over Threshold
PSA	Probabilistic Safety Assessment
PRA	Probabilistic Risk Assessment
RCS	Reactor Cooling System
SAMG	Severe Accident Management Guidance
SSC	Structure, System and Component
WP	Work Package
L	





DEFINITIONS

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

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





	tensity level of the hazard event.
	• Fragility analysis considers all failure mechanisms due to the occurrence of an external hazard event and calculates fragility parameters for each mechanism. This is true whether the fragility analysis is used for an external flood hazard, fire hazard, high wind hazard, seismic hazard, or other external hazards. For example, for seismic events, anchor failure, structural failure, and systems interactions are some of the failure mechanisms that would be considered.
Fragility Curve	A graph that plots the likelihood that a component, system, or structure will fail versus the increasing intensity of a hazard event.
	• In a PRA, fragility curves generally are used in seismic analyses and provide the conditional frequency of failure for structures, systems, or components as a function of an earthquake-intensity parameter, such as peak ground acceleration.
	 Fragility curves also can be used in PRAs examining other hazards, such as high winds or external floods.
Hazard	The ASME/ANS PRA Standard defines a hazard as "an event or a natural phenomenon that poses some risk to a facility.
	 Internal hazards include events such as equipment failures, human failures, and flooding and fires internal to the plant.
	• External hazards include events such as flooding and fires external to the plant, tornadoes, earthquakes, and aircraft crashes."
Hazard Analysis	The process to determine an estimate of the expected frequency of exceedance (over some specified time interval) of various levels of some characteristic measure of the intensity of a hazard (e.g., peak ground acceleration to characterize ground shaking from an earthquake). The time period of interest is often taken as 1 year, in which case the estimate is called the annual frequency of exceedance.
High winds	Tornadoes, hurricanes (or cyclones or typhoons as they are known outside the U.S.), extratropical (thunderstorm) winds, and other wind phenomena depending on the site location.
	OR
	Winds of a certain size that could potentially damage or affect the operability of a nuclear power plant.
High wind hazard anal- ysis	The objective is to evaluate the frequency of occurrence of different intensities of high winds.
Human Reliability Anal- ysis	A structured approach used to identify potential human failure events and to sys- tematically estimate the probability of those events using data, models, or expert judgment.
Initiating Event	An identified <i>event</i> that leads to <i>anticipated operational occurrences</i> or <i>accident conditions</i> .
	• This term (often shortened to <i>initiator</i>) is used in relation to <i>event</i> reporting and <i>analysis</i> , i.e. when such <i>events</i> have occurred. For the consideration of hypothetical <i>events</i> considered at the <i>design</i> stage, the term <i>postulated initiating event</i> is used.
Large early release	The rapid, unmitigated release of air-borne fission products from the containment to the environment occurring before the effective implementation of off-site emer- gency response and protective actions such that there is a potential for early health effects.
Large early release frequency (LERF)	Expected number of large early releases per unit of time.
Loss of coolant acci- dent (LOCA)	Those postulated accidents that result in a loss of reactor coolant at a rate in excess of the capability of the reactor makeup system from breaks in the reactor coolant pressure boundary, up to and including a break equivalent in size to the double-ended rupture of the largest pipe of the reactor coolant system.
Loss of Offsite Power	The loss of all power from the electrical grid to the plant.





(LOOP)	In a PSA/PRA, loss of offsite power (LOOP) is referred to as both an initiating event and an accident sequence class. As an initiating event, LOOP to the plant can be a result of a weather-related fault, a grid-centered fault, or a plant-centered fault. During an accident sequence, LOOP can be a random failure. Generally, LOOP is considered to be a transient initiating event.
Postulated Initiating Event (PIE)	An event identified during design as capable of leading to anticipated operational occurrences or accident conditions.
	• The primary causes of <i>postulated initiating events</i> may be credible equipment <i>failures</i> and <i>operator</i> errors (both within and external to the <i>facility</i>) or human induced or natural <i>events</i> .
Structures, Systems and Components (SSCs)	A general term encompassing all of the elements (items) of a <i>facility</i> or <i>activity</i> which contribute to <i>protection and safety</i> , except <i>human factors</i> .
	• Structures are the passive elements: buildings, vessels, shielding, etc.
	• A <i>system</i> comprises several <i>components</i> , assembled in such a way as to perform a specific (active) function.
	• A <i>component</i> is a discrete element of a <i>system</i> . Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.
Severe accident	A type of accident that may challenge safety systems at a level much higher than expected.
Screening	A process that distinguishes items that should be included or excluded from an anal- ysis based on defined criteria.
Screening criteria	The values and conditions used to determine whether an item is a negligible con- tributor to the probability of an accident sequence or its consequences.
Sensitivity Analysis	A quantitative examination of how the behaviour of a <i>system</i> varies with change, usually in the values of the governing parameters.
	• A common approach is parameter variation, in which the variation of results is investigated for changes in the value of one or more input parameters within a reasonable range around selected reference or mean values, and perturbation <i>analysis</i> , in which the variations of results with respect to changes in the values of all the input
Uncertainty	A representation of the confidence in the state of knowledge about the parameter values and models used in constructing the PRA.
	OR
	Variability in an estimate because of the randomness of the data or the lack of knowledge.
Uncertainty Analysis	An <i>analysis</i> to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem.





1 INTRODUCTION

Extreme weather or natural hazards shall be considered an integral part of the safety demonstration of the plant (including spent fuel storage). Threats from natural hazards shall be removed or minimized as far as reasonably practicable for all operating states of the nuclear power plants (NPPs). The safety demonstration in relation to natural hazards shall include assessments of the design basis and design extension conditions, and also beyond design conditions with the aim to identify needs and opportunities for improvement.

At all stages of this guidance and especially from an industrial end-user perspective, one must keep in mind that the development of Extreme Weather Hazards probabilistic analysis must be conditioned to the ability to ultimately obtain a representative risk analysis.

All natural hazards that might affect the site shall be identified, including any combinations of hazards (e.g. earthquake and tsunami). Justification shall be provided that the compiled list of natural hazards is complete and relevant to the site. If and only if it is relevant to do so (risk representativeness, industrially feasibility), the extreme weather PSA has to be developed also for combinations of external natural hazards and internal hazards, occurred independently or as a result of the external natural hazards.

The goal of this report is to provide guidance on practices to model EXTREME WEATHER hazards and implement them in extended Level 1 PSA. This report is a joint deliverable of work package 21 (WP21) and work package 22 (WP22). The general objective of WP21 is to provide guidance on all of the individual hazards selected at the End Users Workshop [1]. The objective of WP22 is to provide the solutions for different parts of EXTREME WEATHER Level 1 PSA.

ASAMPSA_E end-user workshop held in Uppsala showed [1] that there have been 10 important external hazards identified as the minimum required to be addressed by the project. These hazards are the following:

- seismotectonic hazards (earthquake);
- external flooding;
- extreme air temperature;
- snow pack;
- lightning;
- storm (tornado, hurricane);
- biological infestation;
- aircraft crash;
- external fire;
- external explosion.

The purpose of this report is to provide guidance on extreme weather hazards that could lead to consequences threating the safe operation of NPPs, including description of the specific phenomena and recommendations for implementation of extreme weather hazards and modelling of extreme weather conditions in extended L1 PSA.

This guidance will consider the following extreme weather hazards:

- extreme wind (including storm, tornadoes),
- extreme temperature (including maximal and minimal temperatures, rapid change of temperatures),
- extreme snow pack (including icing and snow pack).

In general, considering various natural hazards the extreme weather hazards group include events related to extreme ambient temperature (low or high), strong winds (including tornadoes, typhoons, hurricanes) or intense water precipitation without flooding. Based on the analysis of external events reported to the IAEA Incident Re-



porting System (IRS) database [3], most of the events affecting nuclear plant operation are caused by extreme weather conditions (next frequent groups are the biological water intake fouling hazards and lightning hazard). The extreme weather conditions are manifesting by heavy snow or rain, drought, frost, freezing, ice, wind, missiles and debris.

Analysis of IRS database records leads to the conclusion that the extreme weather conditions group of external hazards had no severe impacts on nuclear safety; they induce only few events with safety significance. This could be due to the fact that in some cases the occurrences are foreseen, the evolution is slow and mitigation measure could be implemented in due-time. The external phenomena mostly affected the systems and equipment of heat sink or power supply, and they have induced the following consequences [3]:

- electrical disturbances (e.g. due to extreme strong wind),
- loss of offsite power (e.g. due to extreme strong wind, extreme snow),
- components damage, inside or outside the NPP (e.g. the combination of inside high air humidity and walls low temperature can lead to excessive condensation and consequently to the failure of electrical equipment; instrument lines may freeze due to low temperatures, and this may lead to spurious signals or misleading information for the operators; frost spreading inside buildings can lead to equipment/piping break by bulge during ice formation, and important leakages can occur during unfreezing),
- compromising the cooling functions this could be due to blockage of air intakes (due to snow, frost or freezing or due to air blown debris), or low water level for cooling function (drought) (e.g. due to cold weather and ice build-up, which may clog the water intake, causing eventually malfunctioning of the heat sink; high wind blowing in the direction of a cooling-tower can create important water movements in cooling-tower ponds which can lead to a cooling water system (CWS) pump tripping by "low water level" protection,
- harsh conditions for working outside and heavy conditions for implementing the accident management measures and emergency plans (including communications) in case of storm (wind, missiles, debris), frost, freezing rain, heavy snow and heavy rain,
- heavy conditions for site accessibility in case of storm (wind, missiles, debris), frost, freezing rain, heavy snow and heavy rain.

The potential combinations of the extreme weather hazards could have multiple critical effects on the plant operation (e.g. loss of offsite power induced by high winds, in combination with blockage of cooling water intakes induced by frost).

The combinations of hazards experienced by NPPs is presented in [4], e.g. freezing rain, strong winds and low temperature (France, 30/12/2005); high wind and frost (Hungary (14/03/2013).

Sometimes, the meteorological hazards have occurred in combinations with internal failures, and these simultaneous occurrences are inducing more difficulties in mitigation of the consequences (Germany, 23/01/1995) [4].

The meteorological events have certainly the potential to affect several reactors at the same time (multi-unit effect) and they may have even a trans-boundary effect in case of interconnected electricity transmission networks.

In addition, the combinations of external extreme hazards considered in this report are addressing seasonal peculiarities (for example, summer heat and drought, low temperatures and icing, etc.). Since collection of sufficient amount of statistical data for the abovementioned external extreme hazards is a difficult task due to their heterogeneity, unrepresentative information (description of events and/or small number of events), major uncertainties, etc., and since safety assessment of such hazards is mainly performed using bounding analysis and deterministic





approach, this report also propose approaches for analysis of NPP hazard response and options to simplify the methodologies in view of difficulty to receive necessary data. The report present approaches with the use of hazard intensity notion (hazard curves), approaches for identification of possible initiating events, accounting of secondary effects and possible impacts on Systems, Structures and Components (SSCs) (fragility curves).

As this report is a joint deliverable of work package 21 (WP21) and work package 22 (WP22) the structure and material provided in the report reflect this quite clearly by two main chapters.

The first chapters are dealing with current practices to model hazards and to assess the frequencies for each type of hazards or combination of hazards (including correlated hazards) as initiating event for PSAs: sources and quality of hazard data, elements of hazard assessment methodologies, identification of hazard parameters, hazard data preparation and analysis, methods for hazard assessment and other subjects of hazard assessment. Various examples of assessment methodologies are presented in subchapter 2.3. It reflects application of extreme value theory, statistical estimation of probabilities using different type of meteorological data, consideration of uncertainties and issues of hazard assessment in relation to the PSA tools. The next, subchapter 2.4 presents the classification and criteria to properly assess hazard combinations. Then examples (in subchapter 2.5) and methods for assessment of these combinations (in subchapter 2.6) are discussed.

The second part of the report (chapter 3) deals with the structure and solutions of extreme weather PSA. The material presented in this chapter mainly presents the relevant work divided into four subjects:

- 1) Impact on the SSCs modelled in L1 PSA event trees (subchapters 3.1 and 3.2);
- 2) Impact on Human Reliability Assessment modelling in L1 PSA (subchapter 3.3);
- 3) Site impact and emergency response modelling in L1 PSA event trees (subchapters 3.4 and 3.5);
- 4) Link between external initiating events of PSA and NPP design basis conditions (presented as state-of-the-art methodology in subchapter 3.6).

At the end of this report, attention is dedicated to simplified approaches for consideration of extreme weather hazards based on a discretization of the hazard and the fragility curves using a limited number of hazard intensities. The description of a more detailed approach (use of continuous hazard and fragility curves for the whole range of hazard intensity of interest) is presented in subchapter 3.6. Nevertheless, it is necessary to state that the use of continuous fragility and hazard curves is a more likely approach because this simplifies the probabilistic model logic in terms of the number of event trees (ET). In spite of the fact that obtained results could be more precise, this approach needs a specific code and computational power resources (time). On the other hand, the approach using discretization of the hazard and the fragility curves allows describing issues related to combinations of hazards, secondary effects and emergency response more demonstrably and easier.

The full scope probabilistic model of L1 PSA is considered as a basis for assessment of extreme weather conditions. This model shall be adapted where relevant to define conditional core damage frequency (CCDF) and other quantitative results.

Finally, after the overview of open issues (in chapter 4), the conclusion and recommendations of the document are presented in chapter 5. Then the last sections include a list of open issues, list of references, list of tables and figures. The appendix 1 contains an overview of the methodologies for the hazard assessment of extreme winds and tornadoes presenting complexity of the related phenomena. Then, in appendix 2, the specific cases and features of national experiences on extreme weather assessment are demonstrated.





2 PRACTICE TO MODEL HAZARDS

2.1 HAZARDS DATA

2.1.1 SOURCES OF HAZARDS DATA

Sources of data required for hazard assessment

It is necessary to collect the available data related to the weather hazards to characterize observed weather conditions (e.g. frequencies of wind speed and direction, hurricanes and tornadoes, extreme precipitation, extreme temperature conditions, increased solar radiation). In the determination of hazards, the following sources could be used:

1. Site specific data

The data collected regarding the characterization parameters for the extreme weather hazards are recorded in the meteorological data bases. Operational experience of nuclear installations regarding events caused by extreme weather conditions are the best data source to determine the frequency of initiating events. The relevant part of NPP Units' Safety Cases (environmental impact assessment), the results of studies on the stages previous to NPP unit's design and available literature data can be used as an initial data sources for collection. Database of plant operational events should contain information regarding plant specific event, as well as general meteorological information. An on-site meteorological investigation program (include measurements of the wind and temperature profiles) should be initiated for evaluating the characteristics in relation to atmospheric dispersion phenomena [2].

To collect weather hazard data, meteorological parameters should be continuously measured and recorded onsite. Depending on the site-specific conditions it might be necessary to measure the parameters in different locations to get representative data. The size of the region considered in the hazard assessment should be large enough to include all features and areas that could be relevant in the characterization of the meteorological event and the associated natural phenomena.

In cases where the site-specific data are sparse or cover only very short observation times, data from other regions that are sufficiently relevant (i.e. similar climatic, meteorological and topographic conditions) to the region of interest may be used in the determination of hazards. Comparative analysis of on-site and adjacent off-site records should be carried out to validate the use of the off-site data. Appropriate and acceptable simulation techniques may also be used. In general, data obtained for similar regions or by simulation techniques may also be used to augment the available site specific data.

In some cases, where the existing meteorological stations for collecting data in the region are inadequate or insufficient, supplementary observation stations should be set up, to supplement the existing collected data [2].

2. Meteorological statistics and maps produced by local and national meteorological institutes

Information collected at local meteorological stations normally includes data on wind, temperature and precipitation and are typically used to derive useful statistics. Such data can provide for meteorological events histograms of frequency versus intensity.

Climate normal and extreme values of parameters, such as air pressure, air temperature, air humidity, wind speed and direction characterize the meteorological environment and are measured routinely by national meteorological services as well as by international and local organizations. Measurements are collected, archived and made avail-



able by national meteorological services; they may be used with the careful consideration of the criteria and methodologies recommended for assessing the hazards [2].

Highly-accurate meteorological forecast models that include long-term and short-term forecasts, global and regional models, real-time raw data from weather station network, and calculations for regions can be developed. Weather data are related to current weather data, daily forecasts, and historical data and they can be provided in forms of helpful stats, graphics, and history charts. Typically, daily forecasts are available for up to 2 weeks. A variety of interactive maps are available worldwide concerning precipitations, clouds, pressure, temperature, wind, and other parameters of the meteorological events. Weather maps can be connected as layers to a wide range of maps.

Data sources to model the hazards are mainly time series data. The data required to model hazard and estimate meteorological hazard frequencies are mainly observation time series as long and homogeneous as possible. These initial observation time series must be at least daily, and should record daily maxima (or minima): maximal and minimal daily temperature, daily wind gust speed or daily snow depth. Homogeneity means that the measurements are made in the same conditions throughout the observation period, so that no break or changes in the environment are responsible for disturbing the identical distribution of the data.

The meteorological data are provided by the National Weather Services (NWS), global meteorological centres, environmental organizations, local weather data providers, airports and others.

There is an ongoing effort to collect and to analyse the meteorological data, including the intended outcome of various projects - some examples of such initiatives are given below:

- Europe, European Centre for Medium-Range Weather Forecasts: <u>http://www.ecmwf.int;</u>
- *European Climate Assessment and Datasets (ECA&D)* project provide daily time series available: <u>http://eca.knmi.nl/</u>, together with indications on their homogeneity (through homogeneity maps). Time series are available for daily minimum and maximum temperature, snow depth and wind gust. Together with local observed times series, the site provides gridded data, which correspond to an interpolation on a regular grid of all the time series. This may help finding information for a location where no measurements could have been found.
- United States, National Oceanic and Atmospheric Administration: <u>http://www.noaa.gov;</u>
- Canada, Environment Canada: <u>http://weather.gc.ca;</u>
- Japan, Japan Meteorological Agency: <u>http://www.jma.go.jp;</u>
- International, METAR data from airports: <u>http://en.wikipedia.org/wiki/METAR</u>, http://openweathermap.org;
- *MeteoGroup's Historical Weather DB*: <u>http://www.meteogroup.com/en/gb/services/historic-weather-data.html</u>. Including a wide range of weather parameters (wind speed and direction, temperature, dewpoint, cloud cover, radiation and precipitation), MeteoGroup has one of the most comprehensive Data Base of global historical meteorological data in the world. Many of the parameters are available in hourly intervals and daily summaries are also provided such as maximum and minimum temperature, and total rainfall.
- European Severe Weather Database (ESWD) <u>http://www.eswd.eu.</u> Including networks of voluntary observers, meteorological services and general public, ESWD has as objective to collect and provide detailed and quality-controlled information on the severe storm events over Europe (information on the tornado, severe winds, large hail, heavy rain, vortex, dust devil, heavy snowfall/snowstorm, ice accumulation, avalanche and lightning). Data collection is based on information from reports received by e-mail, newspa-





per, television or radio broadcast, photographic or video footage of the inflicted damage, websites, and testimony of an eyewitness of the damage. Data can be used for academic purposes, declaring the project involved, period, event types and area for which data are requested. For data use in large funded projects, an access fee is involved.

Historical (even unofficial data) and instrumentally recorded data, as applicable, regarding the occurrences and severity of extreme weather conditions in the region of the site should be collected and carefully analysed for reliability, accuracy and completeness.

2.1.2 SIMULATION DATA AND QUALITY

The data required to model hazard and estimate meteorological hazard frequencies are mainly observation time series as long and homogeneous as possible. These initial observation time series must be at least daily, and should record daily maxima (or minima): maximal and minimal daily temperature, daily wind gust speed or daily snow depth. Homogeneity means that the measurements are made in the same conditions throughout the observation period, so that no break or changes in the environment are responsible for disturbing the identical distribution of the data.

As weather data are generally provided by NWS or through initiatives launched by meteorologists and climatologists, meteorological data are of relatively good quality. It is however important to check some key features, as follows:

1. <u>Data completeness</u>: It is important that the time series have not too many missing data. Long periods of missing data are difficult to reliably correct and must be avoided, if necessary by removing the concerned period from the considered time series. Data collection should be as complete as possible and should include the acquisition of new data. In many cases, the acquisition of new data will be the only tool to narrow down the uncertainties of the outcome of the assessment. To avoid the larger uncertainties in the data, sensitivity analysis or plant reinforcement feasibility studies can be used.

2. <u>Known extremes:</u> It can be useful to check that known extremes are present in the sample and do not correspond to missing values (important storms for wind gust, cold or heat waves for temperature etc.). If they are not, other information sources are needed (nearby measurements to infer a plausible value or in replacement of the firstly selected time series if observation length permits).

3. <u>Possible breaks in time series</u>¹: It can be necessary to check time series for possible breaks and to use relevant tools. For instance, Environment Canada developed and made available a software package (RHtestsv3 [6]) to check time series for possible breaks.

Re-analyses of numerical simulation data are common products for climate studies. They correspond to a sophisticated data assimilation with a climate model in order to offer a global dataset of climate observations all around the world for climate models initializations and validations. However, they generally give a large scale view of the phenomenon, not really suitable for extreme studies. Some weather services may provide local re-analyses with a refined spatial scale which can be more appropriate. Furthermore, works are ongoing, especially in European pro-

¹ A break (structural) appears when we see an unexpected shift in a time series. It's called a structural break when a time series abruptly changes at a point in time. This can lead to huge forecasting errors and unreliability of the model in general.





jects, to produce finer scale re-analyses products (European project UERRA). Synthetic data may be produced for other hazards, for example, Jerome Weiss [5] used a numerical hind cast of wave heights to study this hazard for the French coasts.

In case of rare meteorological phenomena (e.g. tornadoes), the affected area is relatively small, and this fact may make the accumulation of relevant and adequate data difficult. In case of rare weather phenomena, an estimation of the intensity of the phenomenon may be determined on the basis of conceptual or numerical models of the phenomenon, coupled with statistical methods appropriate for the rate of occurrence and the intensity of the event at the site [2]. The size of the region to be investigated should be determined on the basis of the specific characteristics of the meteorological and geographical environment of the area in which the site is located and the hazard under consideration (e.g. tornadoes or hurricanes) [3].

2.2 HAZARD ASSESSMENT

The possible procedure for meteorological hazard assessment is related to the likelihood or frequency estimation of values of extreme meteorological variables (parameters) and may consist of the following steps:

- a) Identification of meteorological variables or parameters;
- b) Hazards data preparation, analysis and assessment of data quality;
- c) Application of various methods for hazard assessment, including methods for:
 - choice of probability distribution with best fit to the data;
 - data processing in order to obtain various statistical aspects (e.g. expectation, standard deviation, etc.) for the purpose of estimation of probability distribution function parameters or other characteristics of variables under investigation.

Extreme annual values of meteorological variables (parameters) are described by random variables, which are characterized by some specific probability distribution. In other words, data sample is linked with specific probability distribution. The most common in practice extreme value distributions are Gumbel (also known as Fisher-Tippett or Type I), Frechet (Type II) and Weibull (Type III) distribution. However, large sample is needed in order to assess the goodness of fit of each of these distributions.

For the assessment of external events the following research works might be carried out:

- events that may have influence on the safety and design solutions of NPP are identified;
- parameters of meteorological phenomena, hazards and their possible consequences are defined;
- the statistical data is assessed (amount, reliability, etc.);
- selection of events for further analysis is performed;
- detailed analysis of identified essential events is performed.

Choosing methodologies of statistical data processing and probable event probabilistic calculations the following principles should be taken into account:

- <u>approbation</u>: only those methods are used which are given, for example, in publicly available IAEA documents, official probabilistic safety analysis reports or scientifically justified works;
- <u>conservatism</u>: due to lack of data or uncertainty of calculation results, more conservative assumptions are made and thus probabilities of external events can be overestimated;
- <u>simplicity</u>: only well known, reliable statistical and probabilistic methods are used for the assessment of external events probabilities and analysis of statistical data.





2.2.1 IDENTIFICATION OF PARAMETERS

Meteorological parameters follow a seasonal cycle and the continuous survey of any meteorological parameter reveals annual extreme values. It is also observed that this extreme value varies randomly from year to year.

Recommendations for analysis of certain extreme weather hazards are presented in Section 2.3 in more detailed manner. Some Bulgarian experience related to the choice of governing hazard parameters, requirements, relevant results of stress-tests and their conclusions are presented in the 'ANNEX 2.1. Extreme Weather Assessment in Bulgaria'. Nevertheless, general points of extreme weather parameters characterization are presented below:

Extreme Winds/Storms and Hurricanes (N40 [7])

For the analysis of extreme winds, NS-G-1.5 [8] provides a general description and loadings. In particular, the following aspects should be considered when defining the design basis:

- wind class (if applicable),
- wind speed [averaged over specified times] and rate of change of wind speed,
- gustiness [roughness of the wind and peak wind speed],
- suction effects [due to pressure differentials and rate of change of pressure],
- total duration of the impact and recurrence,
- interaction of neighbouring structures [group effects],
- dynamic effects exerted by the wind on the roof, curtain walls and glass openings,
- possibility the wind to trigger sand storm.

An international scale of wind speed (Beaufort scale [9]) can be applied for a visual evaluation of the wind speed. Thereby, the Beaufort number can be used as parameter for storms/hurricanes.

Tornado (N41 [7])

The potential for the occurrence of tornadoes in the region of interest should be assessed on the basis of historical and instrumentally recorded data for the region as well as on theoretical meteorological considerations.

The hazards associated with tornadoes should be derived and expressed in terms of parameters such as:

- rotational wind speed,
- translational wind speed,
- duration of the wind intensity above specified levels,
- radius of maximum rotational wind speed,
- pressure differentials and rate of change of pressure,
- possibility the tornado to drop debris on the plant site.

In the assessment of the hazard, missiles that could be associated with extreme winds and tornadoes should be considered.

Extremes of air/ground/cooling water temperatures (N25-N27 [7])

The hazards associated with high/low temperatures should be derived and expressed in terms of parameters such as:

- instantaneous and daily average maximum and minimum air temperature,
- recurrence of max/min temperature for different range of years (1, 10, 20, 100 years, depends on a data availability).





Snowpack (N25 [7])

The most suitable parameter for snowpack characterization is a water equivalent snow depth (meters). This parameter can lightly and directly be converted into loads units and used to build the hazard curves based on pressure units. This approach could be comfortable because obtained hazard curves family can be simply used for fragility analysis (usually, the design values of loads measure in pressure units).

In its turn, the most widespread snow data are:

- total snowing duration/intensity,
- snowpack characterization,
- snowpack depth,
- frequencies (repeatability) of extreme snowfall.

Icing (N 34 [7]) - in part ice formation

Taking into account that communication lines and power transmission lines are mainly vulnerable for this impact (ice increases the load on the wires) the hazards associated with icing should be derived and expressed in terms of diameter of icing. Icing can affect also water intake basins, water channels and in some cases diesel fuel storages.

2.2.2 HAZARDS DATA PREPARATION AND ANALYSIS

As indicated in the Section 2.2.1 meteorological hazards are characterized by multiple output parameters, some of which may be statistically dependent. For simplicity, the hazard curve is generally described in terms of a limited number of parameters (typically one). The other parameters that would be needed for a complete description of the hazard are typically considered in the response analysis and fragility evaluation (see Sections 3.2 and 3.6.2 of this report).

During selection of considered characteristics, attention should be paid to SSCs design bases regarding availability of sufficient set of information for their fragility analysis. For example, if design values of wind maximal load on building walls are not known, it is difficult to define vulnerability of this structure with respect to the considered parameter (wind speed), and additional research (for example, strength calculation) is needed.

Before a start of the data preparation it is recommended to study the approaches and parameters, based on which has been designed and justified structures durability. For this purposes the corresponding national standards (for instance appropriate standards [10] to [13]) consulting with the specialists can be used.

The collected data shall be analysed and converted in a form suitable for PSA application. Hazard curves (hazard intensity curves) that involve assessment of frequency of various intensities of external hazards shall be used as input data describing external extreme hazards. They can be received by the development of a phenomenological model of an event and taking into account expert opinion. When developing curves, attention shall be paid to selection of probabilistic distribution of an essential impact on the results; that's why it is recommended to perform analysis for several proposed probability distributions and to select one with:

- 1) the best references for the given type of analysis and
- 2) good fitting of the data sample under concern.

As example, for occurrence of an extreme weather impact, it is needed to examine the dependence of annual frequency of snowfalls, extreme temperatures, strong winds (see also limitations in Section 4.1 of this report) and to obtain the part of relevant hazard curves, since such a distribution foresees the use of the extreme value theory (EVT) and it is suitable from the viewpoint of importance of the maximum values of load it is advisable to use the:





Type 1 (Fisher-Tippett, which is also known as Gumbel)

$$G(z) = exp\left\{-exp\left[-\left(\frac{z-b}{a}\right)\right]\right\}, -\infty < z < \infty,$$

Type 2 (which is also known as Frechet)

$$G(z) = \begin{cases} 0, & z \le b \\ exp\left\{-\left(\frac{z-b}{a}\right)^{-\alpha}\right\}, & z > b \end{cases}$$
 or

Type 3 (Weibull) distribution [2]

$$G(z) = \begin{cases} exp\left\{-\left[-\left(\frac{z-b}{a}\right)^{\alpha}\right]\right\}, \ z < b \\ 1, \ z \ge b \end{cases}$$

where G(z) - extreme value distribution function, *a* - scale parameter, *b* - location parameter, α - shape parameter (as another notation may be found in the literature see also Section 2.3.1).

The appropriate studies [14] have shown that the question of distribution selection has a significant impact on the results and the Gumbel distribution was recommended, in general.

2.2.3 APPROACHES FOR HAZARD ASSESSMENT

The meteorological hazard assessment is commonly based on the application of the statistical EVT, through its two common approaches: annual maxima and peak over threshold (POT). Stuart Coles among others describes the fundamental probability results of extreme value theory and its statistical application to natural hazards [15].

The results can be summarized as follows: if X_t denote a time series of a quantity of interest, let $M_n=_{max}t=1,...,n X_t$ be the maximum of X_t over n days. The foundational result of extreme value theory states that if X_t are independent and identically distributed, and M_n can be linearly renormalized in such a way that its distribution converges as n grows, then it will converge to an extreme-value distribution [16], [17]. Further theoretical results state that the distribution of exceedances $P(X_t > x + u | X_t > u)$ should be well approximated by a generalized Pareto distribution above a sufficiently high threshold u [18]. If X_t are not independent but are still identically distributed, the asymptotic distributions do not change, so long as certain relatively weak mixing conditions are met [19].

Meteorological data are not independent, but generally the "weak mixing conditions" are met, at least for air temperature or wind. But more fundamentally, they are not identically distributed: they generally present an annual cycle, or even some inter-annual variability or trends. The main problem to apply the aforementioned result is thus to ensure the best possible identical distribution. The annual cycle can be tackled by selecting the season of interest, for example. Other techniques to deal with this issue consist in using covariates and will be discussed in the dedicated section below. Another problem arises from the fact that the convergence to the extreme-value distributions is asymptotic, i.e. it is true when the number of values tend to infinity, which is never the case in practice. If Mn is an annual maximum, then n=365, which is finite but quite large. But then, a minimum number of maxima are needed. A trade-off has thus to be found between those two requirements, commonly named bi-as/variance trade-off, for which no theoretical results exist. This issue is particularly acute for snow depth in countries, like France, where snow can be rare and the amount of events per winter does not exceed 5 to 10 in the best case (or worst case, depending on the adopted view point, statistical or societal). Being the maximum of even 10 events can barely be assumed as being the maximum of infinity, or at least a great number, of occurrences. Here, other techniques, like simulation or regional or historical perspective have to be investigated. In such cases



European standards [10] advise the use of a log-normal distribution, warning that then the extrapolation to very long periods may be unreliable.

Modelling instead of historical data analysis

When a sufficiently long time-series cannot be found or if the asymptotical character of the convergence cannot be met, event modelling can be required. To do so, physical or statistical models can be used. For example, a stochastic model for air temperature reliably reproducing extreme events has been proposed by EDF/R&D [20], [21] and can be used to produce larger samples of frost events.

In general, one can consider the following possibilities of using data from numerical simulations:

- Meteorological data from the numerical weather forecasts made in the past. Most national weather services have sets of prognostic data from simulations performed during many last years. These data can be useful for reanalysis. As an example one can mentioned the following projects of ECMWF (European Centre for Medium Weather Forecast): ERA-40 data for period 1957-2002, ERA-15 data for period 1979-1993, ERA-Interim global atmospheric reanalysis from 1979, ERA-20C first ECMWF atmospheric reanalysis of the 20th century i.e. from 1900-2010.
- The above mentioned data can be applied in ensemble systems, allowing for estimating probabilities of the occurrence of rare meteorological phenomena under consideration. This allows for taking into account extreme conditions that could have happened in the past with some probability (even very small). Additionally, the data are available on the grids, which are much denser than monitoring meteorological network, and therefore geo-statistical techniques can be easily applied to obtain data for the whole area of interest.
- Data from reanalysis can also be applied for performing climatic modelling, i.e. by providing projection of the development of weather conditions in the period of the future operation of NPP.
- Simulations can also be performed for other facilities than NPP, and then by application of geo-statistical methods some estimation for NPP can be found. This however is of very limited use, because good data are needed for such simulations in order to avoid big uncertainties.

2.2.4 ISSUES RELATED TO ASSESSMENT

Non-stationary data and trends

There were non-stationary data and trends such as the effects of climate change on meteorological hazards and flooding. As mentioned previously, meteorological data are generally not identically distributed, and climate change adds another reason for that. According to the last Intergovernmental Panel on Climate Change (IPCC) report [22], the impact of climate change on extreme events is not as robustly assessed for all extremes: if increases in the frequency and intensity of heat waves and decreases in the frequency of cold waves are robust signals for all land areas, this is not the case for wind storms, for example. However, as the result is robust for temperature, it is necessary to take it into account. A commonly admitted way to do so consists in considering the extreme-value distribution parameters as changing with a covariate, generally time (because it is the easiest to extrapolate). But then, the definition and estimation of a return level have to be changed, and there is up to now no standard definition in the non-stationary setting [23]. An example of comparison of methods can also be found in [24].





Use of expert judgment & gualitative estimation

Whatever the methodology used to estimate extreme levels, a critical analysis of the result must include expert judgment and comparison to previous estimations or values for meteorologically comparable locations if any.

Uncertainty assessment

Extreme value estimations are extrapolations and as such present uncertainties. The first of them comes from the statistical errors made when fitting the extreme value distribution to the observed sample. Different techniques exist to estimate this type of uncertainty by providing a confidence interval. The most classical ones, deltamethod and profile likelihood, are described in [15]. In some cases, and especially when trends in the parameters have been considered, bootstrap techniques are more appropriate. This technique consists of generating, by random withdrawal with replacement in the sample being analysed, a large number of equivalent samples from which the same estimates are made [25]. In this way, a distribution of the desired quantities (e.g. the high quantiles of the extreme value distribution or return levels) is obtained from which the empirical quantiles $(1-\alpha)/2$ and $\alpha+(1-\alpha)/2$ α)/2 are estimated, which define the limits of the confidence interval at a given level (e.g. 95%: α =0.95; 95% of the values are contained within this interval). Note that in the case of a non-stationary sample, samples must be withdrawn either from a stationary quantity or "block-wise" by defining blocks on which the quantity may be assumed stationary. Other uncertainties may arise from the fact that the estimation is made from as large as possible but still limited number of observed events which may not include all possibilities. This uncertainty is less easy to quantify. An historical perspective may help, if the historical events can still be considered as representative under present conditions. Finally, when trends are considered, uncertainties arise from the choice made for their identification and extrapolation (mathematical form of the trend, extrapolation horizon).

Methodological limits

There were limits of extrapolation to extremely low occurrence probabilities based on data coverage. As data coverage is always limited, extrapolation to extremely low occurrence probabilities is questionable. Depending on the form of the tail distribution, the confidence interval may not be too large, but the limited length of data coverage used to fit the distribution cannot guaranty that all possibilities have been sampled. On the other hand, if a very extreme event has been observed over a limited period, its empirical frequency may be overestimated, and its impact on the robustness of the fitting may be large and lead to quickly widening confidence intervals. Methods exist to take historical events into account, like methods based on censored data, but then the representativeness of the historical event in the present context must first be carefully assessed and potentially adapted. To our knowledge, no example or guidance to do so is currently available.

Updating of assessment

Du to advance of science and technology, it is stress necessity to periodically renew hazard assessment due to new data, evidence or advance of science. Because of the previously mentioned uncertainties arising from the always limited perspective we have on the hazards and their possible evolutions, it is recommended to update the estimations on a regular basis in order to add new information and take advantage of knowledge progress.





2.3 EXAMPLES OF ASSESSMENT METHODS

2.3.1 APPLICATION OF EXTREME VALUE THEORY AND METHODS

Estimation of low frequencies of rare natural hazards like extreme values of weather events is a challenging extrapolation exercise. Some selected special mathematical techniques should be applied. These methods are typically based on the extreme value theory, which deals with the analysis of extreme deviation from the median or the mean. In this respect a number of various mathematical tools can be useful, like: the first extreme value theorem of Fisher-Tippett-Gnedenko [16], [17] leading to possible choices of general extreme value distributions, or the second extreme value theorem of Pickands-Balkema-de Haan for tail-fitting, or the methods related to deviation theory. Before applying one or the other method one should answer the following crucial questions: which method to use, how to estimate parameters and how to verify goodness of fit. These report and section give a short overview of statistical techniques that can be useful for a practical approach to these problems.

Annual Maxima/Minima Series (AMS)

The analysis of the data with the annual extreme values (in principle any period can be considered) is based on the first extreme value theorem (known as Fisher-Tippett-Gnedenko theorem [16], [17]). The theorem says that if there exists a non-degenerate distribution function as a limit of probabilities of maxima series then, this limit distribution can be one of the three possible types: Gumbel, Fréchet or Weibull, known as type I, II and III respectively. Their cumulative distribution functions are:

Type 1 (Gumbel)

$$P(\mathbf{X} \le x) = \exp\{-e^{(x-\mu)/\sigma}\}.$$

Type 2 (Fréchet)

$$P(X \le x) = \begin{cases} 0 & x < \mu \\ \exp\left\{-\left(\frac{x-\mu}{\sigma}\right)^{-\xi}\right\} & x \ge \mu \end{cases}$$

Type 3 (Weibull)

$$P(X \le x) = \begin{cases} \exp\left\{-\left(\frac{x-\mu}{\sigma}\right)^{\xi}\right\} & x \le \mu\\ 0 & x > u \end{cases}$$

These three families of distributions can be combined in one, known as generalized extreme value (GEV) distribution, leading to the following formula for the cumulative distribution function:

$$F(x;\mu,\sigma,\xi) = exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

In above formulas μ is known as the location parameter, σ - the scale parameter, and ξ - the shape parameter (ξ >0 - "long tailed" case, ξ =0 - exponential tail, ξ <0 - "short tailed" case). Another notation may be found in the literature and this report, e.g. in section 2.2.2.

In fact, under some assumptions on the positivity of the type II and negativity of type III, they both can be linked to the type I via logarithm function - roughly speaking if X is random variable of the distribution type II or III, then log(X) or log(-X) is of type I.

The theorem is valid for independent random variables and as it has asymptotic character then, in principle, one needs enough statistical data to apply it directly. Therefore, some deviations or other distributions are also used in





practise. Nevertheless, this approach is often applied, for example, for the prediction of extreme weather events, like large floods or surge storms.

Peak Over Threshold (POT)

The POT method is based on the analysis of data exceeding some threshold over defined periods. Two quantities are typically estimated: the number of such events and how big such exceedance is. The first one is usually estimated by Poisson distribution, while the second one is characterized by the generalized Pareto distribution. The cumulative Pareto distribution function is defined by the following formula:

$$F_{\xi}(y) = \begin{cases} 1 - (1 + \xi y)^{-1/\xi} & \text{if } \xi \neq 0 \\ 1 - e^{-y} & \text{if } \xi = 0 \end{cases}.$$

Here ξ is, as above, the shape parameter. One can easily introduce the location and scale parameters μ , σ by utilizing transformation $y \rightarrow (x-\mu)/\sigma$.

A kind of hierarchy is introduced for the class of the Pareto distributions. They are known being as of type I, II, III, IV and the Feller-Pareto. The type IV contains three previous as special cases, while the Feller-Pareto generalizes type IV. These distributions are applied in hydrology for example, in order to model daily maxima of rainfalls and river discharges.

The open question is related to defining the threshold, which should be done carefully, as it has impact on the statistics and not properly set (for example too low) can deteriorate the results.

Survival and hazard functions

The comparison of Pareto type distributions is often made by the survival function, which is simply the complementary of cumulative distribution function (i.e. defined as S(t)=1-F(t), where F is cumulative distribution function). This is strictly connected to such parameters like failure rate or mean time between failures via hazard function which could be determined as follows:

$$H(t) = \frac{F'(t)}{S(t)}.$$

The failure rate is a conditional probability of the failure density function. The hazard function is, in fact, a continuous version of failure rate.

There are two estimators, worth mentioning, which could be applied to estimate survival and hazards function, respectively: the Kaplan-Meier and the Nelson-Aalen.

The Kaplan-Meier is a non-parametric estimation of survival function *S* based on maximum likelihood principle. Assuming that S(t) is the probability that lifetime exceeds time *t*, and given sample of the form $(t_1, n_1, d_1),...,(t_N, n_N, d_N)$, where t_i is observed time, n_i is the number at risk prior to time t_i and d_i number of failures at time t_i , the estimator can be defined as follows:

$$\widehat{S(t)} = \prod_{t_i < t} \frac{n_i - d_i}{n_i}.$$

Please note that this formula is given for censored data - in non-censored case n_i is the number of elements with no failure just prior to time t_i .

Similarly, the Nelson-Aalen estimator is also a non-parametric estimation for incomplete or censored data given by the following formula:

$$\widehat{H(t)} = \sum_{t_i < t} \frac{d_i}{n_i}.$$

Here d_i is the number of failures at time t_{i_i} while n_i is the number at risk at time t_i .





In this respect one can also mention the proportional hazard model introduced by Cox. In this model it is postulated that the parameters affecting hazard can be scaled proportional to time. The model of hazard at time *t* has the following form:

 $h(t, z_1, \dots, z_m) = h_0(t) exp\{\sum_{i \le m} b_i z_i\}.$

The quantities b_i are explanatory variables, z_i are model parameters and h_0 is the baseline hazard.

Tail fitting approach

The Pareto distribution is often used for modelling the tail of some other distributions. For this purpose the second extreme value theorem (Pickands-Balkema-de Haan) can be applied. The theorem says that the asymptotic tail distribution of random variable *X* (where true distribution is unknown) can be approximated by generalized Pareto distribution. By tail it is understood the exceedance of certain threshold. Mathematically it is expressed as follows:

$$F_z(y) = P(X - z < y | X > z) = \frac{F(z + y) - F(z)}{1 - F(z)}.$$

Then the following limit holds:

$$F_{z}(y) \underset{z \to \infty}{\longrightarrow} \begin{cases} 1 - \left(1 + \frac{\xi y}{\sigma}\right)^{-1/\xi} & \text{if } \xi \neq 0 \\ 1 - e^{-\frac{y}{\sigma}} & \text{if } \xi = 0 \end{cases}.$$

Goodness of fit

-

Several techniques can be used to verify goodness of fit for extreme value distribution. In this respect one should mention simple plotting methods. Consider for example Gumbel distribution - taking logarithm for the probability $P(X \ge x)$ one gets $x = \mu + \sigma \ln[-\ln(1 - F(x, \mu, \sigma))]$ to plot observation data of type I. This should lead to the straight line for sampling of the form $(x_i, \ln[-\ln(1-p_i)])$ for observed data x_i and plotted points p_i . Some authors consider different plotting techniques, where p_i are defined in various way - for example by median ranks, mean rank, or symmetric distribution ranks. This can be also further combined with the least square method for estimating location and scale parameters μ and σ . Selection of position points p_i is an open question and should be somehow motivated.

Another approach is based on Monte Carlo simulations and application of Kolmogorov-Smirnov, Cramer-von Mises, or Anderson-Darling statistics. Assuming that $(x_1 < x_2 < ..., < x_n)$ is ordered statistics of some cumulative distribution function $F_0(x;\Theta)$, where Θ is the set of parameters, the tests are based on the verification of the null hypothesis H_0 : $F(x)=F_0(x;\Theta)$. The following statistics are used:

- Kolmogorov-Smirnov: $D_n = \max_{1 \le i \le n} [\delta_i]$, where $\delta_i = max\left(\frac{i}{n} F_0(x_i; \theta), F_0(x_i; \theta) \frac{i-1}{n}\right)$.
- Cramer-von Mises: $W_n^2 = \sum_{i=1}^n \left[F_0(x_i; \theta) \frac{i 0.5}{n} \right]^2 + \frac{1}{12n}.$
- Anderson-Darling: $A_n^2 = -\sum_{i=1}^n \frac{2i-1}{n} \{ \ln(F_0(x_i; \theta) + \ln(1 F_0(x_{n+1-i}; \theta))) \} n.$

Based on these statistics some modifications or other statistics have been also proposed and are used in modelling. Some suggestions have been made in [26] saying that in general the Anderson-Darling statistics coupled with the symmetrical ranks and usage of the estimator based on the least square method can be recommended to use in practice.

For GEV distribution Zempléni test can be used based on the following statistics:

$$\varphi_n(x) = \sqrt{n} \min_{a,b} \max_{x} |F_{n(x)} - F_n^2(ax+b)|, \ F_n(x) = \frac{1}{n} \sum_{i=1}^n I_{(-\infty,x)}(X_i).$$



EURATOM

There exist also tests utilizing the correlation coefficient like the one based on the product-moment correlation between the sample order statistics and their expected values. These tests are relatively simple to perform.

Estimators

A number of methods can be applied for estimation of the distribution parameters. Among them one should mention the following ones [26]:

- moment estimator: explicit formulas are deducted from sample mean and standard deviation;
- simple linear estimator: based on simplification of likelihood equation (which, in principle, can be solved numerically only);
- best linear unbiased or invariant estimator (BLUE/BLIE): based on minimizing generalized variance or mean square error;
- asymptotic best linear unbiased estimation: based on asymptotics of variance or covariance of BLUE;
- maximum likelihood estimator: based on maximum likelihood principle can lead to numerically solving equations;
- probability-weighted moment (PVM) estimator: based on the moments with the weights which include, for example, cumulative distribution function;
- ranked set estimator: ranked simple mean is used with the optimal weights, leading to ranked set best linear unbiased estimators;
- conditional method: based on determination of marginal conditional densities, which are applied to carry out individual inferences on the parameters;
- minimum distance method: based on finding minimum of Cramer-von Mises distance of the form: $\min_{\mu,\sigma} \int (F - G(\frac{x-\mu}{\sigma}))^2$, where F is empirical distribution and G the one which parameters are to be estimated:
- bias-robust (B-robust) estimator for GEV: based on utilizing the influence function;
- optimal bias robust (OBRE) estimator for GEV: related to the moment based estimators;
- estimation of tail index of the distribution: different techniques usually utilising some asymptotic behaviour.

Some practical approaches for constructing tolerance limits for extreme value distributions have been also proposed [26]. A more general approach can be based on large deviation theory dealing with the asymptotic behaviour of the distribution tails. This theory is based on the results on the convergence of probability measures and hence is difficult to apply directly. There are some relations with thermodynamics via entropy or information system and risk management. As this theory is relatively new one can expect that in the future its role will be slightly increasing.

Censored and incomplete data

As it has been already mentioned lack of required statistical data is one of the main problems in estimating frequencies of extreme natural events. Some improvement can be possibly expected when the techniques for censored or incomplete data are applied. However, typical imputation methods should be used carefully as simply replacing missing data with substitutes usually does not improve statistics in terms of appearance of extreme values. Probably partial imputation with expectation-maximization algorithm could be used in some cases.

Similarly, application of asymptotic estimators for censored data could be useful, as asymptotic estimator reflects behaviour of very large sample, while censoring deals with partially known observations. Some estimators, in this case, like the ones based on likelihood equation can lead to the system of nonlinear equations that can be solved





only numerically. As an example of such an approach is to use maximum likelihood principle to the likelihood that can be expressed in the following form [26]:

$$[F_x(X_l)]^r \prod_{i=r+1}^{n-s} p_x(X_i) [1 - F_x(X_r)]^s.$$

Here X_i and X_r are left and right censoring fixed points with r lowest and s largest data (r and s are random variables), while F_x is one of the cumulative extreme value distributions.

Future perspectives

Application of the presented above statistical methods will be always limited by the availability of enough good statistical data. In order to tackle the problem of the lack of data one should step out of the extreme value theory application at the single site and go toward RFA, stochastic modelling, historical data and simulation data. As an example of the latter, one can mention possible application of climate models and ensemble techniques used in weather forecasting. Combination of data coming from different sources will be probably necessary. In this respect statistical techniques similar to the ones used in data assimilation can be useful – in order to apply them information about data uncertainty is needed. Estimation of uncertainties, both for input data and the results, is important at any rate.

2.3.2 ESTIMATION OF PROBABILITY OF ANNUAL EXTREME EVENTS

Extreme value probability distributions are used for investigation of extreme meteorological phenomena and its size. Gumbel probability distribution (Type I) often is used for the purpose of probability assessment of extreme events [26], [27]. In general, this distribution can be used to model maximal or minimal values [27]. This distribution can be used for the assessment of extreme winds, precipitations, snow cover, temperature, tornados, snow-storms and flooding. Gumbel cumulative probability distribution function is expressed as follows:

$F_{\max}(x) = e^{-e^{-(x-\mu)/\sigma}}, \quad -\infty \le x \le \infty, \quad \sigma > 0.$

where μ - frequency parameter, σ - deviation parameter. Estimates of these parameters (as obtained by the method of moments) are calculated as follows:

$$\mu = \overline{X} - \gamma \sigma,$$

$$\sigma = \frac{s\sqrt{6}}{\pi},$$

where \overline{X} - estimate of sample mean, $\gamma = 0.5772$ is Euler's constant, s - sample standard deviation estimate.

Gumbel probability density function is expressed as follows:

$$f_{\max}(x) = \frac{1}{\sigma} e^{-\frac{x-\mu}{\sigma}} \cdot e^{-e^{-\frac{x-\mu}{\sigma}}}.$$

Then the probability that the even X will not exceed the size x over some period of time is:

$$P(x) = P(X \le x) = F_{\max}(x) .$$

For the assessment of occurrence of maximal extreme event values, the complement of Gumbel distribution is used, also known as guarantee function, which shows the probability that random variable X will exceed some value x:





$G_{\max}(x) = P(X > x) = 1 - F_{\max}(x),$

$G_{\max}(x,\mu,\sigma) = 1 - e^{-e^{-(x-\mu)/\sigma}}$.

In case of Gumbel distribution for maximums, guarantee function (or warranty) is understood as a quantity, inverse to the return period over which one exceedance of the assumed threshold is likely to occur. If annually the quantity exceeds the threshold with probability 1 - P(x), then expected interval of this return or return period is

$$T(x) = \frac{1}{1 - P(x)} \, .$$

Taking into consideration the expressions of distribution parameter estimates, one obtains the following model for the maximums of extreme events:

$$G_{\max}(x,\overline{X},s) = 1 - e^{-e^{-\left(x - \left(\overline{x} - 0.5772\frac{s\sqrt{6}}{\pi}\right)\right)/s\sqrt{6}}}.$$

Let's denote $y = (x - \mu)/\sigma$. The return period for the case of Gumbel extreme value distribution is expressed as follows:

$$T_{\max} = \frac{1}{1 - e^{-e^{-y}}}$$
.

When return period is known, one can calculate the maximal size that will be exceeded once over that return period T_{max} . From equation above it follows that

$$1 - e^{-e^{-y}} = \frac{1}{T_{\max}},$$

therefore

$$y = -\ln\{\ln(T) - \ln(T-1)\}.$$

Since $y = (x - \mu)/\sigma$, then maximal value x_{max} for the return period T_{max} is:

$$x_{\max} = \mu + \sigma \left(-\ln\{\ln(T_{\max}) - \ln(T_{\max} - 1)\} \right)$$

This equation means that it is likely that maximal size x_{max} will be exceeded during the return period T_{max} .

Maclaurin theorem gives some approximations:

$$y \approx \ln \left(T_{\max} - \frac{1}{2} \right)$$
, when $T_{\max} > 10$ years and

$$y \approx \ln(T_{\text{max}})$$
, when $T_{\text{max}} > 25$ years

Gumbel minimal value distribution (similar to Gumbel probability distribution) is used for events such as minimal temperatures or drop in water level of the lake. The distribution function is

 $F_{\min}(x)=1-e^{-e^{(x-\mu)\sigma}}$, $-\infty \le x \le \infty$, $\sigma > 0$. where μ - frequency parameter, σ - deviation parameter. Estimates of these parameters (as obtained by the method of moments) are calculated as follows:

$$\mu = \overline{X} + \gamma \sigma ,$$





$$\sigma = \frac{s\sqrt{6}}{\pi},$$

where \overline{X} - estimate of sample mean, $\gamma = 0.5772$ is Euler's constant, s - sample standard deviation estimate.

Gumbel minimal value probability density function is as follows:

$$f_{\min}(x) = \frac{1}{\sigma} e^{\frac{x-\mu}{\sigma}} \cdot e^{-e^{\frac{x-\mu}{\sigma}}}.$$

Since equation above already shows the probability that quantity X exceeds the threshold x, i.e.

$$F_{\min}(x) = P(X < x),$$

 $F_{\min}(x,\mu,\sigma) = 1 - e^{-e^{(x-\mu)/\sigma}}$,

there is no need to calculate the guarantee function.

Final expression of the extreme value Gumbel distribution the minimums is as follows:

$$F_{\min}(x,\overline{X},s) = 1 - e^{-e^{\left(x - \left(\overline{X} + 0.5772\frac{s\sqrt{6}}{\pi}\right)\right)/s\sqrt{6}}}.$$

The return period in this case is obtained by the equation

$$T_{\min} = \frac{1}{1 - e^{-e^{y}}},$$

where $y = (x - \mu)/\sigma$.

When return period is known, it is possible to calculate the minimal value which will not be exceeded over that return period T_{min} :

$$1 - e^{-e^{y}} = \frac{1}{T_{\min}},$$

therefore

$$y = \ln\left\{\ln(T_{\min}) - \ln(T_{\min} - 1)\right\}.$$

Since $y = (x - \mu)/\sigma$, then minimal value \mathcal{X}_{\min} for the return period T_{\min} can be calculated by the following expression:

$$x_{\min} = \mu + \sigma \left(\ln \left\{ \ln \left(T_{\min} \right) - \ln \left(T_{\min} - 1 \right) \right\} \right) \cdot$$

The meaning of this equation is that it is likely that the minimal value x_{\min} will not be exceeded over the return period T_{\min}

Again, Maclauren theorem gives approximations:

$$y \approx -\ln\left(T_{\min} - \frac{1}{2}\right)$$
, when $T_{\min} > 10$ years and

 $y \approx -\ln(T_{\min})$, when $T_{\min} > 25$ years.

2.3.3 ESTIMATION OF CHRONOLOGICAL EXTREME EVENTS PROBABILITY

Some extreme events data are not recorded annually, but instead over some period of time records are made of cases which met extreme event criterion. In such cases, data sample is made not of annual but of chronological

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data observed over some period of time. Here two things are important: observation period in years (denote it by M) and number of extreme events of that time period (denote it by m). The frequency of extreme event x over a year is

$$D(x) = \frac{m}{M}$$
.

This measure shows how many times on average event are observed over a year. It is a quantity, which relates extreme events chronological data with annual values. In order to relate results with annual values, some modifications in equations are needed.

In case of Gumbel maximal value distribution, one has the following:

$$G_{\max}(x) = P(X > x) = (1 - F_{\max}(x)) \cdot D(x),$$

$$G_{\max}(x,\mu,\sigma) = \left(1 - e^{-e^{-(x-\mu)/\sigma}}\right) \cdot \frac{m}{M}.$$

Where $G_{\max}(x)$ now is not probability that variable X exceeds a threshold x every year, but express annual frequency, that variable X exceeds some threshold x. The return period is expressed as follows:

$$T_{\max} = \frac{1}{1 - e^{-e^{-y}}} \cdot \frac{M}{m},$$

where $y = (x - \mu)/\sigma$.

Maximal value x_{max} for the return period T_{max} is calculated according to the equation:

$$x_{\max} = \mu + \sigma \left(-\ln \left\{ \ln \left(T_{\max} \cdot \frac{m}{M} \right) - \ln \left(T_{\max} \cdot \frac{m}{M} - 1 \right) \right\} \right).$$

In case of Gumbel minimal value distribution, one has the following expressions:

$$P(X < x) = F_{\min}(x) \cdot D(x),$$
$$F_{\min}(x, \mu, \sigma) = \left(1 - e^{-e^{(x-\mu)/\sigma}}\right) \cdot \frac{m}{M}.$$

Where $F_{\min}(x)$, as in the case of Gumbel maximal values distribution, is no longer a probability that even X will not exceed a threshold x over a year, but instead it shows the annual frequency, that X will be smaller than a threshold value x.

The return period is expressed by the following equation:

$$T_{\min} = \frac{1}{1 - e^{-e^{y}}} \cdot \frac{M}{m},$$

where $y = (x - \mu)/\sigma$.

Minimal value x_{min} for the return period T_{min} is calculated by

$$x_{\min} = \mu + \sigma \left(\ln \left\{ \ln \left(T_{\min} \cdot \frac{m}{M} \right) - \ln \left(T_{\min} \cdot \frac{m}{M} - 1 \right) \right\} \right).$$

2.3.4 ASSESSMENT OF EVENTS OCCURRING IN SOME PARTICULAR PLACE

Sometimes it is of interest to have a probability of event occurrence (e.g. extreme wind or forest fire) not in whole region of the area (with area equal to A squared kilometres), that the data sample was collected from, but instead in some smaller part of it (e.g. NPP site or small region which includes the site). In such cases, probability





obtained from annual or chronological data is divided by the size of the area. In other words, one makes an assumption that extreme events are independent and distributed uniformly over the area [28].

In addition, if place of event occurrence or impact is not point-like, but is in the area of size a (e.g. tornado impact area), and if one wants to assess not only probability of occurrence but that it will occur in some specific area, then extreme event occurrence probability estimate based on annual and chronological data (and divided by A), has to be multiplied by the impact area (zone) size a. In this way, factor a/A is obtained, which describes the likelihood, that an event will occur in the considered zone.

Then in case of chronological data and Gumbel distribution of maximums we have the following:

$$G_{\max}(x) = P(X > x) = (1 - F_{\max}(x)) \cdot D(x) \cdot a / A,$$

$$G_{\max}(x, \mu, \sigma) = (1 - e^{-e^{-(x-\mu)/\sigma}}) \cdot \frac{m}{M} \cdot \frac{a}{A},$$

where $G_{max}(x)$, when taking into account all observation period M and the number of events m, express an annual frequency of even X occurring in the zone of size *a*.

As in the case of annual or chronological extreme events, return period and maximal size of event for this return period can be obtained as well:

$$T_{\max} = \frac{1}{1 - e^{-e^{-y}}} \cdot \frac{M}{m} \frac{A}{a} , x_{\max} = \mu + \sigma \left(-\ln\left\{ \ln\left(T_{\max} \cdot \frac{m}{M} \frac{a}{A}\right) - \ln\left(T_{\max} \cdot \frac{m}{M} \frac{a}{A} - 1\right) \right\} \right)$$

In case of the Gumbel minimal values distribution the above equations are modified accordingly, as in the calculations with annual or chronological extreme events.

The above-mentioned multiplication factor can be expressed in other way (as is done in some NRC documents):

$$\frac{m}{M} \cdot \frac{a}{A} = \frac{aD(x)}{A} = \frac{S}{MA},$$

where s is a sum of all area where event occurs or has an impact, M is observation period in years.

An average event occurrence or impact area *a* may be treated as independent of the territory and measured from the sample of data. In addition, event occurrence frequency D(x) in the considered territory could be associated not only to the whole analysed territory, but it can also be calculated taking into account separate parts of size A_i or close areas with similar meteorological conditions, where data sample is more accurate. If it happens that frequency of events registered in other close areas is higher, then in order to have a conservative estimate, the maximum selected frequency is $d_{max} = D_{max}(x)/A_i$.

2.3.5 ESTIMATION OF UNCERTAINTY USING CONFIDENCE INTERVALS

Confidence intervals for the extreme events probability distribution (Gumbel distribution) are obtained by the use of standard deviation of binomial probability distribution

$$S_d = \sqrt{\frac{F(x) \cdot (1 - F(x))}{N}},$$

where F(x) is a cumulative distribution function (0 < F(x) < 1), N - the size of the sample.




In addition, Student's *t* statistics is used for the confidence intervals of cumulative density function F(x). The value of *t* statistics for 90 % confidence limits is close to 1.7 when *N*>10. Besides, binomial distribution is symmetric when F(x)=0.5, but becomes asymmetric when F(x) is close to 0 or 1. Therefore, when calculating upper and lower bounds of the confidence intervals, F(x) is used as a weighing function for standard deviation S_d . Hence, bounds of confidence intervals are calculated as follows:

 $L = F(x) - 2 \cdot 1.7 \cdot (1 - F(x)) \cdot S_d ,$

 $U = F(x) + 2 \cdot 1.7 \cdot F(x) \cdot S_d.$

The above methodology for calculating confidence intervals can be found in the book [29].

2.4 HAZARD COMBINATIONS

The objective of this section is to present and evaluate the possible hazard combinations for those extreme weather (meteorological) hazards that were selected earlier during the ASAMPSA_E project (i.e. high wind, tornado, extremely high and low air temperature and snowpack). Report [7] served as the most important basis of the discussion in this section. A hazard correlation chart was established in [7] taking into consideration all single external hazards. The possible hazard combinations were determined on the basis of expert judgement and evaluation of past experience. The aforementioned hazard correlation chart is considered comprehensive; therefore, no further hazard combinations are addressed in this section.

Report [7] identifies the following three major types of hazard combination categories:

- causally connected (correlated) hazards,
- associated hazards,
- combination of independent hazards (coincident hazards).

These three general combination categories were looked at one by one describing all extreme weather related hazard combinations relevant to these categories.

External event of meteorological phenomena may be manifested itself as one event or as a combination of two or more external events. Possible combinations consist of events that have a chance to happen at once, e.g. rise of water level may happen together with extreme winds.

In this section a procedure for the screening of potential external events that might happen in combinations is also reviewed. A list of all possible combinations of events is unreasonable due to the extremely large number of combinations. For instance, more than 1000 combinations of only two external events are possible [30]. Therefore, it is necessary to perform an initial screening of events for further investigation. For this purpose, one needs to define selection criteria.

Identification of external events combinations is performed by the use of a list or combining separate external events and phenomena (human activity related events, meteorological phenomena, flooding, geological and seismic events). The identification of possible combinations of external events depends on the engineering and expert judgement and is not well developed procedure. In what follows, a possible method will be presented for the analysis of possible combinations.





2.4.1 CLASSIFICATION OF HAZARDS COMBINATIONS

Correlated hazards

With respect to extreme weather hazards, the following types of causally connected hazards should be investigated based on the approach outlined in section 3.1 of the report [7]:

- an external event may induce an extreme weather event,
- an extreme weather event may induce another external event,
- an external event is a prerequisite for an extreme weather event,
- an extreme weather event is a prerequisite for another external event.

Associated hazards

As discussed in section 3.2 of the report [7], associated hazards refer to events that are probable to occur simultaneously due to a common root cause.

Coincident hazards

In general, considerations should also be given to those hazard combinations that include coincident independent hazards without any correlation. Combination of independent hazards should be identified and selected by applying screening methods accompanied with expert judgement. In absence of screening a comprehensive list of hazard combinations, including the extreme weather hazard in question, could be assembled that is not possible to assess in an appropriate manner due to the large number of the identified combinations.

2.4.2 CRITERIA AND CONDITIONS FOR COMBINATIONS

In the following Table 1 some criteria, which application should lead to the list of possible combinations of external events (considerably smaller than mentioned above [30] and practically treatable) are presented. The relevant SKI Report "Guidance for External Events Analysis" [30] is summarised in various ASAMPSA_E reports (e.g. [34]).

Independence	Definition	Influence	Individual event selection criteria
Events occur inde- pendently of each other in time AND Probability of simultane- ously occurring events is low	Events are independent in time AND Several external events are included in individual event definition	Events are independent in time AND Events affect the same NPP safety function AND Combined effect on safe- ty function is not larger than what would be in case of most severe event.	Individual external events selection criteria are applicable to the combi- nations as well.

Table 1 Criteria for irrelevant combinations of external events (hazards)





The criteria for selection of events (hazards) combinations may be related to the consideration of these conditions:

- 1. More general definition of events Several external events are included in a more general definition of event.
- 2. Events interdependence

Base for the definition of important external events (their combinations) is whether they are dependent or not.

3. Different safety functions of NPP are affected

If condition 2 is satisfied, then other condition is considered: whether different NPP safety functions are affected. If events in combination affect the same function, the 4th condition has to be applied.

- 4. The degree of impact on NPP safety functions If two dependent external events affect the same safety function, these events still might make an important combination. The effect in combination may be more severe than effect of separate events.
- 5. Individual external events criteria If a combination is judged to be important even after the application of all the above rules, then individual external events criteria has to be applied for the combination as well.

For the considered combinations of independent events (hazards), one could obtain probabilities of those combinations. If events $A_1, A_2, ..., A_n$ in combination are independent then probability that they will occur at the same time is equal to the product of each event probabilities:

 $P(A_1, A_2, \ldots, A_n) = P(A_1) \cdot P(A_2) \cdot \ldots \cdot P(A_n)$

where n - the number of events in combination.

Larger number of independent events in combination and more severe consequences of events with small frequencies lead to the smaller combination annual frequency (becomes closer and closer to the incomparable values, which due to errors may be considered as equal to zero). Annual frequency of combination of dependent or partially dependent events is higher than what one would obtain if independence is assumed.

According to the IAEA [2], combinations of hazards may be excluded from the analysis, if they satisfy the following conditions:

- hazards combination is not physically possible;
- hazards in combination does not have any different joint effect on NPP;
- the annual frequency of hazards combination is equal to or less that a threshold.

Combinations of independent external hazards (occurrence of such coincident hazards) are often very unlikely. Some literature [30], [31] even indicates that it is meaningful to consider those external hazards, which are rarely dependent and rarely correlated. In practice, sometimes hazards in selected combinations may be dependent only locally at specific NPP site. Dependence of two external hazards in combination may be illustrated in the influence table, as presented in the report [32].

It is important to note that some individual hazards (phenomena) already are combinations of hazards, so that analysis of such compound already covers analysis of individual hazards. Once combinations of such external hazards are made and when dependencies and influences are established, one can apply previously defined criteria in order to select unimportant combinations of external hazards. Such analysis may depend on site and NPP design characteristics and is performed at the stage, when information necessary to assess the frequency and effect of combination is known.

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2.5 EXAMPLES OF HAZARD COMBINATIONS

Credible combinations of hazards and phenomena should be considered for the hazard assessment. Examples of hazards combinations are:

- drought could be combined with very high temperature events that increase the need for the provision of cooling and at the same time cooling water reservoirs might be reduced,
- drought (due to high air temperature) could be combined with strong wind and smoke from forest fire,
- with a combination of snow and wind, there is a potential for a loss of offsite power and a simultaneous failure of diesel generators due to air intake blockage, and the possibility of formation of snow banks,
- with a combination of low temperature, high humidity and wind, there is a potential for a loss of offsite power due to the high-voltage lines breakage,
- high winds, high seawater levels and debris in cooling water are correlated, so that there is a possibility of a simultaneous loss of off-site power and a loss of emergency diesel generator cooling.

It was found out a large number of hazards correlated with meteorological hazards [7]. Thus, it has to be taken into account possible combinations of events and collected appropriate data related to corresponding combinations occurring (for associated hazard combinations especially), as well as, performed screening process [34].

For practical purposes, separate subsections (2.5.1- 2.5.3) of this report characterize hazard combinations relevant to an extreme weather hazard that is in the intended scope. Consequently, the following extreme weather hazards were discussed separately focusing on hazard combinations relevant thereto:

- 1. high wind
- 2. tornado
- 3. extremely high air temperature
- 4. extremely low air temperature
- 5. snowpack.

2.5.1 EXTREME AND STRONG WIND RELATED COMBINATIONS

High Wind

In report [7] high wind and storm (including hurricane, tropical cyclone, typhoon) are investigated as one item on the hazard list. Consequently, the hazard combinations presented in the hazard correlation chart is relevant to a group of straight wind related events. This section follows a similar approach, i.e. the hazard combinations relevant to high wind and storm (including hurricane, tropical cyclone, typhoon) are discussed hereby, due to similarity in impact characteristics on nuclear power plants as well as in parameters which represent the best load induced thereby.

According to the hazard correlation chart, hazards related to the categories of hydrological hazards, meteorological events, biological hazards, forest fire and external man-made hazards can be causally connected to high wind. Moreover, no external events were identified from among the hazards listed as single external hazards in report [7] that may induce or is a prerequisite for high wind. In contrast, the following external hazards were determined as a consequence of high wind:

- waves in inland waters,
- wind generated waves,
- sea: storm surge,
- coastal erosion,





- snowstorm,
- sandstorm,
- salt spray,
- wind blown debris,
- airborne swarms, leaves,
- wildfire,
- ship impact,
- collisions with water intake / UHS,
- ship: solid or fluid releases,
- aircraft crash: airport zone,
- aircraft crash: air traffic,
- stability of power grid,
- fire: human/technological activity.

On one hand, most external hazards listed above are events that may be caused by high winds (i.e. all external man-made hazards, forest fire, some meteorological events as well as some hydrological hazards). On the other hand, high wind is a prerequisite for some hydrological, meteorological and biological events too, i.e. waves in inland waters, storm surge, snowstorm, sandstorm, salt spray, wind-blown debris and airborne swarms, leaves. This means that these events are only the consequences of high wind or a similar external event, hence they cannot occur in themselves, independently of high wind or a similar event.

The hazard correlation chart contains three associated hazards that include high wind. It can be concluded, that harsh meteorological conditions may induce high wind and at the same time one (or more) of the following meteorological events: extremes of air pressure, hail or lightning. In this manner the root cause may be the harsh meteorological condition and the associated hazards are high wind and another consequence of the harsh meteorological conditions listed above.

The frequency of high winds that have a significant effect on the safety systems of nuclear power plants is usually low. Consequently, the frequency of a combination involving high wind that has the potential to induce failure of plant safety systems and another hazard independent therefrom commonly falls below the frequency screening threshold set for single external hazards. Moreover, if a combination of independent hazards cannot be screened out, the intensity of the hazard other than high wind is usually not severe enough to have a significant effect on the plant.

Since the occurrence frequency of high winds that are capable of affecting the safety systems of a nuclear power plant is low, the only case an independent external hazard should be evaluated in combination with high wind is if the impact of high wind on the plant holds for a long duration of time. The duration of extremely high wind events is about a few hours; therefore, the duration of the primary impact on the plant and on its vicinity is short. Efficient mitigation actions can also be performed in some days (e.g. fire-fighting, removing wind-blown debris), respectively the time needed for successful mitigation against the impact of high wind can also be considered relatively short (e.g. in contrast to flooding that may take a much prolonged time to cope with). On the other hand, the static stability of SSCs (especially structures) and the off-site power supply system may be affected by the direct or secondary (i.e. wind-blown debris, etc.) effects of high winds and the reinforcement of the relevant structures or the recovery of the loss of off-site power might take a longer time period. Another external event having a considerable and similar type of impact (e.g. snowpack) on structures affected by high wind or in case of LOOP an impact on the safety power supply system of the plant (e.g. blockage of air intake of diesel generators by airborne leaves) can occur during this period, which should be taken into consideration in the identification of





event combinations. Furthermore, the heating, ventilation and air conditioning (HVAC) systems may also be affected by high wind. The restoration of the damaged HVAC system might take a considerable amount of time, while a hot summer or a cold winter might affect some safety related I&C components, which may lead to plant transients. Thus the damage potential of high wind on the HVAC system and the consequences of high or low outside temperatures (not necessarily very extreme ones) should be assessed.

<u>Tornado</u>

Since in report [7] tornado is a stand-alone item of the hazard list, this separate section discusses the specificities of the tornado hazard, instead of characterizing high wind and tornado hazard in a general manner as one event group. With respect to identification of hazard combinations, many similarities and some differences can be identified between high wind and tornado hazards that are highlighted hereby.

First of all, similarly to high wind events, hazards related to the categories of hydrological hazards, meteorological events, biological hazards and external man-made hazards can be causally connected to tornadoes. According to the hazard correlation chart, tornadoes are not causally connected to forest fires, as opposed to high wind events. Moreover, no external events were identified from among the hazards listed as single external hazards in report [7] that may induce or are a prerequisite for a tornado event. In contrast, the following external hazards were determined as consequences of a tornado event:

- flash flood,
- flooding by water routed to the site,
- hail,
- lightning,
- waterspout,
- salt spray,
- wind-blown debris,
- airborne swarms, leaves,
- industry: explosion,
- industry: chemical release,
- military: explosion, projectiles,
- military: chemical release,
- ship impact,
- collisions with water intake / UHS,
- ship: solid or fluid releases,
- ground transportation: direct impact,
- transportation: explosion,
- transportation: chemical release,
- aircraft crash: airport zone,
- aircraft crash: air traffic,
- stability of power grid.

With the exception of waterspout, wind-blown debris, and airborne swarms and leaves, all the hazards listed above are events that may be caused by a tornado. On the other hand, a tornado is a prerequisite for the listed three exceptions, i.e. waterspout, wind-blown debris, and airborne swarms and leaves are only the consequences of a tornado or a similar external event. These three events are a subset of the seven events for which high wind is a prerequisite.





In the hazard correlation chart there is only one associated hazard that includes tornado. The root cause of this hazard combination may be a harsh meteorological condition and the associated hazards are tornado and extremes of air pressure as another consequence of the harsh meteorological condition. Three associated hazards were identified for high winds including extremes of air pressure too.

With respect to the identification of independent hazard combinations, the same applies to tornado hazard as to high wind hazard.

2.5.2 EXTREME TEMPERATURE RELATED COMBINATIONS

Extremely high air temperature

Similarly, to the discussion on high wind and tornado hazards, extremely high and low air temperatures are characterized in this standalone section regarding identification of hazard combinations. This was motivated by the independent treatment of these two hazards in the hazard correlation chart in report [7].

The hazard correlation chart contains only one hazard, namely floods from snowmelt that is causally connected to extremely high air temperature. Extremely high air temperature may induce floods from snowmelt, but excessive snowmelt can take place without having extremely high air temperature in the vicinity of the site. Consequently, no external events were identified from among the hazards listed as single external hazards in report [7] that may induce or is a prerequisite for extremely high air temperature, and also extremely high air temperature is not a prerequisite for any other event.

According to the hazard correlation chart of the report [7], there are several associated hazards that include extremely high air temperature and certain meteorological events or forest fire. For all these associated hazards the root cause is a harsh meteorological condition (e.g. a long lasting heat flux) and the associated hazards are extremely high air temperature and one (or more) of the following consequences of the harsh meteorological condition:

- high ground temperature,
- high cooling water temperature,
- high humidity,
- low humidity,
- drought,
- low ground water,
- wildfire.

With respect to extremely high air temperature related independent hazard combinations, the following two aspects should be considered for the purposes of hazard combination identification:

The frequency of extremely high air temperature that has a significant effect on the safety systems of nuclear power plants in case of HVAC system operation is usually low. Consequently, the frequency of a combination involving extremely high air temperature that has the potential to induce failure of plant safety systems and another hazard independent therefore not affecting the HVAC system commonly falls below the frequency screening threshold set for single external hazards. On the other hand, if an external event affects the HVAC system and the air temperature is (not necessarily extremely, but) high, indoor SSCs may fail due to high room temperature. For the identification of these coincidental event combinations, the design basis of the HVAC system should be analysed. For instance, the HVAC system may not be designed for earthquake at some existing plants; consequently a seismic event (even a relatively moderate one) may induce the failure of the HVAC system. If the air temperature is high simultaneously, this





scenario may lead to severe consequences on the plant. Thus the damage potential of external events on the HVAC system and the consequences of high air temperature (not necessarily very extreme ones) should be assessed.

• Due to the fact that extremely high air temperature is slow in developing and in declining:

- there is sufficient time to take preventive actions to mitigate the occurrence of some foreseeable transients that may be induced by extreme air temperature,
- the impact of extremely high air temperature on the plant holds for a long duration of time.

The frequency of occurrence for the combination of extremely high air temperature and another, independent hazard should be assessed with considerations to the usually long duration of extreme air temperatures.

Extremely low air temperature

The hazard correlation chart contains three hazards, i.e. surface ice, frazil ice, ice barriers that are causally connected to extremely low air temperature. Extremely low air temperature is a prerequisite for all of the three identified events. This means that the events are inevitable consequences of the extremely low air temperature event. On the other hand, it can also be concluded, that no external events were identified from among the hazards listed as single external hazards in report [7] that may induce or is a prerequisite for extremely low air temperature, or may be induced by extremely low air temperature (except for the above three categories of events that require extreme cold weather as a prerequisite).

According to the hazard correlation chart of the report [7], all associated hazards related to extremely low air temperature include another event that is part of the hazard category of meteorological events or man-made hazards. For all these associated hazards the root cause is a harsh meteorological condition (e.g. long lasting cold weather phenomena) and the associated hazards are extremely low air temperature and one (or more) of the following consequences of the harsh meteorological conditions:

- low ground temperature,
- low cooling water temperature,
- high humidity,
- low humidity,
- drought,
- low ground water,
- icing,
- white frost, rime,
- permafrost,
- recurring soil frost,
- snowstorm,
- mist, fog,
- stability of power grid.

With respect to the identification of independent hazard combinations, the same applies to the extremely low as to the extremely high air temperature event.

2.5.3 EXTREME SNOWPACK RELATED COMBINATIONS

In report [7] precipitation (rain or snow) and snowpack are considered as a single item of the hazard list. Consequently, the hazard combinations presented in the hazard correlation chart is relevant to one of the events from



the group including rain, snow and snowpack. As snow and rain are not in the scope of this report, and the combination of hazards related to snow and rain may differ considerably from combinations including snowpack, this section focuses only on hazard combinations relevant to snowpack.

It can be concluded from the hazard correlation chart, that snowstorm and the instability of the power grid are the events that are causally connected to snowpack. On one hand, snowstorm may cause an accumulation of snowpack on safety related buildings. On the other hand, the instability of the power grid may be caused by snow-pack. Moreover, no external events were identified from among the hazards listed as single external hazards in report [7] that is a prerequisite for snowpack, and also snowpack is not a prerequisite for any other event.

According to the hazard correlation chart of report [7], all associated hazards related to snowpack include another event that is part of the hazard category of meteorological events. For all these associated hazards the root cause is a harsh meteorological condition and the associated hazards are snowpack and one (or more) of the following consequences of the harsh meteorological conditions:

- low air temperature,
- low ground temperature,
- low cooling water temperature,
- snow avalanche.

In general, it can be stated, that extreme snowpack is moderate in developing and slow in declining. However, the snow can be removed from the roofs of safety related buildings that can reduce the duration of and the impacts caused by the hazard. In case of extreme snowpack, the snow removal actions may not be performed in a very short time, however, it would not take more than some days or a week. In this manner, the time needed for successful mitigation against the impact of snowpack can still be considered relatively short (e.g. in contrast to flood-ing that may take a much-prolonged time to cope with). On the other hand, the static stability of SSCs (especially structures) and the off-site power supply system may be affected by the effects of snowpack and the reinforcement of the relevant structures or the recovery from the loss of off-site power might take a longer time period. An external hazard having a considerable and similar type of impact on structures affected by snowpack (e.g. explosion) or in case of LOOP an impact on the safety power supply system of the plant (e.g. flooding of the diesel generator building due to snowmelt beside the buildings) can occur during this period, which should be taken into consideration in the identification of event combinations.

2.6 METHODOLOGIES FOR ANALYSIS OF COMBINATIONS

In terms of hazard combinations analysis, the nature of combinations has to be taken into account. As it was derived in [7]: "Hazard correlations discriminate between: (1) causally connected hazards (cause-effect relation) where one hazard may cause another hazard; or where one hazard is a prerequisite for a correlated hazard. (2) Associated hazards which are probable to occur at the same time due to a common root cause" and in additional, hazard combinations of independent phenomena have been denoted.

IAEA Fault Sequence Analysis (FSA) methodology

IAEA developed a complementary safety analysis FSA methodology and supporting tool to assist in evaluation of the impact of extreme events on NPPs [44], [45]. This method utilised both probabilistic and deterministic safety assessment methods to gain the insights of robustness of plant protection including impact on SSCs against the extreme external hazards and its combinations. The method also considers combined load conditions resulting from the simultaneous occurrence of these hazards. Fundamentally, the FSA method incorporates 'stress test' principles





that have been performed in Europe after Fukushima accident. The method considers sufficiency of defence-indepth provisions, including various dependencies, safety margins, application of specific design features, cliff edge effects, multiple failures, prolonged loss of support systems and the capability of safety important systems for long term operation [45].

The application of FSA method and supporting tools are implemented at Goesgen-Daeniken NPP, Switzerland and Medzamor NPP, Armenia. The methodology is described in detail in IAEA paper [45].

Extreme Event Analyzer (EEA) methodology

Lloyd's Register Consulting (LRC), in cooperation with IAEA, has further developed the FSA method [46]. LRC developed a value-added tool (ExtremeEventAnalyzer (EEA)) to systematically analyse the accident scenarios not explicitly addressed in the design extension conditions using integrated deterministic and probabilistic approaches. The tool has incorporated lesson learned from FSA methodology developed by IAEA, which has been verified by application on Goesgen-Daeniken NPP (Switzerland) and Medzamor NPP (Armenia).

This methodology utilises an internal initiating events PSA model for assessing the impact of extreme events, including the consideration of hazard susceptibility limits of SSCs and impact of extreme external hazards. In EEA method, a number of extreme events (including credible combinations) can be postulated, for example seismic, water levels, extreme temperature, weather conditions etc. The extreme event analysis is linked directly to the PSA model (in RiskSpectrum) to ensure that the whole PSA model is included in the evaluation of the impact of the event or combinations of events. The EEA perform re-quantification of the PSA model including the hazard susceptibility limits of the SSCs. The outcome of the analysis is to [46], [47]:

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

Below is a list of sequential steps to perform while using the EEA method to identify scenarios sensitive for extreme events [46]:

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

EEA method and tool is utilised in a benchmarking study "Extreme Event Analysis - an application of RiskSpectrum EEA at Armenian NPP" is performed under co-operation project between LRC, Nuclear and Radiation Safety Center (NRSC) and Armenian Nuclear Power Plant (ANPP). The purpose of the study was to perform a comprehensive and systematic assessment of robustness and vulnerability of NPPs against the impact of extreme events using EEA method and tool. The EEA method, result and conclusion of this benchmarking study are presented in [47].

Assessment of coincident independent hazards

The frequencies evaluation for independent hazards is the simplest issue, the overall frequency of occurring N independent hazards can be calculated by the definition of independent collection wise events:

$$P\{A_1 \cap A_2 \dots \cap A_N\} = \prod_i^N P\{A_i\}$$

In terms of joint probability density function of the frequencies:

 $f(H_1, H_2, ..., H_N) = f(H_1)^* f(H_2)^* ... * f(H_N)$





where:

 $f(H_1, H_2, ..., H_N)$ - one common probability density function of the frequencies for combined events;

 $f(H_1), f(H_2), \dots, f(H_N)$ - probability density functions of the frequencies for separate independent events.

There is important to notice, that one should be careful in how $f(H_1, H_2, ..., H_N)$ and $f(H_i)$ are defined in terms of units and check that $f(H_i) \leq 1$ for probability estimation. Simply multiplying the "frequencies" may only give the estimate of probability that N events happen during the same time unit, e.g. one year, but not during the same time moment or at least short time interval. There should therefore be important to adjust the time unit and the mission time.

In the case of correlated hazards, the approach is more difficult and requires calculation of conditional probability density function, because:

$f(H_1, H_2, ..., H_N) \neq f(H_1)^* f(H_2)^* ... * f(H_N)$

The appropriate approach and examples were provided in [33]. Thus, the proposed approach for modelling of combination of events in the ET requires the additional analysis to determine suitable top-events parameters carefully.

Independent combination of hazards could be modelled in the initial tree (see the next chapter and example in Figure 2) directly using own frequencies as parameters of top-events through creation a new ET branch. As proposition, modelling of correlated hazards could be performed in the same manner (ET branch creation) but it is necessary to apply a special parameter change function/flag (depends on used software) for calculating of this new branch which change the top-event parameter (frequency) on the specially calculated in accordance with above-mentioned necessity. If the PSA model doesn't provide consideration of full scope of extreme hazards, the dependent hazards can be modelled using ET interface (see the next chapter and example in Figure 3) as additional factor/question (by the way of new top-event implementation).

An example of hazard risk assessment and PSA tool 'RiskSpectrum HazardLite' is explained in appendix 3.

Additionally, the EPRI method (ref. EPRI 103959) used to compute seismic fragilities could be applied to another hazard like extreme weather. For example, mean SSC fragility with hazard curves, the fragility calculation of the all core (core damage fragility), using ET - FT structure, fragility of SSC, new HRA, CCS, for the relevant range of the intensity hazard and for the unknown, random uncertainty parameters B_u, B_r. The results are weighted core fragility curves (sum of weight is unity) which are combined one by one with equally hazard weighted curves to obtain finally the probability density of the core damage frequency taking account the external hazard studied.





3 STRUCTURE AND SOLUTIONS OF EXTREME WEATHER PSA

Before defining the structure of extreme weather PSA it is necessary to make some assumptions. Taking into account the fact that this report should be adapted to the purposes of extreme weather PSA developing of any NPP sites located in different climatic zones, question of hazard screening is not raised in this report directly. More accurate information about hazards screening/events selecting is presented in WP30/D30.3 [34].

The identification of extreme weather conditions shall include the following steps:

- the metrological statistic on the basis of the data of national and international networks and agencies shall be analysed with quantitative and qualitative criteria (see WP30/D30.3 [34]), and thence all meteorological and climatological conditions of the region around the site shall be identified and their effects shall be evaluated,
- phenomena and credible combinations of phenomena potentially resulting from extreme weather conditions shall be determined,
- also, those hazards shall be identified that may not directly impact the plant, but could lead to failure of
 important infrastructure in the vicinity of the site or threaten neighbouring installations, which in turn threaten the safety of plant; especially attention in this way is needed for the impact on the high-voltage lines
 switchyard related damage which may cause significant disruption to the NPP operation; similar could be the
 case with the external communication lines related with relevant internal systems and the case of impact extreme weather conditions on the remote facilities/equipment (e.g. pump stations) from the main site of the
 NPP,
- special consideration shall be given to causal dependencies between various external hazards, including hazards other than extreme weather conditions (see also WP21/D21.2 [7]); examples for such dependencies are forest fires induced by drought or biological hazards triggered by extreme weather conditions (e.g. high water temperatures might be favourable for the growth of algae).

The list of hazards generated shall serve several purposes:

- identification of potential links between hazards with respect to the underlying natural phenomena (e.g. causal links) or with respect to similar impacts on the plant (potential for the implementation of measures providing protection against both hazards);
- revision of natural hazards as part of safety review processes, in response to changes in extreme weather conditions (e.g. climate change) or due to operating experience feedback.

Since some weather conditions may be practically invalid (e.g. forest fire hazard for NPP without forests in the vicinity) for various nuclear power plants (NPP), a certain preliminary screening of hazards (see WP30/D30.3 [34]) is needed to limit the amount of work.

Natural hazards identified as potentially affecting the site can be screened out on the basis of being incapable of posing a physical impact threat or being extremely unlikely with a high degree of confidence. In the same time, the extremely unlikely but possible events have to be carefully considered. Care shall be taken not to exclude hazards that in combination with other hazards have the potential to pose a threat to the facility. The screening process shall be based on conservative assumptions. The arguments in support of the screening process shall be justified.

Thus, in the frameworks of risk assessment from external hazards, one shall collect and assess the data specific for NPPs and site, and relevant general data required for the further quantitative analysis.

For all natural hazards that have not been screened out, hazard assessments shall be performed using deterministic and, as far as practicable, probabilistic methods taking into account the current state of science and technolo-



gy. This shall take into account all available data in the NPP and in the specialized institutions, and produce a relationship between the hazards severity (e.g. magnitude and duration) and exceedance frequency, where practicable. The maximum credible hazard severity shall be determined where this is practicable.

For extreme weather conditions an exclusion of hazards due to their lack of physical capability to cause adverse effects or exclusion based on the extreme unlikelihood have to be analysed for possible prospects of weather conditions in the considered region in future. Since the restriction of local meteorological data such as wind speed, extreme temperatures, precipitation etc. to a few decades only and the effects of climate change lead to very significant uncertainties of the hazard assessments. It should be noted that the available meteorological data are in general not as representative as for earthquake or flooding. As well, special care should be taken not to screen out hazards, which are at present negligible, but may become relevant in the future due to non-stationarity, e.g. climate change / consequences of climate change. Besides, possible combinations of weather conditions that do not pose a threat on their own should be considered before screening out hazards.

The occurrence of meteorological hazards such as rain, wind (including tornadoes), snow, hail, lightning, and extreme temperatures (including freezing) cannot be screened out in many cases for any site.

The output from this screening should be a list/matrix of hazards and their combinations which are relevant to the site and which need to be analysed in detail as the involved phenomena potentially pose a safety threat to the site.

Based on screening results, it could be necessary to analyse vulnerability of a power plant in order to define those SSCs that are fragile in relation to the considered external extreme hazard, depending on representativeness of the risk. If this hazard does not represent a major risk, there might be opportunities to simplify the fragility analysis and use a low detailed methodology (e.g. design level vs. realistic fragility curves).

From an industrial end-user perspective, the PSA methodology must be proportionate to the importance of risks (this can be also required by national laws such as the French Law). The adoption of a graded approach for External Hazards PSA would better focus resources and direct them to identify and address issues that present the highest significance to NPP Risks and Safety. Therefore, there is no relevance to use complex methodologies if a simplified analysis gives sufficient and representative insights.

Preparation of input data for the model includes construction of hazard curves for external extreme hazards and SSC vulnerability curves. An alternative method is to compare parameters of external extreme hazards with design data for SSCs boundary evaluation. Such a method is simplified and can be used only in case of unavailability of any statistics for hazard occurrence. The given analysis will allow correlation of external extreme hazards with internal initiating events from L1 PSA.

The next step is related to changes that should be made to the probabilistic model in order to account impact of external extreme hazards (additional event trees, modification of fault trees, review of basic events and human errors, common cause failures modelled). Under this stage, one shall consider combination of weather hazards and secondary effects, dependent failures and common cause failures (CCF) in the probabilistic model. The final stage includes performance of probabilistic calculations.

Summing up all the potential and detailed tasks and steps of extreme weather PSA they generally can be expressed through the diagram shown on Figure 1.







Figure 1 Flow chart for extended extreme weather hazards

Of course, each step must be adapted and simplified given the industrial choices made to develop these PSA models (graded approach vs. detailed PSA).

If a detailed PSA is preferred, the following text provides basic description of particular steps introduced in Figure 1 (further implementation details and interactions are discussed further).

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

The aim of this step is to determine list of all induced events that can be evoked by extreme weather induced event. Analysts shall review the plant safety systems from the viewpoint of extreme weather specific event. This step should be based on site specific list of correlated hazards (see Section 2.4 and the report of WP21 [7]).

Each analysis should evolve from list or matrix of feasible correlated hazards considering site specific conditions as well as possible events induced by correlated hazards. If we assume that list/matrix of potential correlated hazards ards represents only external hazards, then such (plant specific) list/matrix should be also added by correlated internal hazards. This step should have several (iterative) stages:

- assembling list of all feasible induced events that can influence fundamental safety functions,
- particular event can be screened out only in the case if it has none impact on fundamental safety functions,





- final list of not screened event should be added by description of:
 - effects that influence fundamental safety functions (e.g. events in plant area can damage service water facility, for example takeaway of water from pools by tornado);
 - o mechanisms (failure modes) leading to the adverse effects;
- final list shall also consider heat removal and releases from spent fuel pool,
- in the case of multi-unit side final list shall be reviewed to take into account adverse effects following from extreme weather induced failures of neighbouring units or others nuclear facilities (e.g. fires, operability of control room of analysed unit or its habitability if operator interventions are necessary to ensure fundamental safety functions etc.).

Output of this step is final list of induced events caused by correlated hazards including extreme weather related events. This list contains also basic information describing the effects of determined events on fulfilment of fundamental safety functions and mechanisms (failure modes) leading to the adverse effects.

2. Developing PSA extreme weather hazards SSC List:

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

- Assembling of list of essential SSCs that may be affected by the extreme weather events, see Section 3.6.2.1.
- Assembling SSC list for external induced events, see step 1 (Review Plant Safety), should be oriented only on essential / key components affected by induced events that extreme weather induced failures can threat plant safety.

Output of this step is compound SSC list containing:

- Basic SSC list for rudimentary PSA intended as an input for fragility analysis to assess conditional probability of weather induced failures of analysed unit safety significant SSCs including failures.
- SSC list related to the multi-unit effects intended as input for impact analysis, if appropriate.
- SSC list related to the external correlated events / effects intended as input for impact analysis.

Each item in final list should contain:

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

3. Extreme Weather Hazards Analysis:

Extreme Weather Hazards Analysis forms specific complex step which is performed by specialized team, see Section 1.

This task should provide parameterization of extreme weather hazards, i.e. in form of considered specific hazard curve with variability estimates. The measures for hazards curves building have to be in correlation with fragility measures for SSCs.

Output of this step is set of hazard curve(s) for SSCs that damaging or weather induced fails can threat fundamental safety functions.

4. Walkdowns:



During NPP walk downs, it is required to examine peculiarities of the mounting and current state of NPP components that are potentially significant with respect to analysis of external hazards, see also Section 3.2.3. The plant walkdowns task of essential components and their locations is emphasized in all PSAs. The walkdowns are conducted by a team of systems engineers (including mechanical or HVAC engineers), PSA expert and operators. Also, walkdowns should be aimed at confirmation that SSC meet requirements of standards.

In order for the walkdown to be efficiently performed, review of the design basis, preparation of procedures, collection of design/qualification data and training of the walkdown team are essential. Walkdowns shall cover all SSCs determined within steps 1 - Review Plant Safety and 2 - Developing PSA extreme weather hazards SSC List.

5. Screening:

In the hazards screening by contribution to the CDF when internal hazards having contribution below threshold value are screened out. However internal hazard analyses are performed case by case where (usually) only limited plant area is affected and rest of plant is intact. Extreme weather event forms more challenging situation because different plant-located SSCs as whole is affected by weather influence. This implies that only high capacity SSCs not threated by others SSCs can be screened out of the PSA extreme weather hazards SSC list. Such screening must be based on the review of qualification criteria and qualification documents (using high-confidence results of bounding analysis) of relevant SSCs and verified by walkdown if appropriate. Screening carrying out related specifically hazards occurring /events selecting is presented in WP30/D30.3 [34].

6. Extreme weather hazards fragility analysis

Fragility analysis is performed to evaluate conditional probabilities of SSCs weather induced failures for a given level of hazards intensities for the non-screened items from developed SSCs List. This step includes a development of SSCs fragility curve, if applicable. This step is the most applicable for hazards connected to force load (tornadoes, extreme winds and snow pack). For temperatures impact usually bounding analysis is used.

Typical inputs for this step are:

- Enhanced information from extreme weather hazards analysis (step 1);
- NPP response (safety significant SSCs response);
- Loads (force or temperature) defining relevant SSC demands;
- Evaluation of SSC capacities.

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

- Set of fragility curves to evaluate resistance of SSCs.
- Discrete results of bounding SSCs analysis if fragility curves building is difficult/impossible issue.

In some cases, detailed analysis (e.g. structural etc.) may be performed. The purpose of detailed analysis can be to clarify possible features in extreme weather induced accident progression. Attention should be paid to probable spatial effects (e.g. missiles), secondary effects, paths to mitigating of extreme weather consequences (e.g. special emergency brigade actions, snow cleaning, equipment heating, etc.), aggravating factors etc.

Output of this step is information for clarification emergency sequences and their using during event trees modelling (step 7).

7. PSA modelling:

The aim of this step is the modification and / or developing fault and event trees in order to reflect conditions induced by extreme weather event and to catch effects of all considered induced events. The interface with in-





ternal initiating events sequences is developed on this step. The description of appropriate approaches is presented in Sections 3.1 and 3.6.

Output of this step is extreme weather L1 PSA model suitable for risk quantification (step 8).

8. Risk quantification:

This step involves evaluation of risk and assembling comprehensive output of the results of the extreme weather hazards analysis. The approach of quantification is the same or based on approach for internal events L1 PSAs and requires to identify the dominant sequences, minimal cut-sets including uncertainty, importance and sensitivity analysis, see Section 3.7.

Output of this step is comprehensive information describing extreme weather hazards risk, enabling to identify appropriate measure to decrease risk. Format of L1 PSA extreme weather risk quantification should respect potential requirement of L2 PSA to allow establishing a straightforward interface between L1 PSA and L2 PSA.

9. Reporting and documentation:

Reporting represents overall documentation of work in order to provide set of documentation that enables to trace and reviewing performed work as well as to interpret result in an appropriate manner. Reporting is ongoing task performed as an integral part of particular steps introduced above, see Section 3.7.

Section 3.6 discusses the state-of-the-art methodology for Extreme Weather PSA, which complements Sections 3.1, 3.2 and 3.3.

3.1 SOLUTION FOR THE MODELING OF EXTREME WEATHER IN L1 PSA

Interface with L1 PSA

Similar to most external hazards, the L1 PSA model for internal initiating events is practically always used as a basis for the accident sequence development in extreme weather PSA. Consequently, the availability of the L1 PSA model for internal events and hazards are a prerequisite for performing an extended PSA of any extreme weather hazard. The extended PSA could be based on realistic models and data, including a comprehensive L1 PSA model for use in modelling all phenomena associated with the different extreme weather events.

From an industrial end-user perspective, the proportionality of the assessment is paramount. This could lead to use very detailed and realistic data as suggested here. This could also lead to perform simplified and bounding probabilistic assessments.

In accordance with good practices, preference is given to developing an integrated model for internal and external (including extreme weather) events in contrast to building separate stand-alone models for different categories of events. In order to properly address the impact of an extreme weather event, integrated models should also incorporate aspects that are different from internal initiating events. The major impacts of extreme weather events that could lead to various types of internal initiating events or to core damage directly should be assessed in the selection of the appropriate event sequences from the PSA model for internal initiating events. The probabilities of recoveries and post-initiator human errors should be revised by assessing the impact of extreme weather events on the credited recoveries and human actions modelled in the L1 PSA for internal initiating events. Also, it may be necessary to include and analyse recovery and human actions over and above those included in the internal events PSA model.





Obviously, this integrated model proposal could be inappropriate depending on the goals (Risk-Informed decision making purposes) and the means of the External Hazards PSA development, knowing that an integrated model could not be adapted to industrial uses (maintenance, calculation time, inadequate formalism for Risk Informed Decision Making etc.).

Hazards of various intensities can lead to both L1 PSA initiating event and more severe initiating events or new events.

Therefore, L1 PSA model shall be used as a basis taking into account additional failures of SSCs, spatial interaction, peculiar conditions for personnel, including the personnel of external facilities (e.g. pump-stations) and offsite staff, etc. This, in its turn, requires change of fault tree and event tree logics, adding of new basic events, sets of conditions and features, and revision of parameters of existing basic events of basic L1 PSA model.

The interface with the extended L1 PSA shall be constructed through the development of additional event trees for selected (critical) ranges of hazards, which will become critical for the severity of consequences, and for calculation of which this or that set of features shall be applied. Selection of critical ranges of hazard intensity is performed in an analytical way based on importance of equipment and possible initiating events induced by this or that hazard intensity (discretization of the hazard and the fragility curves using a limited number of hazard intensities). Another approach regarding using of continuous hazard and fragility curves for the whole range of hazard intensity of interest is described in Section 3.6.

Initial tree of implementation (in the form of event tree) of this range of intensity and type of hazards is a unified event tree that includes transfer to the abovementioned interface event trees (see Figure 2). This approach is one of the steps for interface between L1-L2 PSA and can be adapted for extreme weather extended L1 PSA. This tree is only recommended for a comfortable and visual representation of all considered hazards, its ranges and combinations. The top event of such a tree shows the hazard has not occurred. Also, no top events considered simultaneously (see Figure 2), e.g. Hi temp and Low temp are mutually exclusive events and cannot be treated simultaneously and the Figure 2 shows only the distribution of different extreme weather events in a common probabilistic model. The initiator (the first top-event) has a probability = 1. Here in the event tree actually are the basic events and top additional events in sense of the fault-tree model should be considered in the interface with the extended L1 PSA.



Figure 2 Initial tree of hazards implementation

In general, one cannot explicitly recommend the specific approach to modelling failures of equipment, since there are differences in capabilities of the applied software (computer codes) and, in fact, in models. For example, the stated approach can be simplified in view of the possibility to use sets of features/changes/boundary conditions to perform calculations and/or several end states for one event tree (in sense - the state of output is frequency of occurrence). Considering the fact that during the use of hazard curves and fragility curves there is a probability of occurrence of one and the same sets of L1 PSA initiating events for all ranges of hazard intensity, if possible it is



necessary to simplify the abovementioned tree through combination of various ranges of hazards and recalculate it with different conditions in order to specify and optimize the probabilistic model.

Interface event trees (end transfers of event trees) shall specify characteristics of hazards (for example, tornado area, wind direction, air humidity, etc.) and consider possibility for occurrence of L1 PSA initiating event or more severe initiating event. See example of interface event tree for tornado on Figure 3 below. The similar approach to ET building is described for continuous hazard and fragility curves for the whole range of hazard intensity of interest using in Section 3.6.2.2. A developing of top-events in the interface ET requires: the additional hazard parameters (e.g. pass of tornado) have to be analysed, fragility of SSCs assessed and compared with considered hazard characteristics (see also limitations in Section 4.1), actions for mitigation of hazard consequences (for example, response of the emergency teams (on-site and off-site taking into account that off-site location can be subject of more severe damage or the same scale impact, but not designed to withstand), also taking into account that in time actions can even prevent event occurrence) or secondary effects and aggravating factors (for example, possible flying objects, high/low air humidity) etc.



Figure 3

Interface event tree for tornado

3.2 SOLUTION TO MODEL THE EQUIPMENT SSC'S FOR THE EXTREME WEATHER PSA

Solution to model the equipment (failures of equipment) could be as follows: system fault trees of L1 PSA model are supplemented by basic events indicating the likelihood of equipment failure due to external hazards. Parameters of basic events are defined according to results of equipment fragility curves analysis (see Section 3.2.2) and are changed depending on the considered hazard intensity and other conditions through application of this or that set of features (replacement of basic event parameters or relevant fault tree logic switches).

3.2.1 SSC VULNERABILITIES AND ITS ACCOUNTING IN THE MODELLING FRAME-WORK

Systems, structures and components are classified with respect to external extreme hazards (for example, in accordance with NS-G-1.5 [8]) in order to define system requirements, assess consequences of their failure and develop personnel actions to eliminate or mitigate emergencies. The following SSCs classification with respect to external extreme hazards is recommended as initial:

 category 1: SSCs whose functioning should be maintained during and after external extreme hazards and SSCs required to prevent or mitigate an accident;





- category 2: SSCs whose loss of functionality may be permitted, but failure of which can reduce the functionality of category 1 SSC;
- category 3: SSCs whose failure can lead to events with radiological consequences not related to the reactor².
- Non-classified: All other items which can be sources of secondary induced effects (missiles, caving, other spatial interactions).

Typical systems that should be classified as belonging to the first category are as follows:

- the reactor system containment structure (including foundations) or the external shielding structure, if any, to the extent necessary to preclude significant loss of leak tightness;
- the structures supporting, housing or protecting items important to safety, to the extent necessary to ensure their functionality;
- structures protecting the plant from external events;
- the power and instrumentation and control (I&C) cables relevant to safety related items;
- the main control room or the emergency control rooms, including all equipment necessary to maintain the main control room or emergency control rooms within the safe limits for personnel and safe environmental limits for equipment protected against design-basis external events;
- systems or parts of systems that are required for monitoring, actuating and operating those parts of systems protected against design-basis external events;
- the emergency power supplies and their auxiliary systems necessary for the active safety functions;
- the post-accident monitoring system.

Typical systems that should be classified as belonging to the second category are as follows:

 those parts of SSCs whose continued functionality is not required (don't have a direct impact at accident scenario mitigation), but whose failure could reduce the functional capability of any plant features specified above (category C1) to an unacceptable safety level or could lead to injury of personnel of the control room, who are necessary to ensure safety function (HVAC, lightening on the site, etc.).

Typical systems that should be classified as belonging to the third category are as follows:

- SSCs for spent nuclear fuel confinement;
- spent nuclear fuel cooling systems;
- systems for retaining of high-level radioactive waste in gaseous, vapour, liquid and/or solid form.

Such classification is marginal and could be applied only if we assume that during strong wind something is possible/ permissible to stop operating in NPP. There is needed specific classification of impacts related to the safety systems and their interfaces. An approach with the use of SSC classification will simplify screening of considered SSC and reduce the scope of activities on assessment of SSC vulnerability to weather conditions.

For each external extreme hazard, it is necessary to define equipment and power unit (NPP) areas that are vulnerable with respect to this hazard. Definition of the stated power unit (NPP) areas is necessary for the reason that equipment can be damaged by nearby structures (for example, equipment can be damaged by structures destroyed by the tornado if is located outdoors).

 $^{^{2}}$ L1 PSA is oriented to fuel damage in the reactor, spent fuel storage (SFC) is typically subject of separate study, but in the extended L1 PSA could be considered, of course taking into account different location of SFC (on the site / off the site), systems, control, personnel, etc.





Equipment or categories of equipment that cannot be affected by the considered hazards are excluded from the list of SSCs, for which fragility curves are constructed, and relevant basic events preserve their parameters used within L1 PSA.

The following general algorithm could be used to model accident sequence:

- analysis of design documentation and technical specifications for equipment vulnerable to external extreme hazards,
- study of a design basis for SSC (national building standards, international standards) to understand potential vulnerabilities and loading parameters,
- identification of NPP components vulnerable to external extreme hazards,
- identification of initiating event from L1 PSA that is the most approximate and significant with respect to this event (if necessary, additional initiating event shall be introduced),
- change in probabilistic model fault trees considering vulnerable equipment,
- modelling of additional SSCs intended to overcome external extreme hazards (in case of occurrence), for example, protective structures, systems for heating of equipment exposed to low temperatures, etc.,
- change probability of failures for personnel actions (adding of new personnel actions),
- change in event trees (if necessary) related to the selected initiating events,
- calculation of accident sequences for the given selected group of initiating events.

Strong winds and tornadoes

Strong winds can cause bending moments that primarily affect high buildings (containment, ventilation stack, cooling towers), and the rotational force to the rectangular buildings. Fluctuations in wind speed lead to dynamic loads. It is necessary to have results of analysis of structures resistance to loads caused by wind in order to account such hazards.

It is necessary to receive or assess data characterizing the ability of buildings and structures to resist wind loads exceeding the values envisaged by the design in order to assess effects of high wind. Such an assessment will provide with information required for the detailed analysis of risks.

As regards wind loads created by tornadoes, the situation is similar to high winds. The analysis of effect from flying objects requires strength characteristics of important equipment/ building structures or detailed analysis of their resistance to flying objects. Interaction on buildings or equipment due to missiles must only be envisaged if and only if there is a risk on safety.

It is necessary to assess resistance of building structures and equipment located outside buildings and structures to various types of hazards caused by tornadoes (extreme winds), including dynamic moments resulting from wind speed fluctuations, possible removal of cooling water from spray ponds by tornado, etc.

Modelling of accident sequences

The following efforts can be performed within this subtask:

Define vulnerability of a power unit to the given extreme hazards using available design criteria (for high winds) and specific accident sequences (for tornadoes). Then it is necessary to perform in-depth analysis for accurate definition of all possible initiating events caused by these extreme external hazards and their frequencies. This definition should be consistent with SSCs models in the L1 PSA. For example, the turbine hall may not be the object of interest (if it is not safety related and if it cannot induce an initiating event).



- Construct the relevant interface event tree for the considered hazard with transfer to the initiating event from L1 PSA or a new initiating event. For each revealed initiating event, it is necessary to select the relevant event tree from those developed in L1 PSA and define the scope of its required modifications, in particular:
 - required changes of event sequence related to specific nature of the initiating event initiated by these extreme external hazards (change of event tree structure);
 - change of system models reflecting the spectra of possible dependent failures (change of fault trees);
 - repeated calculation of values of probable human errors used in L1 PSA, considering stress caused by the side effects related to these extreme external hazards.

For example, high wind can result in break of flexible communication lines that connect a power unit with 750 kV open switchgear, flexible communication line of 330 kV (when this value is relevant in some countries) open switchgear and the second set of emergency transformers, and this can lead to occurrence of the initiating event from L1 PSA, namely initiating event "Blackout of all normal power supply sections". Therefore, it is necessary to analyze occurrence of this initiating event with respect to wind hazards in view of possible additional failures of SSCs (due to falling of flying objects, falling of supporting pillars, tower cranes, etc.).

For tornadoes, one should carefully study the result of their effect on the following SSCs:

- effect of tornadoes on buildings and structures considered in PSA;
- effect of tornadoes on open water reservoirs;
- effect of tornadoes on air intake devices of the ventilation and air conditioning systems;
- effect of tornadoes on power supply systems.

Depending on the category of tornado and its direction, the following initiating events can occur: blackout, loss of service water or their simultaneous occurrence, initiating event "Blackout of all normal power supply sections" with simultaneous occurrence of additional failure of three trains of the essential service water system (for WWER units). As it was stated earlier, modelling of possible initiating events is performed by means of event tree for the relevant tornado category.

Temperature

Technical specifications for equipment (equipment qualification) presenting limits for this factor could be studied in order to identify components of power unit systems that are potentially exposed to low ambient temperatures in extremely cold winter (only in winter should be in the design criteria).

In addition, it is necessary to conduct a survey of personnel to identify vulnerability from external extreme temperatures in order to collect expert assessments from personnel responsible for power unit control on the list of major SSCs that can suffer from extreme temperatures.

The SSCs assessment shall consider that extreme air temperature can cause not only failure of system components, but also their spurious actuation.

The in-depth analysis of vulnerability of power unit components with respect to high and low temperatures requires collection of data from the technical specifications for equipment (equipment qualification). Besides, it is necessary to analyze effect of air temperature on the temperature of water sources, for example, cooling pond, and to define frequency of exceeding design boundary for the temperature of circulation water, etc.





These phenomena being slow in developing, it is also important to consider, as part of the analysis of extreme temperature, human actions and specific materials which can limit the effects of such hazards. Reliability of these actions must also be analysed (HEP for instance).

Snow pack

The calculation of the snow pack pressure on the roofs of buildings and structures shall be performed based on information on possible height of the snow pack and snow density, if available. Snow density is a function of weather conditions and sometimes its assessment is complicated without data.

The vulnerability of buildings and structures shall be defined primarily based on the snowfall intensity, taking into account availability and possibility of snow removal.

In case of combination of hazards, the snow pack can impede the movement of vehicles and personnel on the site, and makes it difficult for personnel to take needed actions, which shall also be considered in the analysis.

System analysis

In the frameworks of system analysis, revision shall be performed of those system fault trees developed under L1 PSA for internal initiating events, which will be related to event trees in order to analyse external hazards. Revision of fault trees is performed:

- to identify dependent failures that occur due to equipment damage;
- to assess other possible effects of external hazards on probability of SSC failure.

The relevant system models are modified to present types of failures related to external hazards. In the process of system model modification, specific attention shall be paid to modelling of common cause failures. The method used to model common cause failure in the fault tree shall be logically correct and give the most reliable results. When new basic events or operators are added to the model, they shall have unique names. Functional fault trees shall be developed to connect fault tree and event tree.

3.2.2 CALCULATION OF FRAGILITY OR FAILURE PROBABILITY

In general, the use of SSC fragility curves can be applicable for all hazards considered in this report. For example, for equipment vulnerable to high temperatures, there is a possibility for reliability decrease (probability of internal failures) even if critical temperature (according to the technical specifications or certificate) has not been reached, but is close to it. Thus, if possible, it is preferable to consider the fragility curves in any case.

Construction of fragility curves is performed for the predetermined list of SSCs. This list shall be defined also in an expert way supplementation. In case of large number of considered equipment, it could be used results of significance analysis received from L1 PSA. Thus, it is possible to exclude the construction of fragility curves for that equipment, which has imperceptible contribution to the emergency process.

There are several possibilities for computing fragilities and each hazard has its own specificities. Four basic approaches (judgmental, empirical, hybrid, and analytical) have been already good described in [35].

The methodology of constructing SSCs fragility curves is described in NUREG/CR-2300, Volume 2 PRA [36] and other sources (e.g. [37]). Generally, a fragility can be defined as the conditional probability of failure of SSC (or as their structural member) for a given set of input variables. It is expressed as:

$$P[LS] = \sum_{all \ D} P\{LS|D = x\}P[D = x],$$



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where, D = a random demand on the system (e.g., 3 second gust wind speed (m/s), max load (Pa), max/min temperature)³; P[LS/D=x] - is the conditional probability of the limit state (*LS*) at given demand *x*; The hazard is defined by the probability P[D = x]. The conditional probability P[LS/D = x] is the fragility. Previous equation also can be expressed in convolution integral form if the hazard is a continuous function of demand *x*:

$$P[LS] = \int_0^\infty Fr(x)g_X(x)dx,$$

where Fr(x) = fragility function of demand x expressed in the form of a cumulative distribution function and $g_X(x)$ = hazard function expressed in the form of a probability density function.

The fragility of a structural system commonly is modelled using a lognormal distribution,

$$Fr(x) = \Phi\left[\frac{\ln(x)-\lambda_R}{\xi_R}\right],$$

where, $\Phi[...]$ = standard normal cumulative distribution function, λR = logarithmic median of capacity R (in units

that are dimensionally consistent with demand), and ζR = logarithmic standard deviation of capacity R.

For instance, for wind loadings can be applied next algorithm for fragility calculation. Based on the results of the wind response analysis, the demand over the structures is computed as function of the same strength parameter (speed, load, other chosen parameter of wind). Taking into account the above mentioned, the capacity could then expressed in terms of median value of chosen parameter and logarithmic standard deviations B_R and B_U reflecting the randomness in capacity and uncertainty in the median capacity, respectively. For simplicity, the logarithmic standard deviation B_{c_i} defined as the composite variability, is often used to define a single mean fragility curve. For this case it is useful apply a 'high confidence' (is known as the "High Confidence of Low Probability of Failure" (HCLPF) capacity for seismic safety assessment) capacity is conventionally defined by the hazard strength that corresponds with 1% failure probability in the mean fragility curve of the component.

Modelling of additional positive or negative effects from extreme hazards (for example, humidity) is performed by adding of additional top events into event trees. At the same time, at the level of system fault trees it is necessary to consider (through adding of new basic events or/and relevant logic switches) additional effects on SSCs to receive additional sequences (minimal cut sets).

Note that detailed capacity calculations are required only for those modes not screened out during the plant walkdowns due to a judged large wind capacity.

This is also important to know a design basis of SSCs. It can be not enough to build fragility curves just based on max/min temperatures because another factor has an influence to a capacity of SSCs against extreme temperatures is a duration of the temperature holding. That's why it could be better and easier use other methods of SSC fragilities due extreme temperatures identification than fragility curves.

³ On the basis, for instance, on study of a design basis for SSC (see comments in Sections 2.2.2, 3.2.1).



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Fragility curves are important components of accurate risk assessments under the following conditions: the loads (e.g., the demands) placed on a system are either variable or uncertain; the capacity is uncertain because there is spatial or temporal variability in material strengths, the system is inherently elastic, or the system is poorly understood; and the system is brittle but poorly understood (see Figure 4).





Examples of fragility curves as a step function (left) in case of very well understood or brittle systems and S-shaped function (right) for poorly understood or elastic systems.



Mean Roof Fragilities



Figure 5 Example of wind pressure (WP) mean fragilities [49]

In the USA developed a general code-based methodology for wind and tornado fragilities with significant enhancements similar to seismic approach. The use of the derived mean hazard and derived mean fragility curves to estimate failure frequency is accurate to about \pm 15% when compared to an exact integration of the families of curves.



Quantification of the top event in High Wind PSA involves thousands of computations of component and system failures with thousands of cutsets [49]. The computation of component failure frequency from hazard and fragility curves is fundamental to High Wind plant response quantification. The paper [49] examines failure frequency calculations using wind hazard and fragility functions. Multiple issues are investigated, including: (1) the number of wind speed intervals needed for accurate computation of component failures; (2) the wind speed range needed to accurately compute failure frequencies; (3) the differences in the computed failure frequency from the derived mean curve vs. its family of curves; (4) the trade-offs in modelling single vs. multiple wind hazards; and, (5) the range of error bounds for perfectly positively and perfectly negatively correlated failure modes compared to statistically independent modes.

3.2.3 IMPORTANCE OF WALK DOWNS AND PLANT SPECIFIC DATA

The main purpose of NPP walk downs is to collect and specify received plant data. During NPP walk downs, the following plant data shall be specified:

- configuration of components and system structures;
- layout of components and system structures;
- dimensions of building structure components.

During NPP walk downs, it is required to examine peculiarities of the mounting and current state of NPP components that are potentially significant with respect to analysis of external hazards. Also, walkdowns should be aimed at confirmation that SSC meet requirements of standards. A walkdown list shall be prepared in advance on the basis of the SSC choosing analysis (see Section 3.2.1).

Walk down results can play an important role during analysis of dependent failures, spatial interactions (for example, for tornado on the NPP site or due to effect of high winds). It is also necessary to analyse secondary effects of hazards. For example, flying objects in case of high winds or falling/bending of high objects. Such a secondary effect can lead to the initiating event, even if the primary effect does not lead to it.

A walk down can also be an opportunity to assess the feasibility or reliability of mitigating human actions in a hazard context.

3.2.4 UNCERTAINTY IN THE DATA ON EXTREME EFFECTS

Usually, the data on extreme effects are characterized by a large degree of uncertainty. Thus, during construction of risk curves, it is necessary to consider sufficient number of confidence intervals, as well as for construction of SSC fragility curves (as approaches for consideration of extreme weather hazards based on a discretization of the hazard and the fragility curves using a limited number of hazard intensities were chosen). The study of model uncertainty analysis results can be an important factor in determining the reliability of received results and need for their clarification.

Typical sources of uncertainties that shall be considered are as follows:

- data completeness;
- study of phenomena and mechanisms of their impact on SSCs;
- secondary effects;
- assumptions of the developer;
- reliability of engineering assessment;
- human actions.





3.2.5 INTERFACE LEVEL 1 - LEVEL 2 FOR EXTREME WEATHER PSA

This section provides recommendations regarding the definition of Plant Damage States (PDSs), which are used as boundary conditions in the Level 2 analyses, for the extreme weather initiators groups that have been identified to be of most interest by the end-users' group after collection and discussion of results from the ASAMPSA_E endusers survey [38]. The general discussion on definition of PDSs and protocols and recommendations for performing PSA are to be found in the ASAMPSA2 guidelines ([39] and [40]).

Most of the discussion is the same for each of the external events initiator groups, according to experience gained from performing and/or reviewing complete and integrated analyses, and therefore the sections are given for completeness and to make the discussion self-contained for each initiator group and with small variations from each other, according to initiator group expected consequences. The only exception is for the "biological infestation" group, for which no specific analysis has been performed to date. For this group, guesses are given, on the basis of potential (or known) infestation incidents.

Definition of Plant Damage States (PDS) for extreme weather initiating events

Since the definition of, and collection of data for the PDSs are tasks that may fall upon different teams that perform the analyses (L1 PSA and L2 PSA teams), this section is intended primarily for L2 PSA teams.

It must be stressed, as was done for analyses of internal events ([39] and [40]), that this task involves close interaction between the teams performing the analyses. Level 2 personnel has knowledge about what boundary conditions are necessary for characterization of accidents after core damage, and Level 1 personnel knows how accidents progressed up to that point and why core damage occurred. Therefore, this part of the works profits from feedback and potentially iterative work between the two teams in the course of defining the PDSs.

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

It is also strongly recommended that the Level 2 team familiarizes themselves with the results of Level 1 in terms of individual accident sequences or Minimal Cut Sets that show the chain of failures (initiator, dependent systems failures, component failures, and operator errors) and dominating cut sets that ended in core damage. Operator errors in Level 1 are of particular importance for Level 2 analyses if operator interventions that could be considered as part of SAMGs are introduced in Level 1 in conjunction with interventions that are part of EOPs. This is the case for instance for containment venting, initiation of containment sprays, or initiation of firewater (or equivalent emergency system) injection in the RCS prior to core damage in BWR plants. The danger is that these systems may be over-credited in Level 2, if accident progression to the time of core damage is not thoroughly understood by the Level 2 teams.

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

The definition of PDSs that has been used for the internal events analysis has to be verified for applicability to Level 1 accident sequences that are initiated by extreme weather events. The combination of dependent and



independent systems failures due to extreme weather events-induced sequences may require the definition of additional PDSs that were not considered possible for internal events. Finally, operators may be required to perform actions (such as venting of the containment prior to core damage) that would not be considered under accidents initiated by internal events and that change the status of the containment before the beginning of Level 2 analyses.

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

Additional characteristics with particular importance for L2 PSA do not seem to be needed. Any example could be an accident with somehow catastrophic consequences in Level 1 (everything fails), so that any issue impacting Level 2 would be "mute".

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

3.3 SOLUTION TO MODEL - HRA FOR THE EXTREME WEATHER PSA

The objective of this section is to identify personnel actions performed within the accident management strategy and caused by external extreme hazards, and to define human error probability for such actions.

In those cases, when external hazard initiates the internal initiating event, human reliability analysis comes to recalculation of human error probabilities defined in L1 PSA for internal initiating events. Reassessment shall consider stress state of the operator in connection with occurrence of the external hazard, the lack of understanding of the accident sequence progression due to damage of I&C devices, the physical impossibility of some local actions, and the effect of external hazard on the time required for individual recovery actions.

Human reliability analysis could be based on the same methodology that was used for PSA of internal initiating events.

The following factors can be taken into account:

- 1. stress of personnel (including other performance shaping factors) proceeding during and following the occurrence of external hazard;
- 2. physical impossibility to perform certain actions outside MCR;
- 3. lack of information on progression of the accident resulting from I&C failure (probable in cases of extremely high temperatures, loss of venting etc.);
- 4. effect of external hazard on the available time;
- 5. obstacles to transport to/off site personnel, emergency response teams;
- 6. psychological effects if living area for the personnel is affected by extreme weather (i.e. prioritization of new actions as dealing with injured people).

The HRA analysis could be very detailed as personnel may react "in panic" in case of severe external events like earthquake and other. Even events like "magnetic storms" (sun eruptions / protuberances) may affect the mental state of the people.

The possibility to take "spare team" of operators on the affected site shall be estimated.





For certain hazards (predictable hazards), PSA model may also credit specific actions to mitigate the hazard (see Section 3.6.4). Accident sequences (transient initiating failures and other SSC failures and damage forms) that are specific to the impact on an extreme weather event and thus require human interventions not included in the internal events PSA must take into account these actions. Their failure must be assessed.

3.4 SOLUTION TO MODEL ADDITIONAL EMERGENCY RESPONSE

3.4.1 POST FUKUSHIMA MEASURES

Experience gained from the study of the accident at Fukushima Daiichi NPP is considered in details in the report D30.2 [41].

If any measures based on lessons learnt from the accident at Fukushima Daiichi NPP have been implemented at NPP, they should obligatory be considered in the probabilistic model, since they can significantly affect accident sequences related to a complete loss of NPP power supply or essential service water system (ESWS).

3.4.2 MOBILE EQUIPMENT AND EMERGENCY MEASURES

The use of additional technical means and emergency teams to mitigate consequences of NPP accidents can have an impact on the possibility for occurrence of an initiating event and on accident progression scenarios. Specific attention should be paid to analysis of accident progression scenarios and equipment that potentially can be damaged and secondary effects of hazards.

Since the secondary effects may progress in time and depend on severity of a hazard and its confinement, the following factors should be taken into account to consider additional technical means and external support:

- location of emergency teams (important in term of time needed to deliver equipment and take the required actions);
- type and quantity of available special equipment (important in terms of efficiency, and severity of hazards that shall be overcome);
- presence of blockages and other obstacles on the way (important in terms of time for delivery of equipment and for taking required actions);
- category of hazard consequences severity (important in terms of efficiency in their overcoming or possibility to overcome them in principle);
- preparedness for the particular impact.

Thus, for correct accounting of the above factors, it is could be useful to perform analysis of hazard progression scenarios and to explore the possibilities of additional technical means and emergency teams.

The main success criterion to mitigate hazard consequences is the time of "deployment", which plays one of basic roles in the analysis. For a positive outcome (for example, non-damage of additional equipment), the "deployment" time should be less than time for secondary effects to reach "key" points (should this include access ways of personnel to the required equipment or equipment important to safety). Therefore, the "deployment" time shall be defined taking into account training of emergency teams, time for delivery of special equipment taking into account blockages (for scenarios that envisage presence of blockages or obstacles), available NPP emergency response plan, procedures for obtaining permits from the physical protection, etc.





In addition to the "deployment" time, success criterion includes specific nature of a hazard, category of hazard severity, hazard confinement, training of emergency teams, type and quantity of special equipment. The relevant analysis involves searching of correlation between the list of screened emergency events (scenarios of hazard progression) and the possibility of emergency teams to overcome or mitigate the consequences of a hazard.

In modelling response of external emergency teams, depending on the availability of statistical data on overcoming the consequences of hazards taking into account their specific nature, the following two ways can be highlighted to consider mitigation of accident sequences:

- discrete/Boolean/binary (based on results of deterministic analysis), which postulates a complete success or a complete failure in mitigation of consequences (confinement of equipment, ensuring access for personnel, complete overcoming of hazard consequences without its progression into the initiating event). This approach envisages the decision making related an inclusion of additional scenario ways to the model logics, if action of the emergency teams cannot be successful (e.g., due to time limitations, state of environment). For example, add branches with dependent failure of equipment (which cannot be remained operable due to efforts of the emergency teams), incorporate the whole scenario of hazard consequences progression (since efforts of the emergency teams could not help to prevent occurrence of the initiating event), etc.;
- probabilistic, which considers representative statistics on successful/unsuccessful overcoming of relevant consequences of a hazards, taking into account their specific nature. With availability of sufficient and representative statistics, it is necessary to define probability of successful mitigation of consequences and to supplement the model with the relevant events (for example, top events in the interface event tree), which reflect probability of mitigation of hazard consequences.

Application of any of the two described approaches requires collection of additional information and consultations with experts.

3.5 SOLUTION TO MODEL - MULTI-UNIT FOR THE EXTREME WEATHER PSA

The paper [42] presented a classification system that utilizes existing single-unit PSAs and combines them into a multi-unit PSA. Two methods which can be used for creating a multi-unit PSA have been identified. One method is to develop an entirely new multi-unit PSA, and the other is to integrate existing single-unit PSAs. It is stated that the prohibitive cost of developing a PSA and the potential technical impediments of creating a state-of-practice multi-unit PSA make the latter method more feasible both practically and economically because of the ability to utilize existing data and models. An example of attempt to construct a comprehensive methodology that would create a simplified multi-unit PSA by integrating multiple single-unit PSAs into a multi-unit PSA is given in ref. [43].

Since mentioned methodology requires the user to create a Level 3 PSA for each unit at the site, it is much more resource intensive than creating a multi-unit L1 PSA, which can be accomplished by combining existing single-unit L1 PSAs to create the risk profile of a multi-unit site. In this case all of the ways in which units could be coupled needs to be understood. The multi-unit methodology proposed [42] defines a unit as a reactor core and it's front-line and support SSCs. That is, everything inside of the primary containment building and power generation and supporting systems.

There are many types of events that could create a dependency between multiple units from a risk perspective. In order to effectively account for these risks when looking to create a multi-unit PSA, six main commonality classifi-





cations have been established (see Figure 6): initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies. The first step in the proposed process is to sort the events in the single unit accident sequences into classifications. This allows the dataset to be reduced from typical 100 plant systems to just seven classifications (one independent and six dependent) that need to be analyzed.



Figure 6 Commonality classification of dependent events

For the purpose of this report, dependencies on initiating events are relevant. The initiating events can be divided into two subclasses: events that will always affect multiple units, referred to as "definite" events, and events that will only affect multiple units under certain circumstances, referred to as "conditional" events. Those events that will always affect multiple units include many external events including hurricanes, extreme temperatures, and high winds.

In the study [42], the following five different type methodologies have been identified to account for multi-unit dependencies: combination, parametric, causal-based, extension, and external event type methodologies. The definite initiating events that will always affect multiple units would only need to use the combination methodology to be integrated into a multi-unit PSA. Since the single-unit PSAs should contain all of the potential initiating events, they would simply need to be combined. The items (SSCs, initiating events, etc.) that are already common to multiple plants will always be common; they simply need to be represented as one item in the multi-unit PSA so that they are not double counted in the quantification of the site CDF, LERF, LRF, etc. For these items, there will be no effect on the site CDF; however, the importance of the items may increase in the final risk importance measures. This assumption is only true if and only if the common items are shared between the different units and can be used by both units at the same time. As a simple multiplication is not representative of complex dependencies, in some cases the CDF cannot be assessed in a simple manner.

3.6 STATE-OF-THE-ART METHODOLOGY FOR EXTREME WEATHER PSA

This section presents the specificities of PSA model development for those extreme weather hazards that were selected earlier during the ASAMPSA_E project (i.e. high straight wind, tornado, extreme high and low air temperature and snowpack), by going through the general PSA model development process and the associated analysis steps: characterization of PSA initiating events, development of accident sequence models, fault tree development, human reliability analysis, analysis of input reliability data. To avoid unnecessary overlaps, only the most important aspects are summarized here, and reference is made to the relevant section for more details on a given topic. The general methodology for PSA model development presented hereby is applicable to all extreme weather hazards that are in the scope of this report, with the exception of those considerations, that aims to highlight the specificities of a certain hazard. Although this section treats all the different extreme weather hazards in a general framework and contrary to what is written in Section 3.1, the analysis steps presented in the following sections has to be followed separately for each extreme weather event.





3.6.1 CHARACTERIZATION OF PSA INITIATING EVENTS

The first step of PSA model development for external events is the unambiguous definition of PSA initiating events. The identification and characterization of PSA initiating events is performed during hazard assessment, i.e. the output of hazard assessment is the list of PSA initiating events and the relevant characteristics thereof (amongst others their occurrence frequency). Section 2 of this report presents hazard assessment for extreme weather hazards in detail, therefore only the most important aspects are discussed hereby.

For extreme weather hazards, initiating events correspond to the occurrence of the external events themselves (e.g. high wind, high air temperature) that may induce multiple transients at the plant. Most of these induced transients are usually initiating events considered in the internal events PSA. For extreme weather hazards (within the scope of this report) there is no need for addressing different impact zones, since each hazard impacts the whole area of the plant or the site as opposed to a hazard that has only a restricted, definite impact area (e.g. an aircraft crash). Consequently, the characterization of each initiating event in an extreme weather PSA is to determine event frequencies for different magnitudes of the parameter which represents best the load induced by the extreme weather event in question. Some extreme weather events can only be characterized appropriately by more than one parameter, e.g. the instantaneous as well as the daily and weekly average maximum temperature are essential in risk assessment of a nuclear power plant for extremely high air temperature. For these hazards the joint distribution of the risk significant parameters should be obtained during hazard assessment. In summary, in an extreme weather PSA model separate initiating events are assigned to each extreme weather event that were selected for detailed analysis after screening.

There are two basic approaches that can be followed during PSA model development and quantification:

- 1. discretization of the hazard and the fragility curves using a limited number of hazard intensities;
- 2. use of continuous hazard and fragility curves for the whole range of hazard intensity of interest.

In the first approach point estimate, quantifications are performed using mean hazard frequencies for discrete ranges of the hazard intensity (e.g. for distinct ranges of wind speed) and mean values for equipment fragility that are derived from the fragility analyses for each hazard intensity range. This approach designates a certain number of parameter ranges that define different initiating events for a single external hazard. This approach is applied frequently in a seismic PSA, mostly due to the limitations of risk assessment software.

Use should be made of continuous hazard and equipment fragility curves in the second approach, which enables a straightforward numerical assessment of uncertainty and sensitivity, as well as a convenient treatment of numerous fragility curves with largely varying means and variance during quantification.

3.6.2 DEVELOPMENT OF ACCIDENT SEQUENCE MODELS

The main objective of developing the accident sequence models for an extreme weather hazard is to construct an event tree structure that integrates event sequences developed in the internal events PSA and distinctive transients induced by the extreme weather event in question into a generic model that reflects the specifics of the investigated extreme weather initiating event. There are several approaches appropriate to fulfil this objective. This section presents a series of analysis steps applied by a state of the art methodology, however several, slightly different methods have also been used in recent PSA studies. In the method described herein, accident sequence models for extreme weather PSA are developed in the following major steps:

• identification of SSC failure modes that can be caused by the extreme weather event in question,





- identification of transient initiating failures, mitigation system failures and damage forms that can be the consequence of SSC failure modes identified in the previous step, establishment of a list of transient initiating failures that can be induced by the extreme weather event,
- development of a generic event tree for modelling plant responses to the investigated extreme weather event with combinations of single and multiple transient initiating failures.

3.6.2.1 Definition of Failure Modes for SSC

As the first step of accident sequence model development, a list of essential SSCs that may be affected by the extreme weather event in question and hence is subject to fragility analysis is set up. This is done by means of system analysis and fault tree modelling of all plant systems needed to prevent core damage following the extreme weather event. For the extreme weather event a comprehensive list of SSCs is developed taking into account the relevant impact characteristics of the extreme weather event in question as well as all failures that might have an impact on the plant risk, i.e. the failure of the SSCs may either induce a plant transient or disable a mitigation system. For plants in operation a plant walkdown is indispensable to verify and refine the list of SSCs derived from analysis so that the impact of structural failures and spatial system interactions are properly considered during the identification of the relevant SCcs. In fact, for the purposes of identifying all relevant SSCs, fragility analysis and PSA modelling are mutually dependent tasks with a two-way information flow between them. Thus, the failure modes that may be due to the extreme weather event are defined for each SSC identified earlier.

All the possible effects of the extreme weather hazard in question are taken into account in the identification of the relevant SSCs and their failure modes.

Primarily, the effects of loads from wind and snowpack on safety related structures and outdoor facilities should be analysed in detail for the purposes of identification of SSCs and the failure modes thereof. Amongst others, high winds may also affect the power supply system and open water reservoirs. In addition, high winds may induce blockage of air intake systems to the diesel generators and to HVAC (heating, ventilation and air conditioning) systems. The effects of wind generated missiles (flying objects) should also be assessed. Snowpack may also induce blockage of air intake systems to the diesel generators, to water storage tanks as well as to HVAC systems.

For the assessment of risk due to extremely high and low air temperatures, a detailed analysis is needed to evaluate the effectiveness and reliability of the plants' HVAC systems under harsh weather conditions. Temperature limits for the safe operation of all components with considerations to the actuation of temperature protection need to be determined in order to assess the potential loss of active components from this reason. Temperature resistance of electrical, control and instrumentation components located outside of the plant buildings should be assessed in detail to determine the safety margin beyond design basis and to underpin fragility analysis. The vulnerability of mechanical components to extreme temperatures needs to be evaluated. Fragility assessment regarding extreme temperatures needs to be conducted for the off-site power system (grid) too. It should also be analysed whether safe stable plant conditions can be ensured by using power supply from the emergency diesel generators in lack of off-site power with extremely high and low air temperature conditions.

The relevant failure modes may be identified by the use of an inductive or a deductive approach, or the combination thereof. If an inductive approach is used, then all the consequences of an extreme weather hazard are mapped first, and the PSA relevant items are selected afterwards. The deductive approach takes a pre-defined comprehensive list of SSC failure modes as a basis and it tries to determine which might be induced by an extreme weather event. Typically, the deductive approach is followed with the use of inductive thinking to some extent, i.e.:





- the basis (initial list) is a list of failure events derived from the internal events PSA,
- plant response and fragility analysis, and failure mode identification are performed in combination and in an iterative manner to supplement the list of failure modes with failures that are not included in the original internal events PSA (new initiating events and component failure modes not credited in the internal events PSA because of the low probability of those events due to random internal failures, e.g. simultaneous opening of multiple steam generator safety relief valves in a PWR).

3.6.2.2 <u>Categorization of Failure Modes as Transient Initiating Events and Failures in</u> <u>Mitigation Systems</u>

In this step of PSA model development all transient initiating failures and additional system, train or component level failures and damage forms that can be caused by the SSC failure modes identified in the previous step are determined. An illustrative example for high wind and snowpack hazards is the identification of induced plant transients and failures in mitigation systems/components caused by the structural damage of a building. The state of the art methodology assumes that all the equipment installed inside a building fail in case of a structural damage. Extreme weather induced transients, which have not been taken into consideration in the internal events PSA are also defined in this analysis step. To exemplify the typical results of this analysis step Table 2 shows those failure mode consequences of high wind or snowpack induced structural damage of the turbine building in a VVER plant that are important to PSA.

Table 2 Transient and other failures induced b	y the damage of turbine	e building in a VVER	power plant
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GROUP	P: Turbine Building			
Transient initiating failure(s):				
 uni ste ser los 	recoverable loss of all feedwater pumps cam and feedwater header ruptures \rightarrow total loss of (main and emergency) feedwater rvice water line ruptures \rightarrow unrecoverable loss of service water \rightarrow loss of RCP intermediate cooling circuit is of offsite power			
Failure(s):				
 uni uni uni 	recoverable failure of the emergency feedwater system recoverable failure of the secondary side decay heat removal system recoverable failure of the main condensate system			

3.6.2.3 Event tree construction

The simultaneous occurrence of two or more plant transients (initiating events) is mostly screened out from a PSA for internal events due to the low frequency of such multiple events as random failures. In an extreme weather PSA however, multiple transient initiating failures are taken into account because any extreme weather event, as a common cause initiator, may lead to simultaneous occurrences of accident (transient) initiators. The individual transient initiators that belong to such combinations may or may not be considered in the internal events PSA. The systematic identification of each possible combination of impacts and the proper treatment of the correlation among these consequential failures are key elements of the extreme weather PSA modelling process. For comparison between the PSA models for extreme weather events and internal events, it is convenient to think of each possible combination of failures and internal events, it is convenient to a distinct initiating event. In comparison to a single transient initiating failure, multiple transient initiating failures (initiators in an internal events PSA) may place different, usually higher demands and challenges on plant systems and personnel concerning accident mitigation. Moreover, the transient initiating failures caused by an extreme weath-



er event can, in principle, occur in any combination. For example, if the number of transient initiating failures that an extreme weather event can cause is 'n', then the total number of different transient combinations at the onset of accident sequence development is '2n-1' as determined by the different combinations of simultaneous transient initiating failures. Theoretically, this is the number of event trees that are built up for each extreme weather hazard. In the state of the art practice the combinations of transient initiating failures are typically modelled by a generic event tree. That generic event tree starts with an extreme weather event as initiator and then it branches off for the different transient initiating failures 7, where

- EW_1 signifies one of the extreme weather (initiating) events, e.g. high wind,
- I1 and I2 denote the transient initiating failures caused by the extreme weather event in question,
- f(EW_1) is the frequency of event EW_1 (in general a family of continuous hazard curves),
- P(I1) and P(I2) are the probabilities of transient initiating failures I1 and I2 respectively,
- consequence S means a state with no transient initiating failures,
- while the other consequences represent the occurrence of a single transient initiating failure (sequences No. 2 and 3) or the simultaneous occurrence of I1 and I2 (sequence No. 4).

Depending on the plant design features the frequency of simultaneous events I1 and I2 (sequence No. 4) may be much higher than the simple product f(EW_1)*P(I1)*P(I2). For example, the combined likelihood of these failures may be influenced by such factors as correlation among specific component fragilities, structural failures that damage multiple systems, unique consequential impacts from the first failure, etc. Therefore, the numerical value for P(I1*I2) in sequence No. 4 may be substantially higher than the product of P(I1) and P(I2). The logic structure of the extreme weather PSA model is developed so that such dependencies are considered explicitly and also quantification of event sequences is performed in view of these dependencies.

High Wind Initiat- ing Event	Transient Initiating Failure I1	Transient Initiating Failure I2	No.	Frequency	Conseq.
EW_1	l1	12			
		[1	f(EW_1)	S
	ſ				
f(EW_1)			2	f(EW_1)*P(I2)	12
	•		3	f(EW_1)*P(I1)	11
			4	f(EW_1)*P(I1*I2)	11 and 12

Figure 7 Example of Modelling Multiple Transient Initiating Failures

If there is a single transient initiating failure, then the functional response of the plant to that event is described in the same way as in the PSA for internal events: once an accident is initiated, the consequences of the transient initiating failure are supposed to be mitigated by ensuring the same functions by appropriate means (response by plant systems and/or personnel) regardless of whether the transient initiating failure is induced by a random failure or by an extreme weather event (see sequences No. 2 and 3 in Figure 7). Thus, one would expect that the





functional event trees developed for single transient initiating failures in an extreme weather PSA are similar, if not identical, to those used in the internal events PSA. This is true, unless there are specific emergency operating procedures, or plant systems and equipment designed to respond differently to an extreme weather event as compared to the response to a random, non-extreme weather related initiator. Therefore, transient identification and event tree development are performed in the following steps:

- review of the initiating event list used in the PSA for internal events, selection of initiating events (transient initiating failures) that can be induced by the extreme weather event in question
- examination of the selected transient initiating failures to determine whether plant responses are designed to be the same for random and for the extreme weather event or not
- identification of transient initiating failures that can be induced by the extreme weather event, but are not included in the PSA for internal events due to their low frequency
- development of functional event trees for single transient initiating failures
- development of a generic event tree for modelling plant responses to the extreme weather event in question with combinations of single and multiple transient initiating failures.

Some transient initiating failures may not be included in the initiating event list of the internal events PSA because of their low frequency of occurrence from random failure causes. Such events become important due to an extreme weather event, if their conditional probability is sufficiently high to yield, in combination with the frequency of the extreme weather event, a transient initiating failure frequency that is comparable to that of other, screened-in transient initiating failures. These transient initiating failures are also considered in the PSA model for extreme weather events. It is important to ensure a comprehensive coverage of these and other kinds of extreme weather specific transient initiating failures. The results of the fragility analysis are used to finalize the list of transient initiating failures in the extreme weather PSA. In addition, the importance of utilizing findings from a plant walkdown is emphasised for operating plants.

The next step of the analysis process is concerned with the identification of additional systems necessary for ensuring stable core cooling conditions following the occurrence of the extreme weather event in question and with the definition of success criteria for these systems. Also included in this analysis step is the identification of systems that are not safety related but their extreme weather induced failures might impact on the operation of essential plant systems and equipment through spatial interactions. The system interactions that need to be included in the PSA model are best identified during plant walkdown. If a walkdown is not yet feasible, then design data need to be used. It is also important to identify possible new operator actions that may be required to mitigate the consequences of the extreme weather event. Typically, these are actions not modelled in the PSA for internal events but may be needed to ensure stable core cooling conditions because of the potential adverse effects of the extreme weather event. In addition, failures induced by extreme weather (e.g. blockage of access paths, extremely harsh conditions for performing local interactions, etc.) may prohibit or inhibit some operator actions credited in the internal events PSA. These actions are identified in this analysis step too.

A generic event tree is built up for a range of plant transients (with combinations of multiple transient initiating failures) in the last step of event tree modelling. The approach to developing the generic event tree takes into account the fact that the information about plant responses to multiple transient initiating failures is limited. The scope of safety functions that should be fulfilled following the occurrence of multiple transient initiating failures is assumed to be a union of the safety functions modelled for single transient initiating failures. Consequently, no additional safety functions need to be introduced to delineate the structure of the generic event tree. The generic event tree is then built up in accordance with the illustrative example given in Figure 8 (as an extension to the




previous example shown in Figure 7). This figure includes two safety functions, SF1 and SF2 that need to be ensured following the occurrence of (single) transient initiating failures I1 and I2, respectively.

High Wind Initiating Event	Transient Initi- ating Failure I1	Transient Initi- ating Failure 12	Safety Function SF1	Safety Function SF2	No.	Sequence
EW_1	11	12	SF1	SF2		
					1	EW_1
					2	EW_1-I2
					3	EW_1-I2-SF2
			[4	EW_1-I1
					5	EW_1-I1-SF1
					6	EW_1-I1-I2
					7	EW_1-I1-I2-SF2
					8	EW_1-I1-I2-SF1

Figure 8 Example of a Generic Event Tree Structure

In practice the approach taken to developing the generic event tree in its principle corresponds to the theoretical one described above. For practical reasons, a possible representation of the model is the use of a single generic event tree header as the last header after the headers for the transient initiating failures, as opposed to listing the safety function failures as event tree headers one by one. This last header combines all the core damage event sequences from all the single transient initiating failures. This way the number of sequences in the generic event tree can be reduced significantly, and the logic of the model can be kept unchanged (as compared to the theoretical approach described above) at the same time. Hence, a simple reading of such a generic event tree structure is that the upper branch represents (as usual) the success of an event tree header (the given transient initiating failure). The last header combines failures of all the mitigation functions and the associated SSCs as mentioned above.

The development of the generic event tree should not be a mechanistic application of the modelling approach. If the generic event tree is built up mechanistically, then the number of the event sequences would be '2K+1', where 'K' is the number of potential transient initiating failures, and there is one additional (last) header of mitigating systems mentioned above. This may result in a large number of event sequences that are difficult to manage. However, in actual applications there are usually some possibilities to reduce the number of event sequences. One example is as follows: the transient initiating failure inadvertent opening of pressurizer safety valve is not getting any worse if a small LOCA occurs simultaneously. Successful mitigation of the first is equivalent to the successful mitigation of the second. Consequently, the event of inadvertent opening of pressurizer safety valve



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comes first in the event tree, and the tree does not branches off for a small LOCA in those sequences where the occurrence of inadvertent opening of pressurizer safety valve is assumed (lower sequence by inadvertent opening of pressurizer safety valve).

3.6.3 FAULT TREE DEVELOPMENT

Fault trees are constructed to adequately describe the logical combinations of equipment failures and human errors leading to the failure of safety systems to fulfil their intended functions as well as the occurrence of explicitly defined transient initiating failures. Similarly, to the internal events PSA, this is one of the largest efforts in the extreme weather PSA too. On one hand, logical OR gates combine, in an appropriate logic, those failures induced by the investigated extreme weather event that result in a transient initiating point for developing fault trees for the extreme weather PSA with respect to availability of the safety functions. The existing system fault trees are extended and modified for the purposes of the extreme weather analysis. Most importantly, the following tasks are performed to develop system fault trees so that they can be appropriate for use in the extreme weather PSA:

- inclusion of extreme weather induced causes of component failure modes modelled in the PSA for internal events,
- addition of new, extreme weather induced component failure modes that are not included in the PSA models for internal events due to their low probability,
- modelling of dependent failures,
- modelling of extreme weather induced failures of structures (relevant to high winds and snowpack), and failures from spatial system interactions.

The first two steps above are concerned with supplementing the PSA model with "new" failure events, while the last two ones with modelling of different types of dependencies between equipment failures.

A lot of the failure modes considered in the PSA for internal events can be induced by an extreme weather event, too. As a first modelling step, the failure modes that are susceptible to failures induced by the extreme weather event in question are listed. Thus a failure mode included in this list can occur as a consequence of the extreme weather event or due to random effects independent of the extreme weather event. For these failure modes the basic events in the internal events PSA model are transferred into an OR gate that defines the logical connection between both failures causes (i.e. random or extreme weather related) for the same failure mode as illustrated in Figure 9. This type of modification can, in principle, greatly increase the size of the fault trees through multiplying the number of basic events (i.e. separate basic events stand for the same failure modes induced by the different extreme weather events). Fortunately, not all of the basic events of the internal events PSA have to be multiplied. For example, some basic events describe maintenance errors that are not affected by any extreme weather event, and thus these entities should not be modelled repeatedly within the list of extreme weather induced failures. The assumptions made on the dependencies among extreme weather induced failures and the results of fragility analysis can be used to significantly reduce the number of basic events that need to be added to the existing fault tree models - see also a discussion on this issue later in this section. Further, it is often possible to add extreme weather induced failures at a higher level in the fault trees than the component level basic events. Overall, appropriate considerations to all these factors can substantially reduce the number of new basic events that need to be added to model extreme weather induced failures.





Figure 9 Transfer of Failure Modes to Include Extreme Weather Induced Component Failures

In addition to supplementing the existing failure modes in the fault trees of the internal events PSA with similar but extreme weather induced failure modes, it is also necessary to incorporate some failure modes that are not at all included in the PSA for internal events. These are failure modes screened out from the internal events PSA because of their negligible probability as random failure events. However, they may become an important contributor to extreme weather related risk if caused by an extreme weather event with a sufficiently high probability. Representative examples are:

- spurious opening of valves that constitute the pressure boundary of a mitigating system (e.g. due to extremely high or low air temperature),
- spurious closure of a valve on a pipeline that is necessary for the delivery of coolant (e.g. due to extremely high or low air temperature),
- and failures of system piping (e.g. due to structural failure induced by snowpack).

The identification of these failure modes requires a complete review of the existing fault tree models. This should be done by considering all basic events representing safety related SSCs and by determining if they may have any additional failure modes due to the extreme weather event in question. Moreover, the results of plant response and fragility analysis as well as the observations of plant walkdown should be taken into consideration in this analysis step. Newly defined basic events should be incorporated into the model based on these information sources to all necessary places. The identified new failure modes are subsequently incorporated into the fault trees in an appropriate failure logic in accordance with the standard approaches to fault tree development.

Dependent failures are those multiple failure events, whose simultaneous occurrence probability cannot be calculated by simply multiplying the individual event probabilities as in the case of independent events. Several categories of dependent failures are taken into account in the internal events PSA, e.g.:

• functional dependencies:





- o time dependent events,
- o structural dependent events,
- physical dependencies,
- human interaction dependencies,
- residual dependencies.

Modelling and quantification of dependencies vary for the different categories of dependent events. Some of them are modelled explicitly, others implicitly. In both cases, commonly used methods and internationally acknowledged guidelines are taken into account. In addition to the dependencies considered in the internal events PSA, two specific types of physical dependence are also taken into account in the extreme weather PSA: dependence due to correlated extreme weather induced failures, and dependence due to failures of structures or spatial system interactions. These dependencies should be identified by taking into account the results of plant response and fragility analysis as well as the observations of plant walkdown.

The calculation of cut set probabilities/frequencies presents one of the most fundamental differences between an extreme weather PSA and an internal event PSA. In an internal events PSA component failures within a minimal cut set are usually treated as independent events. The dependencies among internal component failures are modelled by an appropriate parametric common cause failure model. Consequently, the probability/frequency of a cut set is evaluated by simply multiplying the random or common cause failure probabilities of each element of that cut set. In an extreme weather PSA the component failures involved in a cut set may be correlated through their respective responses and fragilities. The calculation of the probabilities (frequencies) of cut sets containing correlated events involves multivariate integration of the joint probability distribution function of the cut set elements. This integration tends to increase the complexity of the calculation without sufficient justification of the numerical values of correlation coefficients between the different random variables for extreme weather induced failures. In order to avoid such an unnecessarily complex quantification a two phase screening process is usually followed with regards to the treatment of correlated events. Two types of correlation are considered in the first phase: no correlation or complete correlation. Separate basic events are used in the PSA model if no correlation is assumed due to markedly different characteristics of component response and fragility. If some events are modelled as fully correlated due to similarity in extreme weather related response and fragility, then the correlated events are replaced with a single basic event. This approach leads to a reduction in the number of basic events that are multiplied for the different extreme weather events. After finishing the first phase of the analysis correlated extreme weather induced failures that appear to be significant are re-examined, and refined correlation coefficients are assigned to them (if necessary and justifiable) based on the results of fragility analysis. The quantification of multivariate distributions with correlated random variables is performed for these refined correlated events.

Dependence is introduced by the failures of structures and by the effects of spatial system interactions. Such failures are not included in the PSA model for internal events but they may be very important in the extreme weather PSA. In addition to design data, use is made of plant walkdowns in operating plants to identify such structural failures and spatial interactions, whereas the probabilities of these effects are determined by fragility analysis. Since these failures usually cause damage to several essential plant components, they represent a very important, often dominant type of dependence. This dependence is very similar to functional dependence (in terms of its consequences). It is often modelled explicitly by assigning a single basic event to all those components in an OR gate that are affected by the dependence, see Figure 10. That single basic event represents the failure of a structure or the failure due to a specific spatial interaction. It is noted that Figure 10 is an extension of Figure 9, and it shows that the same failure mode can be induced by a number of different causes. In order to model the given dependence correctly the same basic event is assigned to all the basic events affected. It also implies that it is not



necessary to actually include the new basic event at the level of each affected component because a logic gate can typically be found at a higher level of the fault tree hierarchy where the required basic event can be placed.



Figure 10

Scheme for Modelling Specific Extreme Weather Related Dependencies

3.6.4 ANALYSIS OF HUMAN ERRORS

Human reliability analysis (HRA) is aimed at identification and quantification of human failure events that may occur either prior to a plant disturbance or during evolution of an incident/accident. These are failure events that represent human actions or failures to take human actions which can be considered inappropriate in the given context so that they can substantially contribute to the development of a severe accident. The potential human failure events are identified in the course of event tree and fault tree development. The methods used to quantify the probability of human errors typically vary depending on (1) the type of the action (e.g. maintenance operation or emergency response), (2) the anticipated error modes, the main influences on performance, and (3) the availability of data and other information sources for the estimation.

Based on their direct consequences the inappropriate actions (referred to as human "errors" in the following) are taken into account in one of the following ways in the PSA model for internal initiating events:

- a contributor to an initiating event
- a basic event at fault tree level
- a basic event at event tree level.

The specificities of incorporating human actions and the associated failure events into the extreme weather PSA model can be summarised as follows for the different categories of human actions generally considered in PSA:

Pre-initiator (type A) actions that can result in unavailability of safety related systems or equipment so
that the unavailability is not revealed until a plant transient requires operation of the system/equipment.
Errors in such actions can occur in various tasks, especially maintenance, system alignment and realignment, as well as periodic testing. Type A actions considered in the PSA for internal events are included in the extreme weather PSA model without any modification because these actions are independ-





ent of the accident initiator. However, additional type A errors may need to be taken into account in the fault trees of those systems that are modelled for the purposes of the extreme weather PSA over and above those systems included in the internal events PSA.

- Initiator (type B) actions that contribute to the development of a plant transient. These actions are generally not considered in the extreme weather PSA where the extreme weather hazard is the only (common cause) initiator, although the occurrence of plant transients initiated by snow load can be prevented if snow is removed from some designated areas in a timely manner. To model this effect failure to remove snow from the roofs of some technological buildings and other facilities in time can be taken into account as a contributor to the development of snow related transients. Similarly, due to the fact that the extreme air temperature event is slow in developing and can be predicted well in advance, there is sufficient time to take preventive actions to mitigate the occurrence of some foreseeable transients that may be induced by extreme air temperature. The failure of these preventive actions can also be considered as a contributor to the development of extreme temperature related transients (type B human errors).
- Post-initiator (type C) actions that are taken as response to a plant transient. Type C human failure events (including errors of omission as well as errors of commission) increase the likelihood of undesired consequences (core damage) of an initiating event and the additional system failures, if any. A further sub-group within this category is composed of those actions that are aimed at recovering failed systems or equipment, as well as other, usually non-proceduralized, long term actions to find and use additional means of accident mitigation (recovery or type C actions). Most of the type C errors considered in the internal events PSA are also modelled in the extreme weather PSA due to the similarity of (1) accident mitigation and (2) requirements for operator responses once a transient has been initiated. Additional type C errors may need to be included in the extreme weather PSA model due to
 - accident sequences (transient initiating failures and other SSC failures and damage forms) that are specific to the impact on an extreme weather event and thus require human interventions not included in the internal events PSA
 - specific emergency operating procedures, or plant systems and equipment designed to respond differently to an extreme weather event as compared to the response to a random, non-extreme weather related initiator.

3.6.5 ANALYSIS OF RELIABILITY DATA

The numerical input necessary for quantifying accident sequences consist basically of reliability data needed to calculate the frequencies/probabilities of basic events included in the PSA model. This information need is dependent on the underlying component (basic event) reliability models applied generally as follows for analysis of:

- Initiating events
 Frequency f (1/y).
- Independent Component (Hardware) Failures
 - a) time related failure rate λ (1/h) or
 - b) demand related failure rate/probability λ_{d} (1/demand),
 - c) time data on operational exposure, test and repair, as appropriate (mission time: $T_{mi}s$ (h), repair time: T_{rep} (h), test interval (time between tests): T_{per} (h), test time: T_{test} (h)),
 - d) extreme weather induced failures, fragilities P (failure probability).
- Dependent (Common Cause and Correlated) Component Failures





- a) data on independent failures for each component involved in a common cause failure (CCF) group,
- b) parameter values for the fraction of common cause failures in a CCF group in accordance with the underlying parametric CCF model applied (e.g. *B* factors, *a* factors, *MG*L factors),
- c) correlation coefficients for multiple, correlated failures of SSCs: $\rho_{\textit{ij}}.$
- Human Errors

Probability of an error: HEP.

The frequency of extreme weather initiating events as the only initiators in the extreme weather PSA are characterized by a family of continuous hazard curves. The hazard characteristics are obtained from the extreme weather hazard assessment as input information for the extreme weather PSA (see also Section 2 of this report).

The reliability data for random equipment failures are taken from the PSA for internal events. Additional reliability parameters also need to be estimated for quantifying random failures included in the system fault trees developed newly for the purposes of the extreme weather PSA. The method of parameter estimation follows the practice commonly applied in the internal events PSA.

Extreme weather induced failures of equipment and structures, including transient initiating failures and mitigating system failures, are modelled by different basic events in the logic model for the different extreme weather events. The probabilities of these failures are determined by fragility analysis (see Section 3.2 of this report). The fragility analysis quantifies the likelihood that a component or structure fails, as a function of the parameter which represents best the load induced by the extreme weather event in question. As the extreme weather induced failures are characterized by a family of continuous fragility curves, the fragility analysis explicitly accounts for the effects of randomness in extreme weather characteristics and uncertainty in the component response to a particular extreme weather event.

With regards to common cause failures of plant equipment, the data available in the internal events PSA is used without modification for the purpose of the extreme weather PSA. It is important to note that these are common cause failures of random failure events as opposed to dependent failures due to the effects of a certain extreme weather event. The approach applied in the internal events PSA is followed to estimate the common cause failure parameters of the random equipment failures modelled newly for the purposes of the extreme weather PSA.

3.7 RISK QUANTIFICATION AND REPORTING

The aim of this step is to quantify risk (CDF/FDF damage and LERF/LRF) by appropriate integrating of the extreme weather hazards, fragility and the systems-analyses.

Based on the work in accordance with Sections 2.1 to 2.6 and the flow chart (see Figure 1) quantification of extreme weather PSA is standard (mainly software based) activity like in PSA for internal events, see [2] for further details.

Integral part of quantification process is sensitivity (and importance) analysis. Except of obvious evaluation of importance of basic events (components, systems etc.), which is based on Fussel-Vessely and risk achievement worth factors and sensitivity of used parameters, care should be taken reviewing of used simplification assumptions that have a significant level of uncertainty and which are likely to have a significant impact on the results of the extreme weather PSA. The sensitivity studies should be carried out by re-quantifying the analysis using alternative assumptions or by using a range of numerical values for the data that reflect the level of uncertainty. An uncertainty analysis should be carried out to determine the uncertainty in the results of the extreme weather PSA





that arises from the data and significant assumptions. Importance analysis (even if does not evaluate interaction of factors) forms handy tool to estimate contribution of induced events to the overall results.

Another controversial situation can be caused by double counted basic events. Such potential over counting should be checked by detailed analysis of minimal cut sets.

Results of sensitivity studies, importance and uncertainty analysis should be used to interpret the results of the PSA, to assure the robustness of further decision making based on PSA and identification of further fields of PSA model improvement (if applicable).

The corresponding documentation should provide within the report (or by reference to available material) all necessary information to reconstruct the results of the study. All intermediate sub-analyses, calculations, assumptions, simplifications etc., that will not be published in any reports should be retained as notes, working papers or computer outputs.

4 OVERVIEW OF OPEN ISSUES

Having various open issues in current practices to model extreme weather hazards and implement them in extended L1 PSA, in future, the specific focus could be devoted on the state of the art for hazard modeling/assessment and extended PSA development. These issues are discussed in the guidance and overview in this section below. In short, these issues are named in the list of open issues before the list of references.

4.1 ISSUES OF EXTREME WEATHER ASSESSMENT

Extreme weather conditions are associated with a number of complex meteorological phenomena, which can vary relatively fast, and therefore difficult to model. Additionally, various conditions leading to extreme weather are often not recorded along with the extremes. This, among other things, causes that there is a need for further research in this field. The following open problems can be mentioned:

- 1. It would be desirable to analyse the time of the occurrence of each extreme hazard and simultaneously to evaluate the synoptic situation at that time (synoptic situations the general state of the atmosphere as described by the major features of synoptic charts, in meteorology, any chart or map on which data and analyses are presented that describe the state of the atmosphere over a large area at a given moment in time). Despite of the fact that a lot of work has been already devoted for better understanding of the conditions leading to extreme meteorological situation, there is still a need for the improvement of the models.
- 2. There is a need for the more accurate estimation of the impact of climate change on extreme meteorological events. Nowadays, practically this is not robustly assessed for all the extremes: temperatures, floods, high precipitation, high winds, tornadoes, etc.
- Since many quantities such as rainfall or wind speed are measured at specifically-located monitoring devices, spatial modelling for site-specific assessment is necessary. Development and validation of downscaling methods and tools for analysing and characterizing spatially distributed extreme data can be very useful.
- 4. Currently a single probabilistic distribution model is often proposed for estimating extremes (like high winds or floods). In principle the mixed distribution model could also be used, however it is difficult to





apply. Hence, one of the open issues is to develop practical methodology allowing for applying more complex mixed distribution model.

- 5. There is a need for better uncertainty quantification and developing risk assessment methods for natural hazards triggering simultaneous or common-cause failures. For events that are frequent with respect to available data the aleatory uncertainty limits the ability to predict future events. For rare events, epistemic uncertainty begins to be important, then one needs to consider both aleatory and epistemic uncertainties.
- 6. In case of tornadoes usually observed winds are not likely to adequately describe the extremes, as the areas affected by tornadoes are small and additionally destruction of wind instruments is very probable. Consequently, rather indirect methods are applied to estimate frequencies of extreme high winds associated with tornadoes. This leads usually to higher uncertainties. Development of the methodology (which should be relevant to European context, e.g. considering the phenomena/probability of occurrence of Tornado maight be different in specific region) allowing for minimizing these uncertainties would have practical meaning.
- 7. Improvement of the models for rotating winds, pressure difference and their impact on the structures is very desirable. One of the difficulties comes from the fact that rotating winds of hurricanes and tornadoes can be hardly generated in wind tunnels and model validation is very limited.
- 8. Development of the integrated model for assessing impact of both internal and external effect, e.g. pressures on the building and structures taking into account geometry (possibly complex) and porosity could be useful. Various situations can happen depending on the pressure gradient but, in majority of the times interior elements are always affected such situations, in particular, arise in case of high winds and tornadoes.
- 9. Wind tunnel (or full scope) experiments could be useful for the examination of net forces acting at cooling towers, supported bridges, tanks or chimneys. There is a need of experiments for the improvement of the extreme wind consequence models for these types of structures.

4.2 ISSUES OF EXISTING METHODS FOR PSA DEVELOPMENT

The general procedure, modelling principles and major analysis steps in the development of a L1 PSA model for extreme weather hazards are in good agreement with that of L1 PSA in general. However, some specific analysis tasks need particular considerations or even further efforts, including especially the following:

- 1. In the practice climatological applications is typically using extreme value theory to characterize and quantify each extreme weather hazards. Consequently, this approach is adopted for the PSA model development too. The main difficulty and limitation in determining the occurrence frequency of extreme weather conditions is the lack of observations for those events whose probability should be estimated, since data samples from experience are available for short durations only. The results include significant uncertainties irrespectively of the computational method applied. This is an analysis area in need of further advancement.
- 2. The definition and quantification of extreme weather induced failure modes should be based on an appropriate plant response and fragility analysis. In current assessment methodologies the development of extreme weather fragility curves is not mature enough to take into consideration all the relevant factors that have an influence on the fragility of the SSCs. Consequently, the scope of the fragility curves is limited. Also, continuous fragility curves are not or rarely available for the impact of some extreme events, e.g. for extreme air temperatures.

- 3. With respect to data assessment for extreme air temperature hazards, the temperature in safety related rooms has to be determined taking into account the ambient air temperature outside the building as well as the operability and effectiveness of the HVAC system to enable the quantification of cut sets that incorporate hazard induced failures of indoor components. The maximum capacity of the HVAC system has to be taken into consideration. There is a need to develop an adequate and practically applicable methodology for assessing the failure probability of indoor SSCs.
- 4. There is a lack of well-established methodology on the definition of correlation among an extreme weather event induced failure modes and on the quantification of correlation coefficients. This analysis area also needs further development.
- 5. There are limitations with respect to human reliability analysis applicable to an extreme weather PSA, especially due to the uncertainties in operational strategy under harsh weather conditions (e.g. extremely high/low temperature).
- 6. Full and practically applied methodology for wind and tornado induced missiles modelling needs to be developed.

Regarding the multi-unit PSA presented in Section 3.5 and proposed in Ref. [42], there is a need to make feasibility studies to combine existing single-unit PSAs using the current state-of-practice methods. Before such studies could be done, the dependencies of each component of the plant would need to be identified in some sort of dependency matrix. This is already typically done for single-unit PSAs (e.g. only hard physical connections included, such as a motor-operated valve needing to have power from a predefined source). These matrices allow the PSA model developer to know what to consider when creating the PSA. This same thing would need to be done for proximity, human, and organizational dependencies.

5 CONCLUSIONS

At all stages of this guidance and especially from an industrial end-user perspective, one must keep in mind that the development of Extreme Weather Hazards probabilistic analysis must be conditioned to the ability to ultimately obtain a representative risk analysis.

The existing and state of the art practices can be useful for the modelling and assessment of frequencies for extreme wind, extreme temperature and extreme snow pack. However, relevance of those assessments must be analysed. Besides, dealing with combination of hazards (including correlated hazards) much more open issues appeared. The list of open issues described before the conclusions present few limitations, but there is no evidence that it is a complete list.

On another hand, in this guidance the sources of hazard data and quality of hazard data as well as elements of hazard assessment methodologies and relevant examples are discussed pointing out how these could be used for hazards assessment and for extended PSA. These discussions, at least partly, provide explanations and solutions how to avoid different issues, which appears in the modelling and assessment.

Taking into account various issues of hazard data still there are suitable methodologies for separate hazard assessment. Of course, the uncertainty analysis (possibly including sensitivity analysis) should be part of the assessment and this, at least, will help to cope with issues of data and results uncertainty.

Examples of hazard assessment methodologies just demonstrate availability of some practical methods and tools, which are practically used for calculations estimating frequencies of external events and which provide means for





analysis of different data and its impact on the uncertain result. In all cases, for extreme weather assessment the extreme value theory is used in one or another way. The practical application of it may differ depending on available data and parameters which are considered for the specific hazard.

The issue of hazards combinations is solved by initial classification of dependencies between hazards and criteria, which allows avoiding irrelevant combinations of external events. It is important to note that some individual hazards (phenomena) already are combinations of hazards, so that analysis of such compound already covers analysis of individual hazards. Such analysis may depend on site and NPP design limits and is performed at the stage, when information necessary to assess the frequency and effect of combination is known. In the guidance, as examples, the specific combinations were discussed and then methodologies suitable for the assessment of these hazard combinations were identified.

In addition, the first appendix overviews the best practices of extreme wind and quite complicated tornado assessment. Then, few specific cases and features of national experiences on extreme weather assessment are demonstrated confirming that practice to model extreme weather hazards and their combinations in principle are ready for implementation in extended PSA. Of course, there are still open issues, as mentioned above, but they are mostly related to the uncertain parameters and modelling, thus using probabilistic methods and recommended uncertainty analysis, they do not block the hazards assessment application in extended PSA.

Given the difficulties and considerable uncertainties, the PSA results must be considered with great pragmatism in view of the complexity of the methods and tools needed. The adoption of a graded approach for External Hazards PRA would better focus resources and direct them to identify and address issues that present the highest significance to NPP Risk and Safety. Therefore, there is no necessity to use complex methodologies if a simplified analysis gives sufficient and representative insights.

The start point of extreme weather PSA is to identify amount of collected data related to extreme weather characterization and SSCs resistance for the extreme weather conditions. The type of input data is defined mainly by results of hazards and its combinations screening, and by parameters that correlate with fragilities of SSCs. Preparation of input data for the PSA model includes construction of hazard curves for external extreme hazards and SSC fragility curves. An alternative method is to compare parameters of external extreme hazards with design data for SSCs - boundary evaluation. Such a method is simplified and can be used only in case of unavailability of any statistics for hazard occurrence. In this way, application of hazards and fragility curves is recommended for extreme weather PSA (if applicable) and the main attention of this guideline is emphasized on this approach.

The main threats have to be analysed during site response studies and ways for analysis of appropriate emergency sequences for each hazard (extreme winds, extreme temperatures and extreme snow pack) are also covered by this guidance. The main idea for modelling these sequences is to make an interface with L1 PSA for internal initiating events. As result of the interface development connection with emergency sequences of internal initiators or with more severe initiating events have to be built. Recommended approach for these purposes can be also different and has an influence on reliability parameters and frequencies implementation into the further PSA model. In light of the above this guidance covers two possible ways, which depends on data availability and software capabilities:

- discretization of the hazard and the fragility curves using a limited number of hazard intensities;
- usage of continuous hazard and fragility curves for the whole range of hazard intensity of interest.

Both of these variants are described in the guidance. There is proposed a way for modelling of possible additional secondary effects and aggravating/mitigating factors in the corresponding part of guidance. The main idea of this





approach is to model the additional factors as top events (headers) in the initial event tree and/or interface event trees. Of course, other model solution can be chosen depending on goals and means of the PSA (e.g. Risk-Informed needs).

Guidance contains a specific and detailed description of the state-of-the-art methodology for extreme weather PSA. The description of it covers all main steps for developing of extreme weather probabilistic model.

It can be concluded that there are no difficulties in PSA model's logic and structure building for external hazards. A major limitations and gaps of extreme weather PSA are related to the data preparation and its implementation. Main uncertainties appear from the hazard evaluation and NPP response analysis issues (buildings resistance, missile impact, long-term effects, mitigation of human errors, etc.).





LIST OF OPEN ISSUES

- 1. Limitations in modelling and forecasting the physical phenomena and conditions leading to extreme hazard;
- 2. Uncertainties in estimation of the impact of climate change on extreme meteorological events;
- 3. Lack of site-specific data and limitations of spatial modelling and downscaling methods;
- 4. Unclear application of complex probabilistic models, like mixed distributions;
- 5. Difficulties in quantification of uncertainties for common-cause failures;
- 6. High uncertainties in tornado data and tornado frequencies estimation;
- 7. Validation limitations for tornado physical phenomena and its impact models;
- 8. Difficulties in integrated modelling of hazard internal and external impact assessment;
- 9. Lack of applicable experiments for the improvement of the extreme wind consequence models;
- 10. Limitation in determining the occurrence frequency of extreme weather conditions;
- 11. Scope of the fragility curves is limited (especially for extreme temperatures influence);
- 12. Adequate and practically applicable methodology for assessing the failure probability of indoor SSC's (taking into account outside temperature and HVAC capacity);
- 13. Correlation among an extreme weather event induced failure modes and on the quantification of correlation coefficients;
- 14. Uncertainties in operational strategy under harsh weather conditions;
- 15. Winds and tornadoes induced missiles estimation and modelling;
- 16. Further research needed to predict extreme weather conditions and its phenomena during combined extreme weather events.





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EURATOM

APPENDIX 1. OVERVIEW OF METHODOLOGIES FOR EXTREME WIND AND TORNADO HAZARD ASSESSMENT

General characteristics

In this appendix general characteristic of the related phenomena is discussed. There is a vast literature on the subject, included bibliography contains the positions which were the basis for this appendix. In principle three types of high winds: extreme-straight, hurricane and tornadoes should be considered. The difference between them, first of all, is related to non-rotating gust fronts (like in thunderstorms or frontal passages) or circulating winds in global sense (i.e. around low or high pressure systems), and the rotating winds. The latter ones can be either hurricanes or tornadoes, however the rotation diameter even for small hurricanes is essentially larger than for tornadoes. On the other hand, in most cases the diameter of tornadoes is relatively bigger than the dimensions of typical buildings (it is estimated that about 80% of tornadoes have diameter greater than 100 m).

One of the possible ways to study extreme winds are experiments in wind tunnels and field measurements. Despite the fact that it is extremely difficult to reproduce rotating winds of hurricanes and tornadoes in wind tunnels, still it seems that the effects of pressure produced on the buildings and structures are similar to the consequences of extreme winds if the relative direction of rotating wind is also taken into consideration. Therefore, it is reasonable to consider all types of windstorms equally.

The consequences of high wind on the buildings and structures, dependently on the pressure can be due to external or internal forces. Air flows around or over enclosed building are generated by external pressure. Typically, there is a variation of pressure (caused by the change of wind speed and direction) which have impact on the building surface, in particular for protruding elements - in such a case the energy is lost and therefore large outward pressure arises near their location and has essential impact on the surface behaviour (maybe except of windward and steep roof). In general, the external forces can act on windward, leeward and side walls, as well as the roof. The porosity of the buildings has also some impact on the air flow.

The internal pressure is developed in case of some openings, like broken window, open door, or something similar. Depending on the location of the opening (and generally wind direction) the pressure in the building can be inward or outward. Different situation can happen - the so called "ballooning" takes place in case of the opening in windward wall, then the pressure inside the building increases relative to the outside pressure. As a consequence, additional outward pressure acts on all interior elements. The opposite effect arises in case of the opening in leeward roof surface. Again additional but inward pressure act in the interior. Both internal and external pressures combined can have strong impact on the behaviour on the surface of the building.

On the other hand, the size of opening plays also an important role - if it is sufficiently large then the internal and external pressure can be equalized, for example when tornado passes through the building. In case of the sealed buildings or other enclosures specifically sealed, the effects of the change of atmospheric pressure can be observable. Its scale depends on the tangential wind speed of the tornado. It should be stressed, however that the maxima of the pressure and wind speed cannot occur at the same place. The lowest pressure is in the centre of tornado while the highest one about 500-1500 m from the centre. It is estimated that at the radius of maximum speed the pressure is about 50% of its highest value. The rate of the change in atmospheric pressure is a function of transitional speed and a very rapid rate can have negative impact on heating, ventilation and air condition system.

For structures like cooling towers, stacks, supported bridges, tanks or chimneys, rather than the distribution of wind pressure, mostly net force has to be examined. The consequences of high wind in these cases can be, for





example, overturning or sliding the structure. The scale and magnitude of the force can be estimated in wind tunnels or full scale experiments.

The gust of the wind can produce dynamic pressure on the structures, and their effects, in principle it depends on two relations: gust size vs building size, and gust frequency vs. natural structure frequency. In general, these frequencies are enough different, so the effects are small (but not negligible), except of the tall structures when the effects can be more severe. The magnitude of the dynamic pressure is a derivative of relation between the sizes of the gust and the structure (or the considered element of the structure).

It should be also added that the roughness of the terrain is the parameter that also affects the wind speed. In the simplest form it is defined for urban, suburban, open and smooth areas, and by wind vertical profiles represented by law relationship (with zero at the ground level increasing to the top of boundary layer). More accurate estimation can be based either on dedicated meteorological measurement or on combination with numerical weather forecast models.

In case of violent tornado additional effects should be considered as various pieces of debris (like elements of roof, pieces of sheet metal, timber, pipes, and other objects with high surface area to weight ratios) can be picked up and transported. Tornado can tumble automobiles, storage tanks, and railroad cars. In extreme cases (but rare) large diameter pipes and beams might be also transported. These type of elements behaving like missiles have to be taken into consideration.

Data Collection

In general, the procedure for performing estimation of extreme wind consists of the following three steps:

- acquisition of all available data on extreme wind,
- preparation of data by adjustment in case of not consistent data,
- application of extreme value analysis.

According to three different types of high winds there are some differences in collecting wind data for straightline wind, hurricanes and tornadoes. Data sets of historical extreme winds shall be obtained from weather stations located near the site in order to represent properly conditions at the site. If more stations are located closely to the site, the data can be combined, taking into account the distance and conditions. Some geospatial techniques can be possibly applied in such a case.

One can also consider the usage of data produced by numerical weather forecast models, in particular by climate models for new NPPs.

US NRC recommendation says that on-site meteorological data should meet the following criteria for straight winds (DOE-STD-1020-2012):

- at least ten continuous years of annual extreme wind speed records should be available; if longer periods of record exist, the entire period shall be used,
- it is possible to use meteorological data from on-site stations for which less than ten years of records exist, if there is a sufficient number of historical records from nearby meteorological stations, within a similar topographic environment;
- recorded wind speeds should be at the elevation of 10 meters above ground; if the elevation is not 10 meters' appropriate correction using acceptable logarithmic wind height conversion methods can be applied;





- the type of wind speed parameter recorded over time is to be specified (e.g., fastest-mile, peak speed, 3-second gust speed, etc.),
- the recorded wind speeds should be obtained from anemometers located in flat open terrain, if possible.
- in the absence or lack of sufficient on-site wind record data, it is possible to utilize data collected by national and local agencies for stations close to the site (i.e., generally within 50 km) and located in a same wind environment; it should be noted that stations close to, but separated by mountainous ranges from the site, may not qualify.

In case of hurricanes it is recommended that meteorological data of past historical hurricanes within 400 km from the site shall be collected, including:

- location of hurricane tracks, including information on longitude and latitude, with landfall locations;
- life-cycle hurricane intensity history, with information on Saffir-Simpson hurricane scale;
- reported minimal central barometric pressure near the coast or at point of landfall;
- reported maximum translational and rotational wind speeds near the coast or at point of landfall.

In case of tornadoes the following data shall be collected for tornadoes within the radius of 500 km from the site:

- tornado track, including latitude and longitude;
- tornado intensity, using the Enhanced Fujita, or EF, scale;
- tornado length and width;
- data and information necessary for characterizing potential tornado wind-borne missiles (e.g., weight, size, and shape).

In order to estimate frequency of extreme high wind different data can be applied if available, like:

- fastest-mile speed, used in USA and calculated as the shortest time for passing one-mile distance during some period,
- peak gust speed, typically determined as average over very short period between anemometer response,
- fastest 5-min or 1-min speed, determined either from chart or observers (the latter tends to be underestimated).

Tornadoes occurrence

The average occurrence rate of tornadoes in the U.S. is about 10⁻⁴ per square mile per year. This value can be determined either by global regionalization schemes or by using more regional data. Concerning Europe two citations are given below from the last articles.

Pieter Groenemeijer and Thilo Kühne, 2014: A Climatology of Tornadoes in Europe: Results from the European Severe Weather Database. Mon. Wea. Rev., 142

"The highest density of tornado reports is in western and central Europe. ESWD tornado reports increased strongly from 1995 to 2006 as a result of increased data collection efforts, followed by a decrease that likely has a meteorological nature. There is strong underreporting in the Mediterranean region and Eastern Europe. The daily cycle of tornadoes over land (sea) peaks between 1500 and 1600 (0900 and 1000) local time. The Mediterranean annual maximum is in autumn and winter, while regions farther north have a maximum in summer. In total, 822 tornado fatalities have been recorded in the ESWD, which include 10 tornadoes with more than 20 fatalities. The average annual number of tornado fatalities in Europe is estimated to be between 10 and 15. The F2 and F3 tornadoes are responsible for the majority of the fatalities"





Tateusz Taszarek and Harold E. Brooks, 2015: Tornado Climatology of Poland. Mon. Wea. Rev., 143

"The results of an investigation of tornado occurrence in a 100 years historical record (1899-1998) and a more recent 15 years observational dataset (1999-2013) are presented. A total of 269 tornado cases derived from the European Severe Weather Database are used in the analysis. The cases are divided according to their strength on the F scale with weak tornadoes (unrated/F0/F1; 169 cases), significant tornadoes (F2/F3/F4; 66 cases), and waterspouts (34 cases). The tornado season extends from May to September (84% of all cases) with the seasonal peak for tornadoes occurring over land in July (23% of all land cases) and waterspouts in August (50% of all waterspouts). On average 8-14 tornadoes (including 2-3 waterspouts) with 2 strong tornadoes occur each year and 1 violent one occurs every 12-19 years. The maximum daily probability for weak and significant tornadoes occurs between 1500 and 1800 UTC while it occurs between 0900 and 1200 UTC for waterspouts. Tornadoes over land are most likely to occur in the south-central part of the country known as the "Polish Tornado Alley." Cases of strong, and even violent, tornadoes that caused deaths indicate that the possibility of a large-fatality tornado in Poland cannot be ignored".

Probabilistic Wind Hazard Assessment (PWHA)

PWHA shall be performed for all three types of wind-related hazards, if needed, taking into account the geographical location of the site. In case of tornadoes the design basis rapid atmospheric pressure change has to be determined in order to characterize potential effects of missile strike type. This means that the weight, size, shape and velocity of elements should be estimated.

Typically the results of PWHA are represented by a mean wind-related hazard curve (i.e., wind speed at the site as a function of mean return period in years). It is reasonable to combine the results of straight winds and hurricane as their simultaneous occurrence has very low probability because of essentially different meteorological conditions.

The design basis extreme straight-line wind, tornado wind, and hurricane wind can be based on a mean return period (see DOE-STD-1020-2012), wind region maps and tables.

In principle, return periods for the tornado winds could be the same as the extreme straight-line and hurricane wind speeds, however higher return periods are typically used because of:

- traditionally high return periods are specified for tornadoes basing on the criteria established for commercial nuclear power plants, which corresponds to taking into account uncertainties in the design;
- the straight-line wind speeds are larger than the tornado wind speeds at lower return periods.

Loads

During hurricanes and tornadoes missiles from objects lying within the path of the hurricane wind and from the debris of nearby damaged structures can be generated. Two basic approaches can be used to characterize hurricane-generated missiles: standard spectrum of hurricane missiles, and a site-specific probabilistic assessment of the hurricane hazard. In fact, there are no definitive guidance used for characterization of site dependent hurricane generated missiles. A sequence of random events has to be considered like hurricane occurrence, existence and availability of missiles in the area, rising from the ground, transport of missiles, their impact on safety-related structures, and resulting damage to critical equipment. A number of uncertainties in these events, practically makes it almost impossible to rely solely on probabilistic assessment, hence expert judgement or experimental data should be also utilized, if possible.

Tornado Loads





Structures for the nuclear facility should be designed to resist the maximum tornado load for a given plant site. The basis of the design should be such that the safety class equipment remains functional, also a safe shutdown.

The consequences of tornadoes represented by structural damages can come from three separate phenomena: wind, differential atmospheric pressure and missiles. These effects interact with structures and can cause damage through three principal mechanisms:

- 1. Pressure forces created by drag and lift as air flows around and over structure;
- 2. Pressure forces created by rapid changes in atmospheric pressure resulting in differential pressure between the interior and exterior of the building;
- 3. Penetration, spalling and impact forces created by missiles.

Tornado-generated missiles can carry objects which are further accelerated by the forces induced by the extreme tornado wind speed. The parameters specified in the design basis tornado are translated into pressures and forces acting on the structures and its components. The real analysis performed on the structure is the key element (known as tornado structure interaction). In general, it is assumed that 120 km/h wind velocity can induce the load to be considered.

Application of Extreme Value Theorem

The size of the data set is the first parameter to be taken into account for consideration which method should be applied for the analysis. In the time series is long enough generalized extreme value (GEV) or generalized Pareto distribution (GPD) can be used. Typically, Gumbel (Type I) distribution is applied for annual maxima series. A lot of techniques for determination parameters of distribution can be used: maximum likelihood principle, best linear estimator, probability weighted moment, etc. The advantage of Gumbel distribution is such that it overestimates the return period in case when other than Type I is more proper, which makes the estimation conservative. Applying other methods can be more difficult as, for example POT (Peak Over Threshold) method demands choice of the threshold which has essential impact on the results. On the other hand, more points can be taken into analysis, which means that some standard statistical techniques can be applied for uncertainty estimation. Taking this into account the process of using extreme value analysis should not be automatic and each step and each decision should be justified. In practice data sets are very often small and generally three strategies can be utilized: adding data from neighboring stations, applying simulation models (for example data from ensemble weather prediction systems could be of some value) and parent distribution methods. As a rule of thumb one can assume that the error is proportional to the square root of the number of data, hence it is obvious that short time series must imply higher errors.

Hurricane/ wind Loads

A hurricane is defined a cyclone storm with rotational wind velocity in excess 120 km/h. The dynamic strength of a hurricane builds up over water, but as it comes inland boundary layer drag forces cause a tremendous dissipation of the kinetic energy of the storm and the wind.

To assess hurricane loads, the maximum wind velocities are a key factor. Generally, it occurs to the right of the eye of the hurricane looking along the direction of its path, which is caused by vector addition of the translational and rotational wind components. In case of lack of site specific data, some generic ones can be adopted (see, for example ANSI/ANS 2.3-2011).





Missile Load

In nuclear facility design, safety class structures should be protected against loss of functions due to postulated plant generated and extreme environmental missiles. The effect of missile impact on a target is characterized by the impulse measured by the momentum exchange between the two bodies during the impact. There is ongoing work on the determination of these parameters. As an example we can mention the book of Bangash M. Y. H., "Structure for Nuclear Facilities. Analysis Design and Construction", 2011, were the data are given on tornado and wind-generated missiles and the list of plant-generated missiles and their characteristics.

Missiles are usually classified depending on the source of their generation: as plant generated or extreme environmental missiles. Typical plant-generated missiles include valve stems, valve bonnets, turbine discs and other rotating masses. Extreme environmental missiles which are of major concern include tornado transported objects.

According to DOE-STD-1020-2012 for designing SSCs against extreme straight-line wind, hurricane wind, and tornado wind loads, different load combinations should be used for the extreme loads (like dead, normal flood, live or tornado wind load, including atmospheric pressure change, as appropriate).

There is ongoing discussion on the definition of load factors. For example, 2010 ASCE Standard redefined the wind load from a severe to an extreme/abnormal load category with its design basis load factor changed to 1.0 from 1.6 presented in ASCE-7 2005 Standard. In the latter the return period of 50 or 100 years was used while in 2010 ASCE Standard 700 years return period (for Risk Category II) is given basing on 3 second gust wind.

Such decisions related to the acceptance criteria of risk can have essential impact on the results of PSA analysis.

The way how to combine the load depends on the structure analyzed and the method of analysis. In Bangash book, one can find a number of various formulas, based on American standards or using European codes.

Methodology of the U.S. NRC guidelines

The U.S. NRC guidelines on estimation of winds in PSA are described in NUREG/CR-4492. According to this report the hazards related to extreme winds should be analyzed through the following steps:

- Extreme wind speed distribution model the aim of this step is to estimate an extreme wind probability for each phenomenon and to assess the overall extreme wind probability at a site as a weighted average of the individual phenomenon probabilities for available sufficient extreme wind data and analysis time. This estimation is called a mixed distribution model.
- 2) Distribution of observed extreme winds Extreme winds distribution could be determined based on the frequency distribution of random variables such as wind speed if these distributions are from one of the common distribution families. However, no single theoretical distribution has been found to describe wind speeds. Therefore, it is not possible to make an a priori determination of a distribution form for extreme winds.
- Estimation of tornado intensities the intensity of tornado is related to wind speeds. The most common method of rating intensities is a scale developed by Fujita called F-scale. In F-scale tornado intensities range from F0 (40-72 mph) through F5 (>261 mph).
- 4) Estimation of return periods return periods are frequently used as alternative descriptions of the probabilities of extreme events.
- 5) Data acquisition the aim of this step is the identification of the extreme wind data that are available for the general region of interest. Identified data should be used in extreme wind analysis. All available extreme





wind data should be considered in an extreme wind analysis.

- 6) Observed extreme wind data expressed in terms of fastest-mile speeds (wind speed is the wind speed computed from the shortest interval required for passage of one mile of wind during some longer period such as a day, month, or year); peak gust speeds (determined from dials or analogue wind speed records representing wind speeds averaged over a short period); fastest 5-min speeds (determined from charts) and fastest 1-min observed speeds (typically done visually from a non-recording display).
- 7) Sources for observed extreme wind (tornado) data identification of the extreme wind data available for a region and determination of the various types of extreme wind and tornadoes data recorded for each location are necessary for further analysis.
- 8) Data base preparation observed wind data acquired for evaluation of extremes need some preprocessing before using in risk assessment. The preprocessing includes such an operation as: screening the data for problems (errors or incompleteness of data); adjustment of data into a consistent form; calculation of additional measures based on obtained data.
- 9) Data screening it consists of 1) determining exactly what type of data have been obtained, 2) identifying the location and height of measurement for each speed, and 3) examining the data for spurious values and trends that may indicate unreported changes in anemometer exposure, location, or type.
- 10) Adjustment of observed extreme winds after the initial screening has been completed, the observed wind data base should be made internally consistent. In a typical situation, the extreme wind data will have been measured by different organizations and for different periods of time. As a result, the dimensional units in which the speeds are expressed may not be the same for all data, the data may not be of a common type, and the data are likely to have been obtained at different measurement heights. When this is the case, it is necessary to standardize the data to minimize any differences that may be due to measurement techniques.
- 11) Averaging interval each wind speed observation is, at least implicitly, associated with an interval over which the speed is averaged. The averaging intervals associated with extreme winds range from about 2 s for peak gusts to 5-min. However, the most common extreme wind, the fastest mile, is not associated with a fixed averaging interval. The fastest-mile wind speed averaging interval is a function of the wind speed. Various techniques are applied to provide an accurate adjustment for all conditions and types of observation.
- 12) Measurement height. Near the earth's surface, winds increase with height above ground. Therefore, it is reasonable to make an attempt to take the height of measurement in to account in the analysis of extreme winds in order to estimate variation of extreme winds with height.

An example of the real event and the description of consequences of hurricane can be found in "Effect of Hurricane Andrew on the Turkey Point Nuclear Generating Station from August 20-30, 1992".

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APPENDIX 2. EXAMPLES OF NATIONAL EXPERIENCES ON EXTREME WEATHER ASSESSMENT

ANNEX 2.1. EXTREME WEATHER ASSESSMENT IN BULGARIA

In Bulgaria, the main regulatory requirements toward to the external hazards, as well as directions to the PSA development are specified by the "Regulation on Ensuring the Safety of Nuclear Power Plants [A]. According to the regulation, the specific requirements related to the extreme meteorological impacts are as follows:

Art.29 Engineering surveys and investigations of natural processes, phenomena and factors having potential impact on NPP safety shall be conducted for the region and the site for situating a NPP:

2. within the NPP site boundaries, the following shall be identified:

g) tornado intensity, the peak tangential values of the periphery speed and the speed of the tornado progressive motion; the pressure drop between the tornado periphery and the centre;

5. for a NPP site, the impact on safety of other processes, phenomena and factors of natural origin shall be determined (hurricane, extreme rainfalls, air and water temperatures, icings, thunderstorms, dust-storms and sand-storms, erosion of river and water basins banks).

Also, the safety guide "Probabilistic Safety Analysis of Nuclear Power Plants" [B] gives additional guidelines for enforcement of the regulation. It should be noted that this guide has a recommendatory nature. The guide contains the list of the external hazards that shall be considered in the screening analysis (Section 2.150, p.25). Furthermore, the safety guide, in the section 2.151 states that in addition, the following combinations of hazards shall be considered: harsh winter conditions including snow (e.g. snowfall, drift, blizzards, and snowstorms), low temperatures, ice cover, harsh summer conditions including high temperatures, drought, forest fire, and low river water level.

Moreover, the additional guidelines with respect to the screening of the events are provided, e.g. do not need to be modelled in the PSA events due to hazards presented in sections 2.150 to 2.151, if one of the following conditions is met (Section 2.152, p.25):

-It can be shown based on qualitative arguments that the hazard has a negligible impact on the CDF/FDF (e.g., if the consequences on the plant do not require the actuation of protective safety systems or the consequences are already covered by events having a significantly higher frequency of occurrence);

-A bounding analysis of the CDF/FDF due to the hazard yields a result less than two orders of CDF/FDF obtained from the analysis of internal initiating events.

Regarding to the extreme winds, according to the same document, the analysis shall include a probabilistic evaluation of wind hazards and of wind induced failures, and a quantification of *CDF/FDF* including uncertainties. Furthermore, the comprehensive and up to date database on wind occurrences and peak wind velocities shall be developed consisting of: a site specific historical wind velocity data (short term) and wind data from long term measurement for at least one other location (e.g., from a fixed weather station or an airport near the plant). Also, the long term site specific wind data shall be developed by considering the short term site specific and the wind data from the other locations. The guide explicitly states that if measured wind speeds have to be mapped to specific heights of interest, the Thom equation shall be used (Section 2.173, p.30):

 $v_1 = v_2 (h_1/h_2)^{1/n}$, where:

- v₁ wind velocity at height h₁;
- v_2 wind velocity at height h_2 ;
- n constant, depending on the surface roughness (unevenness).



In addition, the guide also noted that maximum wind speed exceedance frequency curve (yearly exceedance frequency versus maximum wind speed) shall be developed based on the short term site specific wind data using a Gumbel probability distribution for the data fit and extrapolation. The guide provides additional guidelines: a plant walkdown shall be conducted for the identification of vulnerable SSCs and potential sources of flying objects; realistic wind fragilities shall be estimated for the relevant SSCs. According to the same guide, the uncertainties shall be taken into account; the load case "extreme wind" shall be represented by an adequate number of initiating events; for each wind category, a loss of offsite power shall be assumed; for wind speeds greater than 180 km/h, failure of glass (windows) shall be assumed. The corresponding damage (e.g., due to water ingress, pressurization) in the affected building or room shall be considered in the PSA. A part of this, in addition, the potential and effects of indirect winds threats shall be identified and discussed.

With respect to the tornado, the analysis shall include a probabilistic evaluation of tornado hazards and of tornado induced failures, and a quantification of the risks as CDF/FDF, including uncertainties. Furthermore, the occurrence of tornadoes shall be assumed to be uniformly distributed within a rectangular area of 12 500 km² around the nuclear power plant. The mean annual frequencies of tornadoes shall be assumed as follows (Section 2.183, p.31):

- F0 and F1: 2.3.10° per year;
- F2: 2.2.10⁻¹ per year;
- F3 and higher: 6.3.10⁻² per year.

The strike areas for tornadoes with various intensities shall be assumed as follows (Section 2.184, p. 31):

- F0 and F1: length = 3.8 km, width = 70 m;
- F2: length = 5.1 km, width = 150 m;
- F3 and higher: length = 19 km, width = 320 m.

It should be noted that the directions towards to the tornado followed the same directions to the extreme wind, presented above, e.g. shall be conducted a plant walkdown; the realistic fragilities shall be estimated for the relevant SSCs; for each tornado velocity category, failure of glass (windows) shall be assumed; the corresponding damage in the affected buildings or rooms shall be considered in the PSA; the potential and effects of indirect tornado threats shall be identified and discussed.

Based on the stress tests results, the information provided below gives an overview of the issues related to the extreme weather impacts on the Kozloduy NPP site.

According to the Bulgarian National Report [3] developed within the European Union stress tests, the following climate characteristics underlay the design bases of the nuclear facilities of Kozloduy NPP site:

- Average annual temperature +11.6°C;
- T_{av} for July +24.3°C;
- T_{av} for January -1.5°C;
- T_{max} absolute +43.0°C;
- T_{min} absolute -29.0°C;
- Average annual relative air humidity 70%;
- Average annual precipitations 520 mm;
- Snow cover not durative, maximum up to 30-40 days, typically do not exceed 15-20 cm;
- Maximum recorded snow cover 80 cm with 3% recurrence;
- Dominating wind direction West and North West;
- Average annual wind speed 1-4 m/s;





- Days with wind speed over 11.0 m/s 69;
- Days with wind speed over 16.0 m/s 4-5 days;
- Extreme wind speed 45 m/s.

On the basis of the considerations provided by the Bulgarian National Report, dominating for Kozloduy NPP are the west winds, followed in frequency by east and northwest winds. At probability P=1% (once per 100 years) the maximum velocity of wind in Kozloduy NPP and Oryahovo are respectively 37-42 m/s. Dominating are west winds with wind frequency 34.9-35.5% at winds 4.2-5.6 m/s.

At probability P=0.01% (probability once per 10000 years) the calculated wind velocity is 45 m/s, which is accepted as extreme, at application of the estimated impacts on the civil structures and facilities ensuring nuclear and radiation safety.

According to the analysis of National Institute of Meteorology and Hydrology of Bulgarian Academy of Science performed in 2009, the characteristics of 16 sand spouts observed during the period from 1986 to 2009 and evaluated for the zone with the radius of 178 km around Kozloduy NPP are: maximum velocity - 332 km/h (92.2 m/s); wind speed - 263 km/h (73.1 m/s); motion speed - 69 km/h (19.2 m/s); radius corresponding to the maximum wind speed air flow 45.7 m; probability of sand spout occurrence with the above characteristics in the area of 12 500 km² around Kozloduy NPP is $6.3.10^{-7}$ for 1 year and with speed over 332 km/h - 1.26.10⁻⁸ for 1 year.

The probability of wind spout over the given section of area 100 000 km² during one year is estimated at $5.05.10^{-6}$. The maximum wind speed 92.2 m/s will lead to pressure on the structures of 5.2 kN/m^2 .

Furthermore, regarding to the humidity and freezing, according to the report, the average annual humidity is 78%. With specific combination of temperature, humidity and wind speed, the probability of icing and freezing increases. The most likely combinations temperature-wind-humidity necessary to determine the combined ice and wind loading on the facilities are: a temperature between 0 °C to -4 °C, wind speed between 0 and 3 to 5 m/s and relative humidity along Danube River between 95 and 100%.

On the basis of data from the meteorological monitoring system in the last four years (valid for 2011) a combination of such conditions was not observed in the region of Kozloduy, which is mainly due to lower levels of humidity. The risk of icing conditions on the basis of the last 11 years (valid for 2011) has averaged 2% annually. This means that freezing is relatively rare.

Regarding to the extreme snowfalls, according to the cited document [C], the snow in the region is volatile and with relatively shallow depth due to the fact that stable snow cover is typical of regions with average January temperatures below -3 °C. The average annual snow cover height does not exceed 20 cm. Of the greatest recurrence of 24-30% is the height of 11-20 cm. Considered in decades, in winter months, snow cover height for not more than 3-4 days is about 5 cm. This allows for excluding the possibility for the water reserves in the snow cover in the region of Kozloduy to be involved in possible flooding even during sudden warming. Height of snow cover of 70-80 cm has a low recurrence - only 3% (1 to 2 days, based on the past data for 1977). This value is considered extreme.

With regard to the ice phenomena, in the Bulgarian report on the stress tests states that in the case of continued detention of negative temperatures in the Bulgarian section of Danube River for several days may lead to the onset of freezing of the river. After impoundment of water supply system "Iron Gate" likelihood of ice occurrence in Oryahovo station decreased from 79% to 62%. For the period from 1963 to now there has been no complete freezing in the section of the river.



Concerning to the extreme temperatures, according to the stress tests report, the average annual temperature for the region is from 11.3 to 12.0 °C. The monthly outdoor air temperature for July is $t_{VII} = 24.5$ °C. Absolute maximum temperatures range from 38.4 to 43.3 °C. According to the Kozloduy meteorological monitoring system data for the period of 2000-2011, the absolute maximum temperature for Kozloduy NPP site is $T_{max} = 43.3$ °C, measured on July 24, 2007 at 17:00. As extreme temperature 43.3 °C is defined. Average January temperature is $t_1 = -0.9$ °C. The absolute minimum temperatures in the region range from -20.0 to -26.6 °C. According to the meteorological monitoring system data for the period of 2000-2011 absolute minimum temperature is $T_{min} = -24.4$ °C, measured on 8 February 2005 at 5:00. As extremely low temperature -26.6 °C is accepted.

With regard to the normal operation of Kozloduy NPP there are the following possible combinations of meteorological impacts [C]:

- Combination of temperature-wind-humidity within the limit of temperature between 0°C and -4°C, wind speed between 0 and 5 m/s and relative humidity between 95 and 100%, at which preconditions for freezing are established.
- Combination of high temperatures, extremely low precipitations and low standing of Danube River Potential for reaching the extremely low water level of elevation 20.50 is below 1%; this has not happened for the entire period of the plant operation.

Regarding to the extreme weather conditions, according to the Bulgarian Action Plan [D], the following additional measures are provided to increase robustness of the Kozloduy nuclear power plant:

- Analysis of the extreme weather conditions of the Kozloduy site using probabilistic methods in the IAEA methodology by exploring combinations of extreme weather conditions;
- Assessment of possible damage to the regional road infrastructure around the plant under extreme external impacts and assessment of the reliability of routes providing access to equipment, supplies and personnel access to the plant.

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ANNEX 2.2. EXTREME WEATHER ASSESSMENT IN HUNGARY

The objective of hazard assessment was to determine event frequencies for different magnitudes of the parameter which represents best the load induced by an external hazard. Hazard assessment was based on the data collected by the Hungarian Meteorological Service at station Paks during the past few decades. The following observations were taken into consideration:

- maximum gust of wind [m/s],
- instantaneous and daily average maximum and minimum air temperature [°C],
- maximum 10, 20, 60 minute and daily precipitation intensity [mm/min],
- maximum thickness of snow [cm],
- maximum load of frost and icing [g/mm].

In accordance with the international practice of climatological applications, we made use of extreme value theory to characterize and quantify each external hazard. Hazard curves were established by fitting Gumbel distribution on the annual extreme values of the most up to date site specific meteorological data. Hypothesis testing was conducted to justify that the Gumbel distribution was an appropriate approximation of the hazard curves.

Extreme weather conditions were estimated at different confidence levels (5, 15, 30, 50, 70, 85 and 95%) for 1 to 10^{-7} 1/a frequency of exceedance. The results of hazard analyses are not presented hereby for every single hazard, but Figure 1 demonstrates the hazard curves for extreme snow as an example. The results of the analysis show – among others – the plant design basis value for the occurrence frequency of 10^{-4} /a at 50% confidence level (107 cm) and the lower limit of the safety assessment which has the occurrence frequency of 10^{-7} /a (e.g. 175 cm at 50% confidence level). The hazard curves also demonstrate the uncertainty limits of the Gumbel approximation, e.g. the expected thickness of snow for occurrence frequency of 10^{-5} /a is 104 cm at 5% confidence level, while it is 166 cm at 95% confidence level.



Figure 1. Hazard curves for extreme snow relevant to the Paks site





ANNEX 2.3. EXTREME WEATHER ASSESSMENT IN LITHUANIA

Though decision regarding Ignalina NPP decommissioning has been made, however, a demand to ensure nuclear safety in Lithuania does not diminish. The construction of new nuclear objects in Lithuania is also related with Ignalina NPP decommissioning. First of all, these are spent fuel storages, where medium and high radioactivity waste and spent nuclear fuel will be stored. On the other hand, after making a decision regarding Ignalina NPP decommissioning, an issue regarding possibilities to construct a new nuclear power plant is discussed very intensively in Lithuania. Various scientific studies are carried out, where economical, technical and social aspects are being analysed. However, the one of most important part of this issue is safety of nuclear power plant.

Many different technical documents and research reports are stored at Ignalina NPP archive. Major part of this material is used for assessment of potential new NPP construction sites. Besides, it is not restricted only to material analysis submitted by new NPP or stored at Ignalina NPP archive. Search for the relevant materials has been performed in other information sources as well. Preparing the assessment of construction sites in respect to external events the environmental impact assessment (EIA) report and other EIA related data was taken into account.

While analysing extreme meteorological phenomena and events, extreme precipitation was analysed separately. Extreme winds and other meteorological phenomena and events possibly influencing potential new NPP construction sites were investigated as well. The Lithuanian practice on initiating event selection and analysis is in accordance to the methodology elaborated by the IAEA. Although, the specific features of the PSA related requirements used or under the development in Lithuanian is described in another report "Methodology for Selecting Initiating Events and Hazards for Consideration in an Extended PSA". The large part of this description is focusing on the external hazards selection and their combinations, while specific examples from data and methodology for the analysis are presented below.

In order to perform an assessment of events, the following activities have been carried out:

- identify events that may affect the safety and design solutions of NPP;
- determine quantitative parameters (probability, threshold values, etc.) of meteorological phenomena and hazards as well as scope of probable outcomes;
- in the maps and plans indicate locations of potential hazard sources and distances to the NPP;
- assess collected statistical data (capacity, reliability, etc.);
- perform a selection of events for further analysis;
- carry out detailed assessment of selected events.

Lithuania is located in the continental East Europe climate area. One of the main features of the climate in the region is the fact that no air masses are formed over this area. Cyclones are mostly connected with the polar front and determine a continuous movement of air masses. The cyclones formed over the medium latitudes of the Atlantic Ocean move from the west towards the east through Western Europe and the new NPP region is often located at the intersection of the paths of the cyclones bringing humid maritime air.

The variation of maritime and continental air masses is frequent; therefore, the climate of the region can be considered as a transient climate from the maritime climate of Western Europe to the continental climate of Eurasia. In comparison with other Lithuanian areas, the new NPP area is characterized by big variations of air temperature over the year, colder and longer winters with abundant snow cover, and warmer, but shorter summers. Average precipitation is also higher.

In Lithuania, the criteria of extreme meteorological events for nuclear safety are not defined, therefore meteorological phenomenon is considered to be an extreme event when it reaches criteria of elemental or catastrophic meteorological phenomena. These criteria are described in the table below.





Table 1. Criteria of extreme meteorological events

	Criteria*					
Phenomena	Massurament unit	Evaluation, value,				
		critical threshold				
1. Elemental meteorological phenomena						
1.1. Very strong wind	maximum wind speed, m/s	28-32				
1.2 Very strong rain	amount of precipitation, mm;	50-80;				
	duration, h	≤12				
	amount of precipitation, that precipitated within 5					
1.3. Long-lasting very strong rain	days or less, exceeds monthly standard climate rate,	2-3				
	times					
	amount of precipitation, mm;	20-30;				
1.4. Very strong snow	snow pack increase, cm;	20-30;				
	duration, h	≤12				
	average wind speed, m/s;	15-20;				
1.5. Very strong blizzard	visibility, m;	≤1000;				
	duration, h	≥12				
1.6. Very strong hail	hailstone diameter, mm	≥20				
1.7. Very strong composite glazed	glazed frost thickness/diameter on the wire of	≥35				
frost	freezing rain support, mm					
1.8. Very strong freezing rain	glazed frost thickness/diameter on the wire of	≥20				
	freezing rain support, mm					
1.9. Very strong wet snow sleet	glazed frost thickness/diameter on the wire of	≥35				
····· · ··· · · · · · · · · · · · · ·	freezing rain support, mm					
1.10. Hard frost	minimum air temperature, °C;	≤-30;				
	duration of hard frost, number of days	1-3				
1.11. Heat	maximum air temperature, °C;	≥30;				
	duration of heat, number of days	≥3				
1.12. Frost within active plant	daily average air temperature, °C;	≥10;				
vegetation period	air (soil surrace) temperature, °C	<0				
1.13. Drought within active plant	daily average air temperature, °C;	≥10;				
vegetation period	nyarothermal coefficient - a numerical value	<0.5;				
	duration, number of days	>30				
1.14. Drought in the forests	complex forest rate of fire - a numerical value;	≥10 000;				
	visibility m:	<100				
1.15. Very thick fog	duration h	≤100 >12·				
1.16. Very strong storm (complex of						
hazardous meteorological						
phenomena.	fact	is				
thunderstorm	maximum wind speed, m/s:	15-28:				
and / or flaw	amount of precipitation, mm/h.;	≥15/≤12;				
strong rain	hailstone diameter, mm	≥6				
hail)						
2. Catastrophic meteorological phenor	nena					
2.1. Hurricane	maximum wind speed, m/s	≥33				
2.2. Voru strong roin	amount of precipitation, mm;	>80;				
2.2. Very strong rain	duration, h	≤12				
	amount of precipitation, that precipitated within 5	>3				
2.3. Long-lasting very strong rain	days or less, exceeds monthly standard climate rate,					
	times					
	amount of precipitation, mm;	>30;				
2.4. Very strong snow	snow pack increase, cm;	>30;				
	duration, h	≤12				
	average wind speed, m/s;	>20;				
2.5. Very strong blizzard	visibility, m;	≤500;				
	duration, number of days	≥1				
2.6. Very strong hard frost	minimum temperature, °C;	≤ -30;				
	duration, number of days	>3				

* 2011 November 11 Order No. D1-870 "On elemental, catastrophic meteorological and hydrological phenomena criteria approval" of the Minister of the Environment of the Republic of Lithuania (Official Gazette, 2011. No. 141-6642, Vilnius)





<u>Extreme event</u> - In general, natural, technical, ecological or social event that reaches or exceeds stated criteria and endangers humans, their physiological and social conditions of life, property, economy and environment. One of the extreme event causes may be natural, i.e. dramatic changes of climatic conditions that cause natural disasters.

<u>Extreme event criteria</u> - in general, physical, chemical or geographical dimension that describe event extent and consequences and are determined by observations and calculations or used in international practice. Event is considered to be extreme if reaches or exceeds these criteria.

<u>Elemental meteorological phenomena</u> - natural phenomena, which by their intensity, spread and duration can cause damage to the economy, population and can cause natural disasters.

Initial data for climate analysis were collected and obtained from various sources:

- observations of meteorological stations (automatic, instrumental and visual);
- instrumental temporary observations: expeditionary, mobile stations, etc.;
- meteorological satellites;
- synoptic maps: bar topography and ground level;
- aerologic probing;
- other special meteorological stations.

Analysis and documentation of external events evaluation has been implemented in the following steps (see below Fig. 1):

- 1. Identification of external events and related phenomena when description of all possible events and/or related phenomena and possible outcomes are formed;
- 2. Analysis of boundary conditions, in which under determined criteria event characteristic parameters and their value limits are defined;
- 3. Data analysis, which includes information analysis related to event occurrence and collection and study of statistical and other data;
- 4. Event assessment, in which deterministic and/or probabilistic modelling and assessment of individual event occurrence are carried out;
- 5. Analysis of outcomes, in which assessment and description of possible effects and extent of consequences that event occurrence may cause are performed.



Fig.1. Scheme of external event analysis

In Lithuania, probabilistic estimates of aircraft crash, gas explosion and flooding which may induce severe outcomes are smaller than 10⁻⁵ events per year. Much more probable is forest fire, extreme winds, extreme precipitation and temperature, however, their outcomes are not as severe, and, from the safety point of view, they are controlled more easily. Results of performed analysis may be important while making a decision regarding particu-



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lar construction site and planning management of their risk. Pursuant to IAEA recommendations with the emergence of new significant information the analysis of external events should be updated in the future.

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ANNEX 2.4. EXTREME WEATHER ASSESSMENT IN SWEDEN

According to the safety regulations SSMFS 2008:1, all Swedish reactors have to be analysed with probabilistic methods to supplement the basic deterministic safety studies. All power reactors have to perform complete level 1 and level 2 PSA studies including all operating modes and all relevant internal and external hazards for the sites. Today, all power reactors have performed level 1 and level 2 studies. The level 1 studies have been updated continuously with regard to plant modifications. Work has been performed to fill gaps in the level 1 studies and to finalize studies for low power operation, area (internal hazards) events and external hazards.

As a result of the stress test assessments, some areas of improvement for the Swedish NPPs have been identified by the licensees while others have been identified by the regulator when reviewing licensee reports. Swedish Radiation Safety Authority (SSM) followed the work of WENRA and ENSREG to develop a methodology for assessing margins for cliff-edge effects due to external events. The investigation of extreme weather conditions is also defined as one of the measures to be performed by Swedish licensees in relation to natural hazards.

The stress tests performed in Sweden demonstrates that Swedish NPPs can withstand impact from several kinds of extreme weather conditions. However, all extreme weather conditions and situations that can arise in the plants due to impact from extreme weather have not been fully evaluated, therefore further evaluation on extreme weather conditions including its combinations and consequential events are needed [G].

Extreme weather conditions (only related with scope of this report)

The comprehensive risk and safety assessments demonstrate the NPPs resilience against the conditions that might arise at the plants as a result of different kinds of extreme weather conditions. It also shows that a number of areas contain major uncertainties or for some other reason should be investigated further to make it possible to identify opportunities to further strengthen the facilities' protection in connection with these events. For example, the procedures for the working staff in terms of requisite measures in the event of large quantities of precipitation and extreme temperatures should be reviewed [A]. Also, no in-depth analyses of combinations of different weather phenomena have been conducted, such as extreme snowfall together with extreme winds.

Furthermore, it has been established that there is a lack of detailed and thorough descriptions of how the NPPs are impacted in connection with possible ice storms. One engineering assessment, however, is that an extreme ice storm might cut offsite power and risk blocking ventilation systems and hampering access to the site [A]. The fact that in-depth analyses have not been conducted is assessed as a deficiency in relation to current regulations and must consequently be performed.

The extreme weather conditions are based on statistical data collected from past 100 or more years. It also depends on estimation based on site conditions and extreme weather events recorded for NPPs site, which is performed with the assistance of SMHI (Swedish Meteorological and Hydrological Institute). The design basis events for extreme weather include rain, wind, sea water level, outdoor temperature and lightning [G].





#	Extreme weather conditions	Type of event	Remarks	
1	1 Extreme air tem- peratures Slow		At low air temperature, major concern is risk of freezing of piping used for process measurements that could lead to inaccurate values to the reactor protection system. Similarly manual measures are used for low temperature alarm in the ventilation system to avoid the compo- nent(s) freezing risk.	
			In case of high air temperature exceeding dimensional values, accord- ing to engineering judgment this can only cause accelerated ageing of the equipment concerned and not instant malfunctioning [G].	
2	High seawater temperature	Slow	The procedures to reduce the reactor power and to shut down the reactor at sea water temperatures around +25°C are used. After shut-down, no shortfalls for the reactor are expected.	
3	Extreme rainfall and snowfall	Slow	If the ordinary equipment fails to operate as designed and there is time to take manual steps, then extreme rainfall and snowfall are considered as slow events.	
4	Heavy snowfall	-	The majority of the buildings are designed to withstand a very inten- sive snowfall for 1-2 days. The manual measures are considered to avoid the risk of accumulation of snow causing collapse of roofs and damaging safety systems or fuel in the spent fuel pool or other safety importance buildings.	
5	Strong winds	-	The Swedish NPPs are designed to withstand against strong winds, however some shortfalls are reported for older plants and preventive measure are considered.	
6	Tornado missiles	-	All the licensees have applied the missiles defined in the NRC Regula- tory Guide 1.76. There are some buildings where shortfalls have been reported for the missiles described [G].	
7	Frazil ice for- mation	Fast	In the water intake, low sea water temperatures create ice crystals which accumulate on equipment below the surface. The frazil ice formation is unexpected due to recirculation flow in the cooling water canals.	

The reassessment of external events in views of the Fukushima Daiichi accident is performed in Sweden under Nordic PSA group (NPSAG) project [B]. The reassessment methodology is based on external hazards impact on structures, electric environment and impact on sea water (main heat sink). The extreme weather conditions (e.g. wind speed, direction and force) are the most important factors contributing to extreme sea levels for Swedish sites, as shown in below table:

Factor	Ringhals	Oskarshamn	Forsmark
Wind direction	Wind from the west	Complex conditions	Wind from the north
Wind speed	> 20 m/s	> 20 m/s	> 20 m/s
Air pressure	Relation to passing areas Of low air pressure	Modest relation to air pressure variations	No distinct relations
Average water level	The average water level of the North Sea is important. Faster sea level developments	The average water level of Baltic Sea is important. Slow sea level developments (months)	The average water level of Baltic Sea is important. Slow sea level developments (months)
Global sea level	Great importance	Great importance	Great importance
Wind force	Not of great importance.	Local effects between Oskarshamn och Öland	The region around Öregrund causes local amplification. This effect is included in the measurement series.



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The effect of climate changes are noticed in Baltic sea, however the analyses performed are associated with large uncertainties due to wider range of affecting parameters. Below picture [B] shows the French ship Caledonia stranded on Bornholm during the devastating storm on 12-13th November 1872. During the storm a rise in water levels 3-4 meters above normal was recorded in the southern Baltic sea.



Followings methodology is used for analysis of multiple external events [B]:

- 1. Definition of external event
- 2. Screening methodology
 - o Identification of potentially relevant single external events.
 - Screening analysis based on plant's resistance to external events and on retrieval of relevant information on both external events and the facility. This includes data, methods and experience relating to external events, or protection against them in the facility.
 - System response to the event, and comparison between the strength of the external event over time and the plant resistance to the event.
 - Screening criteria are defined for simple and multiple external events. The criteria are applied in the screening analysis to exclude non-relevant external events from further analysis
 - the result from the screening analysis consists of the screening criteria used, the external events that have been excluded and a summary of conclusions and recommendations regarding events that require deeper analysis.

For events that require more detailed analysis, timing aspect of the event in relation to the required mitigating functions is evaluated. For each such function, degree of redundancy, separation and diversity are assessed in order to conclude when functions are made unavailable and the possibilities of recovering the failing function. In general strong wind, tornado, extreme snow and ice storm are considered for 'detailed analysis', however for BWR NPPs these hazards are not leading to any new initiating events in the PSA models and conclusions are drawn that these hazards are covered by existing initiating events, if not screened out earlier.

For Swedish PWR NPPs [I], strong winds and extreme snow are considered as single external events and detailed analysis are performed. In additional to single hazards, following multiple external events is identified:

- strong winds (causing loss of external grid) and organic material in water (causing loss of ultimate heat sink)
- strong winds (causing loss of external grid) and extreme snow (causing loss of ventilation).




Strong winds [I]

In order to assess the maximum force from strong winds, maximum wind speeds at heights 10 m and 50 m were calculated for very long return periods (up to 10,000 years, but tentative extrapolations to longer return periods were also made). Based on these wind strengths, maximum wind loads on some characteristic buildings and structures were calculated. The maximum wind load on structures, including effects from gusts, was calculated to be between 3.5 and 4.5 kN/m², depending on terrain type. It is concluded that most safety critical buildings are able to handle the maximum load. There are some possible exceptions, including the roof of the diesel building. Therefore one scenario to be modelled and analyzed in the PSA was defined:

• S01. Strong wind causing: Loss of external grid AND Damage to diesel building

Extreme snow [I]

Precipitation for the PWR NPPs site have been compiled and analyzed based on precipitation records. The yearly maxima were analyzed using the Fisher-Tippet 1 method and results presented for return periods up to 10,000 years. The analysis indicates that the maximum precipitation during the winter months is about half that of the summer months. This gives a maximum snowfall per day (24 hours) of about 100 mm, i.e., about 1 meter of snow. This value is also supported by information on extreme snow events in southern Sweden. The corresponding roof load is about 2.4 kN/m².

It is concluded that most safety critical buildings are able to handle the maximum load. There is a possibility of damage to the diesel building due to snow load. This will only give a risk contribution in connection with a plant transient, especially if the transient is due to loss of external grid. As the possibility to lose the external grid in connection with heavy snowfall and/or snow storm cannot be disregarded, the following scenario was defined:

• S02. Extreme snow causing Loss of external grid AND Damage to diesel building

Similar analyses were performed for the combination of hazards with strong winds.

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APPENDIX 3. HAZARD RISK ASSESSMENT AND PSA TOOLS

RiskSpectrum[®] HazardLite [48] (hereafter called *HazardLite*) is a light tool for assessing hazard risks, e.g. earthquake, tsunami, extreme weather etc. The input to *HazardLite* includes definition of initiating events ranges, hazard curves and fragilities. The output is an excel workbook containing the results in form of Basic Events. This excel file can be imported into RiskSpectrum[®] PSA for further analysis. In addition, if the Monte Carlo method is selected in the analysis, a series of text files will also be generated for uncertainty analysis in RiskSpectrum[®] PSA.

The information in the following section summarizes the technical elements of the RiskSpectrum[®] HazardLite tool (cf. Section 2 of [48]). As it is a methodological guidance and not a commercial document, other methodology and tools could be considered and implemented.

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

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

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

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

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

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

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

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





The quantification algorithm is described by following steps:

- Point estimate calculation
- Quantification of the hazard frequency, the initiating events
- Fragility
- Calculation of fragility for group of events
- Calculation of fragility for combination of events
- Uncertainty calculation
- Quantification of hazard
- Quantification of fragility

Quantification of hazard, initiating events, point estimate calculation

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

Fragility

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

The fragility calculation is based upon following formula (1):

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

Where:

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

a is the PGA

 A_m is the median capacity of the component

 B_R is the random variability (the randomness w.r.t. the earthquake)

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

Q is the confidence that the conditional probability of failure, f, is less than f^{\uparrow} for a given peak acceleration a.

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

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

in the equation above and to set B_U to zero (1). Then following equation can be defined:

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





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

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

Assume following cut set

 $H_1, F_1, B.$

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

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

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

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

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

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

Where:

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

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

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

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

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

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

Where:

 W_{hk} is the weight of hazard curve k

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





Component groups and combinations

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

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

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

Combination

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

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

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

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

Uncertainty calculation

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

The method is:

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