Safety Reports Series

No. 92

Consideration of External Hazards in Probabilistic Safety Assessment for Single Unit and Multi-unit Nuclear Power Plants

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CONSIDERATION OF EXTERNAL HAZARDS IN PROBABILISTIC SAFETY ASSESSMENT FOR SINGLE UNIT AND MULTI-UNIT NUCLEAR POWER PLANTS

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SAFETY REPORTS SERIES No. 92

CONSIDERATION OF EXTERNAL HAZARDS IN PROBABILISTIC SAFETY ASSESSMENT FOR SINGLE UNIT AND MULTI-UNIT NUCLEAR POWER PLANTS

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FOREWORD

The accident at the Fukushima Daiichi nuclear power plant in Japan caused by the disastrous earthquake and tsunami of 11 March 2011, and the consequences of the emergency for people and the environment, underlined the need to assess the nuclear safety of multi-unit sites against potential external hazards and combinations thereof. The safety assessment of a single unit site against an external hazard is itself challenging; such an assessment of a multi-unit site against multiple concurrent and correlated hazards poses a further challenge to integrating the diverse scenarios in a comprehensive manner.

IAEA Safety Standards Series No. SSG-3, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, published in 2010, provides general guidance for a Level 1 probabilistic safety assessment (PSA) and its application. However, that Safety Guide does not cover Level 1 PSA of multi-unit sites against multiple hazards.

There has been until now no sufficient technical basis or guidance for the safety assessment of a multi-unit plant against external hazards and combinations thereof. The technical aspects of the external events PSA developed in this publication, such as identification and initial screening of hazards or the general PSA process, are applicable to multi-unit sites.

This publication provides technical details for screening site specific external hazards, including combinations thereof, and avoiding those hazards that could trigger initiating events.

This Safety Report complements the IAEA safety standards, providing a technical basis for the screening of potential external hazards and for combinations of such hazards to be used in an external events PSA or in reassessing a multi-unit site against multiple hazards.

The IAEA greatly appreciates the contributions of all those who were involved in the drafting and review of this Safety Report. The IAEA officers responsible for this publication were K. Hibino and O. Coman of the Division of Nuclear Installation Safety.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

The Fukushima Daiichi accident [1] demonstrated that external hazards, or combinations of external hazards, have the potential to impact the entire infrastructure of a site, including all its nuclear facilities. From the lessons learned, any assessment of external hazards needs to consider their effect on multiple units at a site. A full investigation is necessary of the possible combination of natural hazards affecting multiple units at a nuclear power plant. Furthermore, complex scenarios need to be taken into account when considering accident mitigation measures and recovery actions.

The screening process for site specific external hazards for a single unit is described in the PRA Procedures Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants [2].

IAEA Safety Standards Series No. NS-G-2.13, Evaluation of Seismic Safety for Existing Nuclear Installations [3], provides recommendations for seismic re-evaluation of existing nuclear power plants using deterministic and probabilistic safety assessment (PSA) techniques. Probabilistic Safety Assessment for Seismic Events (IAEA-TECDOC-724) [4] outlines the PSA for seismic events. New technical documents are needed that describe the methodology and procedure for an external events PSA that is applicable to other external hazards such as heavy winds and flooding.

Individual hazards have been grouped based on common characteristics, approaches, methods and data. Table 1 lists examples of hazard groups and the individual hazards related to each group. Recently, the IAEA published IAEA Safety Standards Series No. SSG-3, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants [5], which provides a similar approach to hazard grouping. It also discusses the need to consider the combined hazards and induced hazards.

This Safety Report complements the IAEA safety standards, providing a technical basis for screening external hazards and their combinations in an external events multi-unit PSA.

TABLE 1. SAMPLE HAZARD GROUPS

Hazard group	Hazard
Biological events	Detritus Zebra mussels
External fire	Forest fire Grass fire Fire in non-safety building
Extraterrestrial events	Meteorites or satellite strikes
Extreme temperature	Frost Low winter temperature Ice cover High summer temperature
Ground shifts	Avalanche Coastal erosion Landslide Sink hole Soil shrink–swell Earthquake
Heat sink effects	Drought Low lake or river water level River diversion
Heavy load drop	Drop of heavy parts of the turbine during maintenance, fuel assembly drop in the spent fuel pool
High winds	Extreme winds and tornadoes Hail Hurricane Sandstorm
Industrial accidents	Industrial or military facility accident Pipeline accident Release of chemicals from on-site storage Toxic gas release

TABLE 1. SAMPLE HAZARD GROUPS (cont.)

Hazard group	Hazard
Lightning	Lightning strike
Site flooding	Precipitation, intense Flooding caused by landslides or failure of dams or dikes High tide External flooding Seiche Storm surge Tsunami Waves
Snow	Snowpack
Transportation accidents	Aircraft impact Ship impact Vehicle impact Vehicle/Ship explosion
Volcanic activity	Eruption of steam and/or lava, ash cloud

1.2. OBJECTIVE

The objective of this Safety Report is to provide a technical basis for initial screening of hazards to be considered in the single unit and multi-unit PSA process. It outlines a generic methodology for PSA of nuclear power plants against external hazards, which integrates the design, procedural, operational, human factor and protective and mitigating aspects that are essential to model the response of a nuclear power plant to an external hazard, and to assess the associated risk.

The methodology for the external events PSA of a single unit was extended for multi-unit sites and identification of credible hazard combinations.

1.3. SCOPE

This report covers the screening process and criteria for site specific external hazards and their credible combinations that are relevant to single unit and multi-unit PSA. The external hazards include high winds, external floods and seismic and human induced events (e.g. accidents caused by transportation activities or nearby industrial facilities).

1.4. STRUCTURE

Section 2 focuses on the external hazards PSA process and reviews key IAEA publications and relevant international technical resources. Preliminary screening of external hazards, including the screening criteria and walkdown, is discussed in Section 3. Bounding analysis and quantitative screening criteria are described in Section 4. Treatment of induced hazards and combinations of external hazards is discussed in Section 5. Examples of the application of preliminary screening and bounding analysis are provided in Appendices I and II. Different elements of a detailed PSA for extreme winds and external flooding are described in Appendix III.

2. GENERAL CONSIDERATIONS

2.1. EXTERNAL EVENT PROBABILISTIC SAFETY ASSESSMENT PROCESS

The objective of an external event PSA is to estimate the risk to the public. As intermediary risk metrics, the frequencies of severe core damage (Level 1 PSA) or the frequency releases (Level 2 PSA) may be estimated in order to identify structures, systems and components (SSCs) that contribute significantly to the risk so that plant upgrades (i.e. hardware modifications and procedural changes) can be made, if necessary.

2.1.1. Key elements

In general, the key elements of an external event PSA are:

— Probabilistic hazard analysis;
— Fragility analysis of structures and equipment;
— Plant response analysis and risk quantification.

One or more of these key elements are evaluated for each external hazard, depending on the magnitude and severity of the hazard. For this purpose, the external event PSA is conducted in four stages, using progressive screening, as follows:

(1) Identification of potential external hazards that may affect the nuclear power plant site;
(2) Preliminary screening of external hazards based on a set of criteria;
(3) Bounding analysis of screened-in external hazards;
(4) Detailed PSA for selected external hazards.

2.1.2. Procedures and outputs

Figure 1 shows a flow chart of the external event PSA process for a single reactor unit and for multiple units at a site. It begins by identifying potential external hazards that could affect a nuclear power plant site. For each selected hazard, screening criteria (see Section 3.2) are applied to determine if the hazard can be screened out from the PSA. This determination is supplemented by the findings of a site visit and plant walkdown (see Section 3.3). These screening criteria are also applicable to external hazards that impact multiple units at a site. For a specific external hazard that cannot be screened out using the preliminary screening criteria, the analyst has to assess whether the hazard can affect multiple units at the site. If an external hazard affects only a single reactor at a site, the next step is to perform bounding analysis (see Section 4) to estimate the core damage frequency (CDF), release frequency (RF) or frequency of radiological consequences. If these estimates meet the acceptance criteria established by the Member State, then the PSA for the specific external hazard is deemed complete and needs to be documented. Otherwise, a detailed PSA needs to be performed for the external hazard. These estimates (i.e. CDF, RF and frequency of radiological consequences) are compared with the acceptance criteria, and if the criteria are not met, a study of plant upgrades (hardware and procedural) is necessary. When the external hazard is judged to affect multiple units, a detailed multi-unit PSA needs to be performed [6]. Bounding analysis methods have not been developed for use in a multi-unit PSA. It is assumed that the analyst has access to the multi-unit PSA systems model for internal events [6]. This model will be modified to account for the specific features of the external hazard under study. The risk metrics [6] of site core damage frequency (SCDF) and site large early release frequency (SLERF) are calculated and compared with the acceptance criteria, and if the criteria are not met, a study of plant upgrades (hardware and procedural) is necessary.

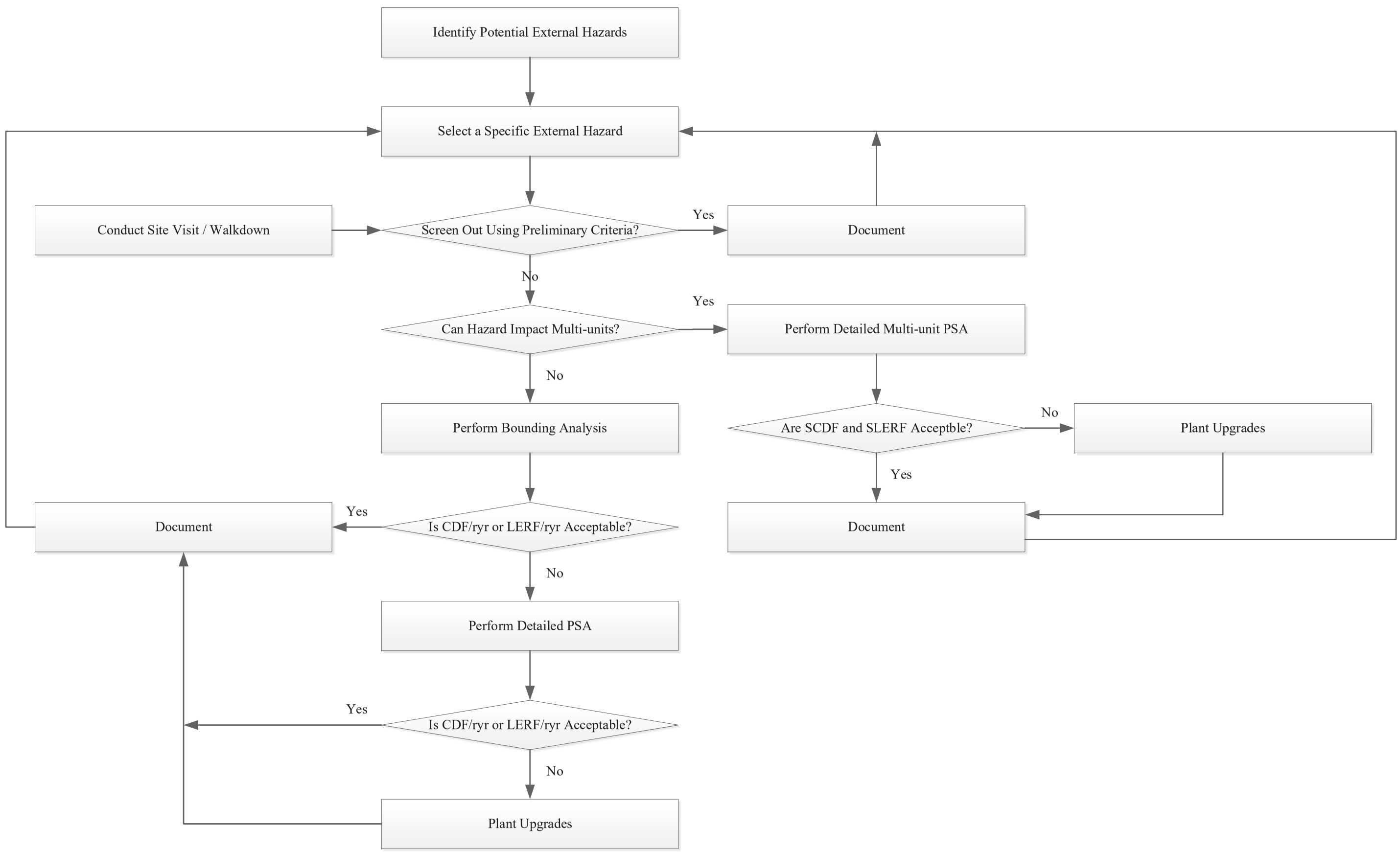

FIG. 1. Flow chart of the external event PSA process for a single reactor unit and for a multi-unit site. CDF — core damage frequency; LERF — core damage frequency; PSA — probabilistic safety assessment; ryr — reactor year; SCDF — site core damage frequency; SLERF — site large early release frequency.

2.2. REVIEW OF IAEA PUBLICATIONS

Over the past 30 years, the IAEA has developed numerous publications on PSAs which deal with internal and external hazards. An example is SSG-3 [5], which describes the development and application of Level 1 PSA for nuclear power plants and also treats some aspects related to the development of the external hazards PSA (high winds, external floods and seismic and human induced hazards).

IAEA Safety Standards Series No. NS-R-3 (Rev. 1), Site Evaluation for Nuclear Installations [7], describes the safety requirements of site evaluations for nuclear installations. Reference [4] deals with the PSA for seismic events; Ref. [8] describes the attributes which establish the quality of a PSA for internal and external hazards. Extreme external events in the design and assessment of nuclear power plants are discussed in Ref. [9].

2.3. STANDARD FOR EXTERNAL HAZARDS PROBABILISTIC SAFETY ASSESSMENT

Since 1999, the American Society of Mechanical Engineers (ASME) and the American Nuclear Society (ANS) have collaborated on developing a standard listing the requirements for Level 1 and limited Level 2 probabilistic risk assessments (PRAs) (evaluation of large early release frequency (LERF)). The latest version of the standard, Addendum B, published in September 2013 [10], establishes requirements for a PRA of internal and external hazards to nuclear power plants at full power. It is aimed at PRAs used to support applications of risk-informed decision making related to design, licensing, procurement, construction, operation and maintenance of operating power plants.

The current version [10] of the standard provides specific requirements for the following hazard groups:

(a) Internal events;
(b) Internal floods;
(c) Internal fires;
(d) Seismic events;
(e) High winds;
(f) External floods;
(g) Other hazards.

The standard provides screening criteria for each of the above hazard groups [10].

For example, the wind hazard analysis under high winds, high level requirements in Ref. [10] states:

“ — The frequency of high winds at the site shall be based on site-specific probabilistic wind hazard analysis (existing or new) that reflects recent available regional and site-specific information. Uncertainties in the models and parameter values shall be properly accounted for and fully propagated in order to obtain a family of hazard curves from which a mean hazard curve can be derived.
— In the tornado wind hazard analysis, USE the state-of-the-art methodology and up-to-date databases on tornado occurrences, intensities, etc. PROPAGATE uncertainties in the models and parameter values to obtain a family of hazard curves from which a mean hazard curve can be derived.”

2.4. PRACTICES IN MEMBER STATES

External hazards are considered in the design and evaluation of nuclear power plants to varying degrees in the Member States. Depending on the site location, some hazards may be considered important and deserving of close attention, while some other hazards may be screened out.

The Committee on the Safety of Nuclear Installations [11] asked the Member States to fill out a questionnaire that included 19 questions, grouped under four headings:

(1) Regulatory requirements and status of an external event PSA;
(2) Definition of scope of an external event PSA;
(3) Analysis methods;
(4) Results and practical applications.

According to Ref. [11]:

The survey found that the role of external events in PSAs is increasing when new regulatory requirements, new versions of existing PSAs, or PSAs performed for new plants are considered. One possible reason for this trend is “that several hazards were not covered by older PSA versions, and safety improvements were implemented for the dominant internal initiators, while the introduction of hazards in the PSAs led to the identification of new problems” such as the relative increase of external hazards in new nuclear power plants. The survey noted that there is a general trend towards full scope PSA, including external events.

"There are also differences in the role of external events PSAs in the regulatory framework. In some countries, external events PSAs has an important role in assessing whether the protection against extreme external events is sufficient, especially as regards older units. In other countries, the emphasis is on deterministic design requirements.

"The approaches used to treat external hazards in PSA are similar in all countries and the responses to the questionnaire did not identify general deficiencies in these methods. The questionnaire did identify a number of differences in application, including differences in: (1) analysis scope (e.g. regarding which hazards were to be addressed...); (2) the screening of events; (3) the treatment of operator actions as affected by the external events; (4) the treatment of dependencies, both hazard and plant related (e.g. modelling of [common cause failures] and [common cause initiators]); and (5) the treatment of multi-unit effects."

Annex I describes the treatment of external hazards in the design and PSA of nuclear power plants in Canada and Finland.

3. PRELIMINARY SCREENING OF EXTERNAL HAZARDS

The screening of external hazards in a PSA has three important goals. The first is that no significant event is overlooked. The second is that the limited resources for the study of significant events are allocated optimally; this is achieved by screening out those external events that do not contribute significantly to plant or site risk. The last goal is that the differences in terms of risk contributions between external events and internal events (i.e. common cause, human error and fragility related failure) need to be recognized and explicitly treated. The external event PSA methodology has been specifically developed to accomplish the last goal (Refs [2, 5, 10]). Based on these goals, the following three subtasks are identified:

(1) Identification of potential external hazards;
(2) Selection of screening criteria;
(3) Identification of (screened-in) external hazards for further study.

A general description of each subtask is given in the following sections.

3.1. IDENTIFICATION OF POTENTIAL EXTERNAL HAZARDS

All potential external hazards (i.e. natural and human induced hazards) that may affect a nuclear power plant site need to be identified. Examples of such lists can be found in the PRA Procedures Guide [2], SSG-3 [5], and Knochenhauer and Louko [12]. In the PRA standard [10], the potential external hazards are grouped into hazard groups; the hazards in each group share a common approach, methods and data. Table 2 is an example of hazard groups and hazards in each group, taken from Ref. [10]. It is important to note that the potential hazards to be considered vary among the nuclear power plants (i.e. location and site features) and the practices in different Member States.

3.2. SELECTION OF SCREENING CRITERIA

3.2.1. Screening criteria

The external events identified are screened in order to select the events for detailed risk quantification. A set of screening criteria is formulated to minimize the possibility of omitting significant risk contributors while reducing the amount of detailed analyses to manageable proportions. As an example, the set of screening criteria used in the supporting requirements of the PRA standard [10] follow (note that SSG-3 [5] has a similar set of criteria for screening out external hazards).

For screening out an external hazard, any of the following five screening criteria provides an acceptable basis:

- Criterion 1: The event is of equal or lesser damage potential than the events for which the plant has been designed. This requires evaluating a plant's design in order to estimate the resistance of its structures and systems to a particular external event.
- Criterion 2: The event has a significantly lower mean frequency of occurrence than another event, taking into account the uncertainties in the estimates of both frequencies, and the event would not result in worse consequences than the consequences from the other event.
- Criterion 3: The event cannot occur close enough to the plant to affect it. This criterion has to be applied while taking into account the range of magnitudes of the event for the recurrence frequencies of interest.
- Criterion 4: The event is included in the definition of another event.
- Criterion 5: The event is slow in developing and there is sufficient time to eliminate the source of the threat or to devise an adequate response.

TABLE 2. SCREENING OF EXTERNAL EVENTS FOR A SAMPLE NUCLEAR POWER PLANT

Hazard group	Hazard	Applicable screening criteria*	Remarks
Biological events	Detritus and zebra mussels	1	There would be adequate warning for these events. Also note that the river is not the ultimate heat sink for the plant.
External fire	Forest fire	1, 3	Updated final safety analysis report states that the nearest forest is approximately 564 m from the control room. The toxic chemicals emitted from a forest fire are CO, NO_2 and CH_4. The calculation demonstrated that the pollutant concentrations outside the control room intake for a variety of wind speeds and Pasquill stability category G are effectively zero. Therefore, the release of toxic combustion products from a forest fire does not pose a hazard to control room personnel. The heat flux and resultant temperature rise on plant structures due to a forest fire were also evaluated. The calculated temperature rise is less than the allowable temperature rise. Therefore, a forest fire will not cause thermal damage to the plant's safety related structures.
	Grass fire	1, 3	Fire cannot propagate to or on the site because the site is cleared; plant design and fire protection provisions are adequate to mitigate effects.
	Non-safety building fire	1, 3	Fire cannot propagate to or on the site because the site is cleared; plant design and fire protection provisions are adequate to mitigate effects.
Extraterrestrial events	Meteorite or satellite strikes	2	This event has a very low frequency of occurrence for any site in the USA.

TABLE 2. SCREENING OF EXTERNAL EVENTS FOR A SAMPLE NUCLEAR POWER PLANT (cont.)

Hazard group	Hazard	Applicable screening criteria*	Remarks
Extreme temperature	Frost	1	Snow and ice govern.
	High summer temperature	1	The highest recorded temperature at the airport near the plant was 42°C (108°F), which is less than the 49°C (120°F) design basis of the plant.
	Ice cover	3	Icing does not occur on the lower reaches of the river; based on records of minimum temperature, the temperature is higher than 3°C (37°F) most of the time. With dams upstream of the plant, an ice jam is unlikely to occur at the river intake, since these upstream dams will modulate the water temperature. If surface icing did occur at the plant, the design of the river intake and the normal water depth of 4.3 m ensure that an ice sheet across the entire river will not interfere with the flow of water into the intake.
	Low winter temperature	5	The lowest recorded temperature at the airport was –18°C (–1°F); the plant's design basis is –27°C (–17°F).
Ground shifts	Avalanche	3	Topography is such that no avalanche is possible.
	Coastal erosion	3	Plant site is inland.
	Landslide	3	In the immediate vicinity of the plant, there are no steep hills.
	Sink holes	3	The site region is not prone to this hazard.
	Soil shrink–swell	1, 5	Procedures are in place to monitor differential settlement.

TABLE 2. SCREENING OF EXTERNAL EVENTS FOR A SAMPLE NUCLEAR POWER PLANT (cont.)

Hazard group	Hazard	Applicable screening criteria*	Remarks
Heat sink effects	Drought	1, 5	There have been years of low water levels in the river; however, the ultimate heat sink is the 30-day supply pond under the mechanical draft cooling towers. In addition, the plant can receive water from the deep wells into the aquifer in the site region.
	Low lake or river water level	1, 5	The plant does not rely on the river for ultimate heat sink; there is a 30-day water supply under the mechanical draft cooling towers.
	River diversion	3	Will not impact the plant. Note that the river is not used as an ultimate heat sink for the plant.
Heavy load drop	Heavy load drop	1, 3	The plant has met the requirements of the US Nuclear Regulatory Commission’s Generic Issue (GI) 186.
High winds	Extreme winds and tornadoes	—	Plant structures are designed for tornadoes and high winds. Bounding analysis needs to be done.
	Hail	1	Hail may occur but there are no openings in the walls or roofs of safety related buildings through which hail may enter and damage essential equipment. Tornado missile protection features, structural walls and roofs are adequate to withstand the impact of hail.
	Hurricane	1, 3	The plant is not on the coast; the hurricane wind effects are treated under the category of high winds.
	Sandstorm	3	This is not relevant for this region.

TABLE 2. SCREENING OF EXTERNAL EVENTS FOR A SAMPLE NUCLEAR POWER PLANT (cont.)

Hazard group	Hazard	Applicable screening criteria*	Remarks
Industrial accidents	Industrial or military facility accident	—	Bounding analysis needs to be done.
	Pipeline accident	—	Bounding analysis needs to be done.
	Release of chemicals from on-site storage	4	Updated final safety report has analysed the hazard from on-site storage of chemicals.
	Toxic gas	4	Included in transportation accident, on-site chemical release and industrial and military facilities accidents.
Lightning	Lightning strike	1	Considered in plant design.
Seismic activity	Earthquake	—	To be included in the PSA.
Site flooding	External flooding	—	Bounding analysis needs to be done.
	High tide	3	Does not apply since the plant is inland.
	Precipitation, intense	4	Included under internal and external flooding.
	Seiche	3	There is no large body of water near the site.
	Storm surge	3	Plant is inland and is not affected by storm surge.
	Tsunami	3	Plant is inland and is not exposed to tsunami threat.
	Waves	3	Plant is inland and is not affected by any wave activity.

TABLE 2. SCREENING OF EXTERNAL EVENTS FOR A SAMPLE NUCLEAR POWER PLANT (cont.)

Hazard group	Hazard	Applicable screening criteria*	Remarks
Snow	Snowfall	1, 4	The maximum observed ground snow load in the plant's region is 0.38 kN/m^2 (8 pounds per square foot); the 100 year snow load is estimated as 10 pounds per square foot. The design basis of the roof live load is 1.44 kN/m^2 (30 pounds per square foot).
Transportation accidents	Aircraft impacts	n.a.	Bounding analysis needs to be done.
	Fog	4	It affects frequency of occurrence of other hazards, e.g. highway accidents, aircraft landing and take-off accidents and is indirectly considered. Fog is rare in the site region, updated final safety report states that visibility of less than 1 mile occurs less than 3% of the time).
	Ship impact	3	The river does not support ship navigation.
	Vehicle impact	n.a.	Bounding analysis needs to be done.
	Vehicle/Ship explosion	n.a.	Bounding analysis needs to be done.
Volcanic activity	Eruption of steam and/or lava, Lahara and lava flow, pyroclastic and ash fall	3	The site is not close to any active volcanoes.

* 1. The event is of equal or lesser damage potential than the events for which the plant has been designed.
2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events.
3. The event cannot occur close enough to the plant to affect it.
4. The event is included in the definition of another event.
5. The event is slow in developing and there is sufficient time to eliminate the source of the threat or to provide an adequate response.

n.a.: data not applicable.
— : data not available.

Note that these qualitative screening criteria were first developed for screening out external hazards in a single unit PSA. Current thinking is that these criteria are equally applicable for screening out external hazards at multi-unit sites.

This initial screening is followed by a second preliminary screening, assuming that the design basis for the event meets the criteria in the Standard Review Plan [13] put out by the United States Nuclear Regulatory Commission.

For certain external hazards, the standard review plan requires the selection of the design basis event at annual frequencies of occurrence between 10^{-7} and 10^{-6} (e.g. design basis tornado following Regulatory Guide (RG) 1.76, design basis explosions on transportation routes near the plant following RG 1.91, and turbine missile protection per RG 1.112). For other events, conservative maximum sizes or intensities are specified (e.g. design basis flooding per RG 1.59). Based on current information and operating experience, the design basis flooding evaluation per RG 1.59 needs to be reassessed in order to screen out any external flooding in the PRA. It is expected that the analyst will review any changes in the site environs to confirm that the data and models used in the selection of design basis events per the standard review plan are still valid. Therefore, the PRA analyst needs to use caution when screening out an external hazard based solely on conformance to the standard review plan.

3.2.2. Discussion of background and basis for preliminary screening criteria

External hazards (natural and human made) are evaluated during the site selection and design of nuclear power plants in all Member States. There are regulatory guides and requirements that govern the selection of design basis external hazards for the plant design.

The preliminary screening criteria are intended to screen out the external hazards that contribute negligibly to CDF. This is done by a combination of qualitative and quantitative screening criteria. The peer review is considered to be a good practice in order to verify and endorse this screening based on plant specific and site specific information.

Examples of applying PRA standard [10] screening criteria are presented in the following subsections.

3.2.2.1. Criterion 1

The event is of equal or lesser damage potential than the events for which the plant has been designed. This requires evaluating a plant’s design in order to estimate the resistance of plant structures and systems to a particular external event.

For example, the safety related structures in nuclear power plants are designed to withstand safe shutdown in case of earthquake and high winds. The requirement to resist high wind generated missiles generally governs the thickness of structural walls and roofs. The reinforcements in the concrete walls and slabs are typically controlled by the stated safe shutdown for earthquake and wind loads. These safety related structures are therefore able to provide some resistance to the load effects and missiles from other external hazards. In order to screen out an external hazard based on this screening criterion, the analyst has to demonstrate that the loads and/or missiles from the specific external hazard are less than those from the design basis events for which the plant has been designed.

3.2.2.2. Criterion 2

The event has a significantly lower mean frequency of occurrence than another event, taking into account the uncertainties in the estimates of both frequencies, and the event would not result in worse consequences than the consequences from the other event.

For example, the upstream dam failure may be screened out if both its mean frequency of occurrence is lower than that of the flooding caused by intense precipitation (runoff) in the site region and its consequences would not be worse than the consequences from the flooding due to runoff.

3.2.2.3. Criterion 3

The event cannot occur close enough to the plant to affect it. This criterion has to be applied while taking into account the range of magnitudes of the event for the recurrence frequencies of interest.

For example, section 3.5.1.6 of the Standard Review Plan [13], states that aircraft hazard need not be considered if the plant is at least 3.22 km (2 statute miles) beyond the nearest edge of a US federal airway. Similarly, RG 1.91 defines the safe distance between plant structures and a transportation route along which explosive material travels. In addition to screening out external hazards, these safe distances are used to calculate the frequencies of accidents exceeding acceptable radiological limits at the nuclear power plant’s site boundary. This criterion can be applied to both single unit and multi-unit sites.

3.2.2.4. Criterion 4

The event is included in the definition of another event.

For example, toxic gas is an external hazard associated with transportation accidents, accidents related to on-site storage of chemicals and accidents on nearby industrial and military facilities.

3.2.2.5. Criterion 5

The event is slow in developing and there is sufficient time to eliminate the source of the threat or to devise an adequate response.

For example, drought will take place over a long period of time, and plant operations will have adequate time to respond to the threat.

These preliminary screening criteria apply to single reactors as well as to multi-unit sites since the frequency of occurrence and magnitude of the specific external hazard are considered when applying the criteria.

3.3. PLANT AND SITE WALKDOWN

A visit to the plant site needs to be made for the purposes of validating the preliminary screening out of external hazards and collecting additional data for further analysis of external hazards that were not screened out.

Plant walkdown has to be specific to the hazard group in order to identify equipment that is vulnerable to external hazards. For existing reactors, the walkdown needs to focus on any changes in the industrial and transportation activities around the site since the original operating license was issued. The focus also needs to be on the impact of any new construction within and outside the units. Specific examples include:

- — Any new airports and airways in the vicinity of the plant that were not considered in the original site selection and design of the plant.
- — Current activities (e.g. landing and take-off) and types of aircraft at these airports and airways and projected activities till the plant’s end of life.
- — Any new highways built near the plant, and the frequency and types of hazardous cargo shipped on them.
- — Any commercial barge traffic on the river or lake near the plant.
- — Any new construction inside the fence of existing units such as maintenance shops and portable office buildings; these may pose a tornado missile threat to the safety related buildings.

— Any changes in the plant procedures for tornado alerts and warnings: are the trailers tied down and are materials stored in the yard also tied down as part of severe weather procedures?
— Identification of SSCs vulnerable to high wind induced failure as well as a high wind missile survey to identify potential high wind missiles that can damage SSCs.
— Changes in the types and quantities of chemicals stored on-site.
— Status of the flood barriers.

The basis for screening out an external hazard can be confirmed through a walkdown of the plant and its surroundings, according to Ref. [10].

The supporting requirement states that if the screening out of any specific external hazard depends on the specific plant layout, this layout needs to be confirmed by a walkdown. The site visit and discussions with plant personnel supplemented by the walkdown of plant surroundings need to focus on the above supporting requirements.

4. BOUNDING ANALYSIS OF EXTERNAL HAZARDS

For external hazards that are not screened out using preliminary screening criteria (see Section 3), a second level of screening could be done using bounding analysis.

The bounding or demonstrably conservative analysis is intended to provide a conservative calculation showing, if true, either that the hazard would not result in core damage or that the CDF is acceptably low. Some or all of the key elements of the external hazard risk analysis could be used to reach and support this conclusion: hazard analysis, fragility analysis or systems analysis (plant systems analysis, human reliability analysis, accident sequence analysis, etc.).

Again, the hazard analyst needs to be cognizant of the recent experiences not only at the site but also in the worldwide nuclear industry. For example, the PRA standard [10] provides the supporting requirements for bounding analysis. If a particular external hazard cannot be screened out based on the bounding analysis, a detailed PSA is warranted.

4.1. QUANTITATIVE SCREENING CRITERIA FOR SINGLE UNITS

The key risk metrics for a PSA of single reactor units in the USA are the CDF and LERF. In an external hazard PSA, the contributions to these risk metrics are calculated; accounting for the uncertainties in the data and models, these risk metrics are calculated as mean frequencies and epistemic uncertainty (confidence) bounds on frequencies. It is noted herein and elaborated in the companion report [6] that these risk metrics are appropriate for single reactor units and do not apply to sites with multiple reactor units.

The numerical values of the risk metrics for single reactor units are generally selected by the Member States based on their own industry practices and regulatory requirements, or following IAEA guidance.

4.1.1. Technical requirements for bounding or demonstrably conservative analysis

For single reactor units, Ref. [10] states: "A bounding or demonstrably conservative analysis, if used for screening, shall be performed using defined quantitative criteria."

Bounding analysis is defined as analysis that uses assumptions such that the assessed outcome will meet or exceed the maximum severity of all credible outcomes.

Demonstrably conservative analysis is defined as one "that uses assumptions such that the assessed outcome will be conservative relative to the expected outcome."

For example, the analyst could assume the maximum size (e.g. 32 kL or 8500 gallons) of a truck carrying explosives on any US federal or state highways when conducting a bounding analysis of explosion effects on the plant structures. In the demonstrably conservative analysis, the analyst may survey the sizes of trucks travelling on the highway near the plant, find that they range from 15.14 to 28.4 kL (4000–7500 gallons) and select a conservatively large size (e.g. 28.4 kL or 7500 gallons) for analysis.

4.1.2. Discussion

For screening out an external hazard, either of the following two screening criteria provides an acceptable basis for bounding analysis or demonstrably conservative analysis (Ref. [10]):

"*Criterion A*: The current design basis hazard event has a mean frequency <10^{-5} per year and the mean value of the conditional core damage probability (CCDP) is assessed to be <10^{-1}.

Criterion B: The core damage frequency, calculated using a bounding or demonstrably conservative analysis, has a mean frequency <10^{-6}.

. . . .

In some cases, Criterion A can allow an efficient way to verify that the original design-basis hazard (frequency) is low and that the CDF is also acceptably low. Using Criterion A requires a refined modeling of the hazard and an approximate evaluation of conditional core damage probability (CCDP)."

The analysis under Criterion A is a subset of the more extensive demonstrably conservative analysis of CDF under Criterion B. The numerical screening values in Criteria A and B need to be set low enough so that if either of them is met, the external hazard can be screened out.

This CDF may be calculated using different demonstrably conservative assumptions, as explained by the following example. Typically, nuclear power plants are sited such that the accidental impact of plant structures by aircraft is highly unlikely. As part of the external hazard PSA, the risk from aircraft accidents may be assessed at different levels. The mean annual frequency of aircraft impact during take-off, landing, or in flight may be determined. If this hazard frequency is low (e.g. 10^{-7}/a), then aircraft impact as an external hazard may be eliminated from further study. This approach assumes that the aircraft impact results in damage to the structure leading to core damage or large early release (this assumption is likely to be conservative). If the frequency of aircraft impacting the plant structures is estimated to be greater, the fragility of the structures may be evaluated to make a refined estimate of the frequency of core damage. Further refinements could include (a) eliminating certain structural failures since they do not result in core damage (e.g. damage to a diesel generator building may not result in core damage if off-site electrical power is available), and (b) performing a plant systems and accident sequence analysis to calculate the CDF. This example shows that for some external hazards, it may be sufficient to perform only the hazard analysis; for others, the hazard analysis and a simple fragility analysis may be needed; in rare cases, a plant systems and accident sequence analysis may be necessary. Other examples of bounding (demonstrably conservative) analysis can be found in Refs [14–16].

In past PSA studies, Criterion B has been extensively used to screen out external hazards by showing that the CDF is less than 10^{-6}/a. Criterion A has rarely been used, since the analyst was able to show either that the frequency of design basis hazard was itself less than 10^{-6}/a or that the CDF was less than 10^{-6}/a.

4.2. BOUNDING ANALYSIS METHODS FOR SINGLE UNIT AND MULTI-UNIT SITES

Screening criteria described in Section 4.1 are applicable to single reactor units. However, screening based on hazard frequency is applicable to both single unit and multi-unit sites. Some external hazards could create multi-unit accidents. For example, external flooding may affect two or more reactors (or nuclear installations) at a site. Another example would be a hurricane (or typhoon). The effects of an aircraft impact could be considered to be limited to a single reactor if systems or buildings are not shared between units.

Some external hazards (e.g. high winds and external flooding) may create a loss of off-site power in addition to impacting the plant SSCs. If this loss of off-site power lasts a long time, operator response may be impeded (for example, the station batteries may need to be replaced if the diesel generators fail to start, fail to run or the station yard is flooded, although the plant structures are protected against a higher design basis flood). This scenario may occur at lower hazard levels (i.e. more frequent than the design basis hazard). The analyst has to examine the potential for such scenarios before screening the hazard on the basis of frequency not exceeding the design basis event. If the loss of off-site power event frequency from all causes is assumed, for example, to be 10^{-2}/a and the non-recovery probability is 10^{-3} within the period of interest (e.g. 72 hours), then an external hazard of less than 10^{-6}/a could be screened out. The analyst also needs to assess whether the plant operating or emergency procedures can cope with an extended loss of off-site power combined with the effects of an external hazard (e.g. inundation of the site due to flooding less than that envisioned in the design).

At a multi-unit site, the design basis for different reactors may not be the same. Therefore, the conditional probability of core damage given the hazard occurrence may vary considerably among reactor units. This needs to be taken into account in screening the hazard, using the hazard frequency criterion.

Screening using bounding analysis based on CDF or LERF can be done only for single units. For a multi-unit site, the analysis needs to take into account the impact a hazard may have on multiple units, redundancy and sharing of systems between the units, and the impact that core damage in one unit will have on emergency response at other units. A bounding or demonstrably conservative analysis is used to show that either the hazard frequency is too low or that the hazard could not result in core damage in other units (or the conditional core damage probability in other units is acceptably small), otherwise a detailed multi-unit PSA needs to be performed.

For typical external hazards requiring bounding analysis, the following approach could be taken: For high wind, screening using bounding analysis based on the low hazard frequency for both single unit and multi-unit sites. For external flooding, performing a detailed PSA for other than ‘dry’ sites. For transportation accidents, screening based on low hazard frequency. Otherwise, performing a detailed PSA for single unit and multi-unit sites.

5. TREATMENT OF INDUCED HAZARDS AND COMBINATIONS OF EXTERNAL HAZARDS

5.1. COMBINATIONS OF EXTERNAL HAZARDS

The design load combinations for nuclear power plant structures have considered normal loads occurring with transient (and infrequent) loads such as earthquakes and tornadoes. Extreme environmental loads such as those caused by earthquakes and tornadoes are not considered together in any load combinations. However, there was a concern that the lower intensities of external hazards (e.g. flooding, wind, snow and earthquakes) could occur simultaneously, and their combined load effect could exceed the load effects from an individual hazard of maximum intensity. Guidelines, for selection of (1) combinations of natural hazards, (2) combinations of external artificial hazards, and (3) combinations of natural and external artificial hazards to be used in the design of power reactor SSCs, are provided in Ref. [17]. The hazards to be considered in these categories were identified. Probabilistic acceptance criteria were defined that would enable designers to select combinations of hazards as design bases for a particular site. Methods for calculating probabilities of combinations were discussed.

5.1.1. Treatment of external hazards in probabilistic safety assessment

External hazard PSA methodology [2, 5] is typically applied to individual external hazards to evaluate their contribution to risk metrics such as CDF and LERF. Parts 7–9 of Ref. [10] provide technical requirements for performing these analyses. Appendix II to this Safety Report has an example of how bounding analysis is done for an aircraft impact.

The external hazard PSA methodology may need to be enhanced to treat correlated or induced hazards by properly modelling the joint occurrence of these hazards in the event tree or fault trees. However, there are no published examples of this treatment of correlated hazards.

5.2. INDUCED HAZARDS

5.2.1. Definition of induced hazards

Induced hazards result when the occurrence of an initial hazard creates conditions that result in a second hazard soon after. An example of an induced hazard that may be encountered during the hazard screening process is high winds in combination with a forest fire. The high winds themselves can affect plant systems (such as heating, ventilation and air-conditioning, and off-site power); they may also induce a fire by scattering hot embers if the region surrounding the plant is not cleared of forest and vegetation. High winds and fire are then not independent events. An earthquake could cause a seismically induced fire by damaging tanks and piping that contain flammable material. Similarly, an earthquake could damage upstream dams and create seismically induced flooding of the plant.

Combined hazards occur when a hazard has multiple manifestations such that a secondary effect often accompanies the primary effect. An example of a combined hazard is a hurricane or typhoon, for which the primary concern is high winds. Such storms are often accompanied by very intense precipitation that can result in localized flooding. In coastal sites, storm surge can accompany the storm. Although they occur roughly synchronously, the related hazards may affect different plant structures and systems. While the high winds (and associated missiles) may affect all safety related structures, the storm surge may concern only the intake structure. A tsunami caused by an offshore earthquake may create flooding at a plant site long after the ground motion from the earthquake has ceased. The flooding could exacerbate the hazard by damaging a safety system while the earthquake loading has damaged another (redundant) system. Induced hazards and combined hazards are discussed under the heading correlated hazards.

Procedures for identifying correlated hazards have not been formalized in the nuclear industry. It is left to the PSA analyst and the peer reviewers to identify these based on the specific plant site. The PSA analyst would also assess which SSCs are affected by one or the other or both hazards and how their failures propagate into an accident sequence. The PSA literature does not have many examples of induced hazards.

5.2.2. Screening of correlated hazards

In Attributes of Full Scope Level 1 Probabilistic Safety Assessment (PSA) for Applications in Nuclear Power Plants (IAEA-TECDOC-1804) [8], the following quantitative screening criteria have been proposed. The objective is to screen these hazards from further detailed analysis in a PSA.

5.2.2.1. Based on design basis hazard event frequency

A correlated hazard can be screened out if (a) the plant has a design basis for both hazards, (b) the plant will not suffer core damage directly if all SSCs that are not designed for that hazard event fail, and (c) the frequency of the correlated design basis hazard event is less than 1% of the internal events CDF for a single reactor unit. If this hazard can affect multiple units on the site, it can be screened out if the frequency of the correlated design basis hazard event is less than 1% of SCDF.

5.2.2.2. Based on design basis hazard event core damage frequency

Correlated hazards can be screened out if (a) the plant has a design basis for both hazards; (b) the plant conditional core damage probability is calculated assuming all SSCs that are not designed for that hazard event fail; and (c) (frequency of the correlated design basis hazard events) × conditional core damage probability is less than 1% of the internal events CDF. If the correlated hazard affects multiple units at a site, it needs to not be screened out.

5.2.2.3. Based on overall hazard frequency

Correlated hazards can be screened out if either (1) a bounding or demonstrably conservative estimate of the hazard frequency (over the full range of hazard event severities) is less than 1% of the internal events CDF, or (2) a realistic estimate of the hazard frequency (over the full range of hazard event severities) is less than 0.1% of the internal events CDF.

5.2.2.4. Based on overall core damage frequency

Correlated hazards can be screened out if a bounding or demonstrably conservative estimate of CDF (over the full range of hazard event severities) is less than 1% of the internal events CDF.

5.3. LIST OF POSSIBLE INDUCED HAZARDS

As stated earlier, identification of induced hazards is left to the judgement of the PSA analyst. It also depends on the hazard and the site conditions. For example, storm surge associated with a hurricane is only significant for coastal sites. Table 3 is only indicative of the induced hazards and is by no means a complete set of such hazards.

TABLE 3. SAMPLE LIST OF PRIMARY AND INDUCED/COMBINED HAZARDS

Primary hazard	Induced/Combined hazards
Seismic (ground motion and loading on SSCs)	Tsunami Internal or external flooding Internal or external fire Landslide Fault rupture Liquefaction
Hurricane (high winds and missiles)	Local intense precipitation Storm surge
Explosion (pressure loading)	Missiles External fire Chemical release
Aircraft impact (impact loading)	Missile penetration Fire

Appendix I

SAMPLE APPLICATION OF PRELIMINARY SCREENING CRITERIA

I.1. HAZARDS SCREENED OUT

The sample plant is located in the central United States of America and has been designed using the current United States Nuclear Regulatory Commission regulatory guides and Standard Review Plan criteria. The plant is near a major river but does not depend on the river for its ultimate heat sink. Appendix 6-A in the PRA standard [10] lists most of the possible external events for a nuclear power plant site. This information was reviewed in the present study and augmented with a review of information on the site region and plant design to identify all external events to be considered. The data in the updated final safety analysis report regarding the geological, seismological, hydrological and meteorological characteristics of the site region as well as present and projected industrial activities (i.e. increases in the number of flights and construction of new industrial facilities) in the vicinity of the plant was also reviewed for this purpose.

Information on the site region and plant design was extensively reviewed to identify all external events to be considered. The data in the updated final safety analysis report as well as other data obtained from the plant personnel and the information gathered in the site visit were reviewed for this purpose. Table 2 lists external hazards for the plant based on the PRA standard [10]; the remarks for each hazard are specific to the plant. The screening criteria were applied to identify the events that need to be further examined in the PSA. For each external event, the applicable screening criteria and a brief remark are included in the table.

I.2. SAMPLE EXTERNAL HAZARDS TO BE STUDIED

In summary, the findings of the preliminary screening are that, aside from seismic, internal fire and internal flooding events that will be included in the PSA, the following hazards are identified as requiring further examination:

(a) Aircraft impact;
(b) Extreme winds and tornadoes;

(c) External flooding, including intense local precipitation;
(d) Industrial and military facility accidents;
(e) Pipeline accidents;
(f) Transportation accidents.

Appendix II

SAMPLE BOUNDING ANALYSIS

The bounding analysis or demonstrably conservative analysis is used to show that either the hazard itself is not credible or that the CDF is acceptably small. In the following, an example of aircraft impact analysis using bounding analysis is given. This section is drawn largely from Ref. [18]. For other examples, see Refs [14–16].

Aircraft hazards were evaluated at the design stage of the sample plant. The updated final safety analysis report states that there are no airports or airport approaches within 16 km (10 miles) of the site and there are no airways within 3.2 km (2 miles) of the site. For airports located at a distance greater than 16 km (10 miles) from the site, none has projected operations per year greater than 1000 d^2 movements, where d is the distance in miles from the site. Available military aerial navigation data obtained from the nearby United States army base show no low-level flight or landing patterns near the plant. Therefore, the updated final safety analysis report concluded that there are no credible aircraft hazards to the plant. In an update to the final safety analysis report, more recent data on aircraft activities around the site were collected. The following discussion on potential aircraft hazard to the plant is based on this recent data.

II.1. AIRPORTS

All airports in the plant site vicinity are located at distances greater than 16 km (10 miles). According to section 3.5.1.6 of the Standard Review Plan [13], the hazard probability for these airports is considered acceptable if the projected annual number of operations is less than 1000 d^2.

The largest commercial airport in the plant vicinity is 24 km (15 miles) from the site. The projected number of aircraft that will be in operation at this airport for different types of aircraft (general aviation, air taxi and commuter, commercial air carrier, and military) were obtained by contacting the United States Federal Aviation Administration. The projected flight data (which include landings and take-offs) shows that the total number of operations from all types of aircraft will be around 40 000 by 2030; this is substantially less than 1000 d^2 (225 000 = 1000 × 15 × 15). The other airports in the vicinity are much smaller. Since they are all at least 16 km (10 miles) from the plant, their aircraft hazard threshold is greater than 100 000 (1000 × 10 × 10) operations, which significantly exceeds their annual traffic.

II.2. AIRWAYS

Recent data show that the plant is approximately 2.1 km (1.3 miles) from the centre line of Federal Airway X. A more detailed review of aircraft hazards was performed because the plant is within the 3.8 km limit (2 statute miles). This review is summarized below.

Federal airways are mostly used by commercial flights and by general aviation for inclement weather and night-time operations. In general, military aircraft do not use the federal airways. Since there are no regularly scheduled direct commercial flights between major cities near the plant, the total number of aircraft using Airway X is likely relatively small. It is assumed that traffic data for Airway X are not available.

The following evaluation calculates the maximum number of airway flights per year above which the acceptable guideline probability of 10^{-7}/a contained in the Standard Review Plan [13] is exceeded. Regulation 14 CFR 71 provides the criteria for determining the width of the airway. It is 7.4 km (4 nautical miles) on either side of the centre line, for a total width of 14.7 km (8 nautical miles):

$$PFA = \frac{C \times N \times A}{W}$$

where

- *PFA* is the probability per year of an aircraft crashing into the plant's safety related structure, 10^{-7};
- *C* is the in-flight crash rate per mile for aircraft using the airway = 4×10^{-10};
- *N* is the number of flights per year along the airway;
- *A* is the effective area of the plant or site area in square km or square miles, see below;

and *W* is the airway width, 14.7 km (9.2 miles).

Using this equation, the maximum number of flights corresponding to the acceptable guideline probability of 10^{-7}/a may be calculated. Standard Review Plan [13] provides guidance on the acceptable method for calculating area. The effective plant area (A) depends on the length, width and height of the facility, as well as the aircraft's wingspan, skid distance and impact angle.

For traffic on Airway X, the fractions of the types of aircraft using the airway were assumed to be the same as the fractions of the types of aircraft using the airport. The US Department of Energy [19] provides representative values for wingspan, skid distance and impact angle for each aircraft type. The effective plant areas for general aviation, air taxi and commuter, commercial air carrier and military aircraft are calculated and an average area is obtained using the fractions of aircraft type as equal to 0.05 mi^2.

To reach the permissible crash probability limit of 10^{-7}/a, the total number of flights travelling along Airway X would need to be about 46 000 per year. This value is higher than the 2030 total of all projected itinerant flights at the airport. Therefore, the presence of Airway X is not a safety concern for the plant.

II.3. CONCLUSION

There are no airports within 16 km (10 miles) of the plant. The projected traffic on Airway X, which is approximately 2.1 km (1.3 miles) from the plant, does not pose a credible threat. Aircraft hazard is not a design basis hazard event for the plant, and this review, using the most recent data, confirms this conclusion. The bounding analysis satisfies the limits specified in Refs [10, 13]. Therefore, aircraft hazard could be screened out from an external event PSA for this plant.

Appendix III

DETAILED PROBABILISTIC SAFETY ASSESSMENT FOR SELECTED EXTERNAL HAZARDS

In this appendix, the PSA methodology and procedures for extreme winds and external flooding are described since these are considered significant hazards for most nuclear power plant sites. This description supplements current IAEA guidance for PSA of these hazards.

III.1. EXTREME WINDS

The major elements of the extreme wind PSA are:

- Wind hazard analysis;
- Wind fragility evaluation;
- Wind plant response analysis, including quantification.

III.1.1. Wind hazard analysis

The extreme winds to be considered are tornadoes, hurricanes (typhoons) and thunderstorms; depending on the location of the nuclear power plant, one or more of these types will affect the site. The outputs of the wind hazard analysis are hazard curves for wind speed (median, mean and fractiles or discrete family of curves).

Missiles generated by tornadoes and hurricanes have the potential to damage SSCs of nuclear power plants and should be included in results of wind hazard analysis.

III.1.2. Wind fragility evaluation

Wind fragility is defined as the conditional probability of failure of an SSC as a function of wind speed. Typically, a family of fragility curves corresponding to a particular failure mode is developed. A lognormal model is used to represent this fragility, with the parameters of the median wind speed capacity (V_m) and the logarithmic standard deviation β_R representing randomness in capacity; the uncertainty in median capacity is also modelled as a lognormal variable with unit median and the logarithmic standard deviation β_U.

Wind loading effects include the aerodynamic forces produced by the dynamic pressure component of the wind flow, the associated atmospheric pressure change within the core (for tornadoes), and impact forces produced by missiles (i.e. objects picked up and accelerated by the wind field). These wind loading effects may damage the building housing the equipment of interest or the equipment itself, if it is exposed.

The analysis of fragility for SSCs depends on the definition of failure modes and the potential interaction of individual failure modes, as discussed below.

III.1.2.1. Individual failure modes

The analysis includes an assessment of each individual failure mode that can produce failure of an SSC. These include:

(a) Wind pressure loads (including atmospheric pressure change, as appropriate);
(b) Missile loads;
(c) Structural interaction failures.

III.1.2.2. Combined wind effects in analysis of individual failure modes

Extreme winds and wind-borne debris are correlated loadings. The higher the wind speed, the greater the number and energy of the wind-borne missiles. Many missiles will impact large SSCs. Hence, a key fragility analysis consideration is to simultaneously treat wind and missile loading.

Failure modes include failure of walls, overturning, sliding and collapse as well as missile penetration and scabbing of concrete. Fragility parameters are estimated for each of the credible failure modes of the SSC. Failure of structures could be overall, such as failure of a shear wall or moment resisting frame, or local, such as out-of-plane wall failure or pull-off of metal siding. Wind pressure loading is based on the methodology contained in design standards [20]. The effect of wind-borne missiles on SSCs can be found in Ref. [21]. Fragility curves for structures are developed in terms of the factor of safety, defined as the resistance capacity divided by the response associated with the design basis loads from extreme winds [15, 22, 23]. The variability of the factor of safety depends on the variability of strength capacity and the response to specified loads. Wind capacity is modelled as a product of random variables and is expressed in terms of wind speed. Besides the strength characteristics, the capacity of a structure to withstand the effects of wind pressure also depends on a number of factors affecting the wind pressure and force relationship. For example, shielding effects of various structures at the site result in increased wind speed through a constricted space or decreased speed where wind may be slowed down by obstructions. Such funnelling characteristics describing the channelling of winds around structures have a very important influence on wind forces. The actual forces are also determined by the structural shapes because wind pressure and forces are related to wind velocity by a shape factor. Another important factor is the vertical distribution of wind velocity, which is a function of terrain roughness. Examples of the development of wind fragilities for structures can be found in Refs [22, 24].

Most nuclear power plant structures have substantial wind resistance if the original design basis included extreme wind loading. Major vulnerabilities have sometimes been identified for non-seismic category structures due to their potential for collapsing on safety related structures or equipment. These structures include exhaust stacks, unprotected walls, outside wiring and cabling. Similarly, many older plants have safety related equipment such as tanks, and equipment located outdoors that is vulnerable to wind-borne missiles. These need to be identified during the walkdown.

In analysing the failure of indoor equipment, it may be conservatively assumed that the failure of a structure causes the failure of all equipment dependent on or within the structure. The structure may not collapse, but the indoor equipment may still be damaged by the pressure drop resulting from a tornado. This damage occurs because of inadequate venting in the structure. The rapid pressure drop results in air escaping from the building; if the exit is not rapid enough, it causes internal pressure. This pressure might lead to failure of block walls, which could collapse onto safety related structures. Indoor equipment is also susceptible to damage from missiles entering through louvres, vents, etc. Damage to internal SSCs may also be caused by wind induced pressurization through openings in the structure.

The systems analyst and the fragility analyst need to work together to develop a list of SSCs to be included in the wind PSA. These could be electrical equipment, mechanical equipment or piping that are housed within the buildings, and outdoor equipment such as tanks.

Wind fragility depends on the original design basis of the nuclear plant. In some countries, the wind design includes tornadoes or hurricanes (typhoons), or both. The structures in these nuclear power plants need to have large median wind speed capacities. In addition, concrete structures designed to resist seismic loading will have inherent resistance to wind loading. The analyst has to take advantage of this in screening out buildings and the SSCs they support. For the remaining buildings and outdoor SSCs, plant specific wind fragilities are developed.

III.1.3. Wind plant response analysis

The wind PSA systems model includes wind caused initiating events and other failures that can lead to core damage or large early release. Typically, the wind PSA systems model is adapted from the internal events PSA systems model by incorporating the wind analysis aspects that are different from the corresponding aspects in the internal events PSA systems model. Further, the analysis consists of developing event trees and fault trees in which the initiating event can be either the extreme wind effect itself or a transient induced by extreme winds. Various accident sequences that lead to core damage (Level 1 PSA) or releases (Level 2 PSA) are identified, and their conditional probabilities of occurrence are calculated. The frequency of core damage or release is obtained by a convolution over the relevant range of wind speeds. Factors to be considered in this analysis include specific wind fragilities of SSCs and non-wind-related unavailability or failure of equipment, operator error, any warning time available to take mitigating steps (e.g. in the case of hurricanes), the possibility of recovery actions by operators and replacements by substitutes to accomplish the needed function, and the likelihood of common cause failures. Since the wind hazard and wind fragilities are input as families of curves representing the uncertainties, the quantification has to properly propagate the uncertainties through the accident sequences to result in uncertainty bounds on CDF and release frequencies such as LERF. Examples of systems analysis for extreme winds can be found in Refs [14, 15, 23].

It is important to capture the dependencies among extreme wind caused failures (e.g. spatial and environmental dependencies). This is true for a single SSC but extreme wind could affect multiple SSCs at the same time. Another important consideration is that at higher wind speeds the fragility of SSCs may be substantial, making the probability of 'success' much less than one; therefore, excluding these success states could lead to erroneous PSA results.

III.1.4. Wind PSA for multi-unit sites

The following paragraphs present some important aspects related to the multi-unit wind PSA. More details regarding the multi-unit external hazards PSA are included in Ref. [6]. The overall wind PSA methodology described above could be modified for multi-unit sites.

Wind hazard is generally applicable to the plant site. Typically, the winds arising from straight winds (thunderstorms and extratropical cyclones) and hurricanes cover a large region, and all buildings and outdoor equipment of a multi-unit site experience the same wind loading. The same could be said about the larger tornadoes of interest to the PSA.

The wind pressure fragilities of SSCs at multi-unit sites are also derived from the wind loading experienced by the SSCs. As such, identical SSCs of multi-units at the site have the same fragilities. The current state of the art procedure for tornado and hurricane missile damage fragility evaluation is to perform a simulation, tracking the potential objects that could become missiles for different tornadoes and hurricanes passing through the site. This procedure is suitable for tracking the simultaneous missile hits or damage to SSCs for multiple units identified by the PSA systems analyst. Currently, no published studies are available to develop approximate conditional probabilities of a second target being hit or damaged (by one or more separate missiles), given the missile hit on the first target. This is a function of the distance between the targets and the structural barrier enclosing the targets.

As a best practice, the development of a multi-unit PSA model for an internal event fully accounting for the shared systems and components between the units would be a prerequisite for a multi-unit wind PSA. The PSA system analyst will make suitable modifications to this multi-unit PSA model for the wind hazard.

Certain initiating events, depending on the plant design, could affect multiple units; an example could be loss of off-site power, since the switchyard is generally shared between the units. Other examples are loss of service water and loss of instrument air. In one pressurized water reactor plant, the condensate storage tanks are cross-tied and shared between two units. The levels are maintained to accommodate an accident on one unit and hot shutdown on the other unit. However, the condensate storage tanks will not last the mission time, and service water is required to meet the mission time for auxiliary feedwater. The analyst needs to properly model the initiating events, shared SSCs, and the availability of different SSCs under multi-unit initiating events. The accident sequence analysis and quantification will proceed using the same methodology as for a single reactor unit.

Modelling of human reliability and operator recovery actions for multi-unit accidents requires additional considerations of the duration of the wind hazard, the damaged state of SSCs in different units, access to certain areas requiring operator action and the availability of an emergency response such as firefighting. The analyst needs to examine various what-if scenarios and assign subjective probabilities [23] to carry out the quantification.

III.1.5. Outputs and uses

Wind PSA (Level 1 and Level 2) for single reactor units provides estimates of CDF and RF along with the significant risk contributors. The uncertainty bounds on this CDF and RF are also developed. These outputs need to be considered in any upgrading decisions if the absolute values of CDF and RF from wind induced events exceed the acceptable limits.

Wind PSA for multi-unit sites provides estimates of SCDF and SLERF along with the significant risk contributors. The uncertainty bounds on the SCDF are also developed. These outputs need to be considered in any upgrading decisions if the absolute values of SCDF and SLERF from wind induced events exceed the acceptable limits.

III.2. EXTERNAL FLOODING

The major elements of the external flooding PSA are:

— External flood hazard analysis;
— External flood fragility analysis;
— External flood plant response analysis, including quantification.

III.2.1. External flood hazard analysis

The external flood hazard analysis involves the evaluation of the frequency of occurrence of different external flood severities based on a site specific probabilistic model reflecting recent available data and site specific information. This analysis needs to take into account all the flooding mechanisms, such as river flooding, coastal flooding due to storm surges, seiches, waves, tsunamis, tides, extreme precipitation, and the sudden release of water from natural or artificial storage (such as dams). Depending on the location of the nuclear power plant, one or more of these types of flooding may affect the site. The outputs of the flood hazard analysis are hazard curves for flood level (median, mean and fractiles or discrete family of curves).

III.2.2. External flood fragility analysis

The objective of the external flood fragility analysis is to identify those SSCs that are exposed to the effects of external floods and to determine their plant specific failure probabilities as a function of the severity of an external flood. The analyst may choose the flood height as a global parameter for describing the severity; all other characteristics of flooding (e.g. dynamic loading and debris) need to be considered in the fragility analysis.

There are no examples of formal probabilistic flood fragility analysis of nuclear power plant SSCs. However, the methodology described below is similar to that used to assess other external hazards (e.g. seismic and wind).

With applications, it could be improved and made more specific to an external flooding situation. Recently, the US Nuclear Regulatory Commission issued an Interim Staff Guidance for performing the integrated assessment for external flooding [25]; it discusses the margin assessment for a chosen set of flood scenarios.

The PRA standard [10] has the following supporting requirement:

> "In the evaluation of flood fragilities of structures and exposed equipment (equipment located at low elevations, intake and ultimate-heat-sink equipment, etc.), USE plant-specific data. In this evaluation, INCLUDE the findings of a plant walkdown. It is acceptable in the fragility analysis for both capacity and demand to apply the standard methodology used for seismic events, with appropriate modifications unique to the flooding event being studied."

The scope of fragility analysis is based on the flood hazard type and magnitude and how the plant (including operators) will respond to a flood. As a first approximation, the systems analyst may group the SSCs of interest to the external flooding PSA into those that are enclosed in buildings and those that are outdoors in the yard. The fragility analyst may then screen some of the buildings based on their elevation with respect to the maximum flood level and their capacity to withstand the flood (depending on the design criteria). External barriers that are considered in this screening include building walls and roofs, flood doors, flood walls and berms.

For the remaining buildings and outdoor SSCs, including any flood barriers, flood fragilities are developed using the structural mechanics methods (i.e. safety factors available in the capacity and demand for a given flood type and flood height). The loads to be considered are hydrostatic, hydrodynamic and debris (missile impact and clogging).

Flood caused failure of equipment is typically due to immersion, although in some instances, particularly applicable to structures, the failure may be due to flow induced phenomena. The analyst needs to account for the ability to survive and to function for each equipment item susceptible to flooding. Usually, it is assumed that equipment submerged by flood waters and not specially protected will fail to perform its safety function. The analysis needs to include length of warning time, since plant personnel may be able to secure equipment in a safe configuration. Further, the analysis has to include whether the failure of that equipment would leave it in a fail-safe position. Also, flood waters may only partially submerge an item, so the analysis has to determine how much partial submersion would be sufficient to cause the equipment to fail.

Failure of structures could be overall, such as in the case of foundation failure, or local, such as failure of a wall or barrier, leading to leakage or major flooding through it. Most nuclear power plant structures are designed to have inherent resistance to flooding. If vulnerabilities are identified for certain structures, the analyst needs to assess whether the equipment housed therein is crucial to overall plant safety. The walkdown plays a major role in identifying potential problems, supplemented by an evaluation of structural drawings. Failure modes to be evaluated for structures include the following:

— Penetration or leak;
— Wall integrity;
— Stability (sliding, overturning, scouring and flotation).

If the flood reaches a piece of equipment (especially electrical equipment), the analyst may judge this to result in failure. Once the flood enters a room, the propagation of the flood to adjacent rooms can be assessed using the internal flooding PSA model, taking into account flood barriers, floor drains, doors and openings.

III.2.3. External flood plant response analysis

The objectives of external flood plant response analysis are to:

(a) Develop an external flood plant response model by modifying the internal events PSA model to include the effects of an external flood in terms of initiating events and the failures caused;
(b) Quantify this model to provide the conditional core damage probability and conditional large early release probability for each defined external flood plant damage state;
(c) Evaluate the unconditional CDF and RF by integrating the conditional core damage probability/conditional large early release probability with the frequencies of the plant damage states obtained by combining the results of external flood hazard analysis and external flood fragility analysis.

Potential operator actions and mitigating measures to be considered are:

— Temporary barriers (time to construct and effectiveness, etc.).
— Closing of flood doors and hatches: are there procedures?
— Draining of the room using pumps (failure rate, human errors, etc.).
— Personnel access to safety equipment or controls (focus of the walkdowns).
— Reduced likelihood of system recoveries after an external flood event.

It is vital that the analysis capture the important dependencies among external flood caused failures (e.g. spatial or environmental dependencies), since the external flood could affect multiple SSCs at the same time.

Additional stresses in an external flood event can increase the likelihood of human error or inattention compared with the likelihood assigned in the internal events human reliability analysis. Similarly, the restoration of safety functions can be inhibited by any of several types of causes; these include damage or failure, access problems, confusion, loss of support staff to other post-external flood recovery functions and so on. Careful consideration needs to be given to these inhibiting causes before recoveries are credited in the initial period, after the external flood event. This is especially true for externally caused loss of off-site power, given that switchyard components or off-site grid towers, which are generally difficult to fix quickly, could be damaged.

The external flooding PSA systems analysis model is typically based on the internal events PSA systems model, to which are added basic failure events derived from the information developed in the flooding fragility analysis. The analysis consists of developing event trees and fault trees in which the initiating event can be either the extreme flood itself or a transient induced by the extreme flood. The event tree and fault tree modelling is done to represent both the flood protection and mitigation aspects of the external flooding. The event tree will first ask whether the flood protection system survives the flood. The flood protection system could be flood walls, which may be breached or overtopped in an extreme flood event. In the evaluation of mitigation capability, event trees and fault trees need to model the different available structural barriers enclosing the SSCs of interest, and the operator actions, such as erecting temporary barriers, following the emergency operating procedures and after water from flooded areas is pumped out. The duration of a flood is an important consideration in determining the probability of operator actions. Various accident sequences that lead to core damage or large early release are identified, and their conditional probabilities of occurrence are calculated. The frequency of core damage or large early release is obtained by a convolution over the relevant range of hazard intensities.

The procedure for determining the accident sequences is similar to that used in seismic PSA systems analysis after it is adapted to apply to the external flooding PSA situation. Other factors to be considered, besides the above mentioned flooding related failures and human errors, include non-flooding related unavailability or failure of equipment, any warning time available to take mitigating steps, the possibility of recovery actions by operators and replacement by substitutes to accomplish the needed function and the likelihood of common cause failures. The clogging of intake structures and other flow paths by debris related to the flooding also needs to be considered; a walkdown is important to ensure that this issue has been evaluated properly.

One key consideration is that most large external floods may occur with significant warning time, which allows the plant operating personnel to take appropriate steps to secure the plant and its key equipment. This warning time and the fact that the plant grade is typically well above any credible flooding phenomena are the principal reasons why external flooding risks are not often found to be important contributors to overall risks. The analysis team may assess as much credit for warning time and compensatory actions as the plant's planning and procedures allow.

III.2.4. Multi-unit PSA for external flooding

The following paragraphs present some important aspects related to the multi-unit external flooding PSA. More details regarding the multi-unit external hazard PSA are included in Ref. [6]. The overall flood PSA methodology described above could be modified for multi-unit sites.

Flood hazard analysis is generally applicable to a plant site since flooding is a site hazard and affects all units at the site to some extent.

The flooding fragilities of SSCs at multi-unit sites are also derived from the flooding effects experienced by the SSCs. As such, identical SSCs of multiple units at the site have the same fragilities. However, the flood height and other effects depend on the separation (both horizontally and vertically) between the units.

As a best practice, the development of a multi-unit PSA model for internal events that fully accounts for the shared systems and components between the units would be a prerequisite for a multi-unit external hazard PSA. The PSA system analyst will make suitable modifications to this multi-unit PSA model for any flooding hazard.

Certain initiating events, depending on a plant's design, could affect multiple units; an example could be loss of off-site power since the switchyard is generally shared between units. Other examples include loss of service water and instrument air. The analyst needs to properly model the initiating events, shared SSCs and the availability of different SSCs under multi-unit initiating events.

The accident sequence analysis and quantification will proceed using the same methodology as for a single reactor unit.

Modelling of human reliability and operator recovery actions for multi-unit accidents requires additional consideration of the duration of the flood hazard, the damaged state of SSCs in different units, access to certain areas requiring operator action and the availability of an emergency response such as firefighting. The analyst needs to examine various what-if scenarios and assign subjective probabilities to carry out the quantification.

III.2.5. Outputs and uses

These are similar to those discussed in Section III.1.5 for extreme winds.

External flooding PSA (Level 1 and Level 2) for single reactor units provides estimates of CDF and RF along with the significant risk contributors. The uncertainty bounds on this CDF and RF are also provided. These have to assist the plant owner or regulator in making any upgrading decisions if the absolute values of CDF and RF from external flood induced events exceed the acceptable limits.

Flood PSA for multi-unit sites provides estimates of SCDF and SLERF along with the significant risk contributors. The uncertainty bounds on the SCDF are also developed. These outputs need to be considered in any upgrading decisions if the absolute values of SCDF and SLERF from flood induced events exceed the acceptable limits.

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Annex

PRACTICES IN MEMBER STATES: EXAMPLES

A–1. CANADA

The Canadian Nuclear Safety Commission introduced in 2005 regulatory standard S-294: Probabilistic Safety Assessment (PSA) for Nuclear Power Plants [A–1] requiring a Level 2 PSA that includes both internal and external events at both power and shutdown states. A footnote, regarding external events, allows the licensees, with the agreement of persons authorized by the commission, to choose an alternative analysis method to conduct the assessment. In such cases, the external event may be screened out from the PSA.

A–1.1. Procedure of external event PSA

As a general practice in Canada, deuterium uranium PSA, seismic events, internal fires and internal floods are assessed through a detailed PSA. For other internal and external hazards, a methodology that describes the screening analysis needs to be submitted to the Canadian Nuclear Safety Commission for acceptance. International references and good practices are the basis for developing such a methodology.

A graded approach is followed in developing an external hazard at power PSA.

A plant's capability with respect to external hazards is initially evaluated using plant specific information and walkdowns. This evaluation is used to develop an analysis plan for the next phase.

Regarding a potential multi-unit impact, external hazard induced failures or independent failures affecting common systems (e.g. emergency power generators) are considered as though they affect all units.

The concept of review level conditions is adopted for natural external hazards where appropriate, analogous to the 'review level earthquake' seismic margin assessment.

A–1.2. Identification of hazards

Canadian nuclear stations follow a systematic approach to identify the complete list of external hazards that might occur during the life of a plant. The process of identifying external hazards is as follows:

— Developing an initial list through consideration of generic lists such as annex I of IAEA SSG-3 [A–2] and appendix 6–A of the PRA standard [A–3];
— Completing the initial list for each site specific external hazard, such as freezing rain or snow pack;
— Including all potential combinations of external hazards, classified as coincidental, correlated and/or consequential events;
— Considering external hazards and the potential combinations that may affect the plant, and subjecting them to screening analysis, bounding assessment, or detailed analysis, as appropriate.

A–1.3. Screening of identified hazards

A set of defined screening criteria are developed based on industry standard and best practices.

The screening criteria adopted by the licensees and accepted by the Canadian Nuclear Safety Commission are consistent with international best practice [A–2] and [A–3]. The screening criteria include both qualitative and quantitative criteria.

Qualitative screening criteria [Phase 1] include screening on the basis of:

— Distance (from the plant);
— Slow development (warning time);
— Bounding (hazard is included within the definition of another hazard);
— Low frequency;
— Impact.

Quantitative screening criteria [Phase 2] are used if it can be shown (using a demonstrably conservative analysis) that the core damage frequency (CDF) is $<10^{-6}$/a. Each external hazard is reviewed against the screening criteria. Hazards that are screened out are dropped from further consideration and need not be evaluated beyond the screening step. For those hazards that are not screened out, bounding or conservative analyses (i.e. analyses that use assumptions intended to ensure that the assessed outcome will be conservative, relative to the expected outcome) are performed to determine the risk of these hazards. A second quantitative screening is then performed to eliminate very low risk hazards from further consideration. The risk from any remaining hazard is evaluated in the next phase.

The analysis’s conclusion will reveal:

— The list of all hazards considered for evaluation;

— The hazards that are screened out from further consideration through the qualitative and quantitative screening criteria;
— A bounding conservative estimate of risk for the remaining hazards;
— The external hazards that require a more detailed analysis.

A–1.4. Climate change

There is a potential for screened out hazards to become more significant during the plant life due to climate change. Therefore, it is recommended that external hazards be revisited. Screening criteria for the PSA are updated every five years. This update is sufficiently frequent that global warming is excluded from PSA analysis. Examples of external hazards that might be modified due to climate change include:

— Water surface variation;
— Meteorological factors such as temperature, wind, humidity and lightning.

A–1.5. Current status and brief descriptions of high wind and external flood evaluation

A–1.5.1. High wind PSA evaluation

Ontario, Canada's deuterium uranium plants are characterized by multi-unit siting (e.g. shared powerhouse and shared containment envelope). For a high wind evaluation, a detailed PSA is used. The PSA analysis addresses the impact of high winds on one reactor unit or, in the shared portions of the plant, on one or more of the other units.

The nature of the high wind hazard is such that, while the damage path may directly compromise only external structures, systems and components (SSCs) and/or building infrastructure, wind generated missiles may also impact SSCs located within buildings.

The initial assessment will be characterized by the use of several bounding, conservative assumptions aimed at identifying the areas of the plant most vulnerable to high winds. If subsequent analysis shows that this approach is overly conservative, then refinements will be made to these assumptions to move closer to the actual (expected) building or SSC response to the hazard.

In order to quantify the risk of high wind events for Pickering A and B stations, a hazard curve presented in terms of occurrence per year versus wind speed is developed based on site specific and region specific data. Various high wind initiating events are identified, corresponding to each of the F-scale wind categories.

A high wind plant logic model is developed for each high wind initiating event, using the technique of event tree analysis.

A list of high wind targets (i.e. SSCs whose failure may lead to an accident sequence), including safety related SSCs, is developed from the high wind event tree logic. A walkdown is conducted to visually examine and record the as-is condition of the items in the high wind target list. A missile survey is also conducted as part of the walkdown, to identify potential high wind missiles that can damage items in the high wind target list.

Following the walkdown, equipment or structures considered to be vulnerable to high wind induced failure are assessed by fragility analysis to estimate the straight wind speed that they can be expected to withstand. The median wind capacities of these targets are used as input to obtain the straight wind fragility curves. Additionally, missile survey data are modelled in TORMIS (TORnado MISsile Risk Analysis Methodology Computer Code) [A–4] to obtain the missile fragility curves for all items identified on the target list.

The outcomes of the straight wind fragility analysis and missile fragility analysis are entered into a fault tree model developed based on the high wind event tree logic. A single top high level severe core damage high wind model is developed which is then merged with the existing internal events PSA model.

The merged fault tree is solved to generate cut sets representing the various accident sequences that could lead to severe core damage following each high wind initiating event. From this, a CDF for the reference accident unit is estimated.

At the conclusion of the analysis, the following results will be available:

— Areas of the plant with particular vulnerability to high wind hazards;
— High wind hazards that potentially have the greatest contribution to risk;
— A bounding estimate calculation of CDF for the representative unit resulting from high wind hazards, with a characterization of how the design and layout differences of the other units may impact risk;
— Uncertainty, sensitivity and importance analysis consistent with the internal events PRA standard.

A–1.5.2. External flood evaluation

The flood evaluation uses a bounding analysis and follows the guidance of IAEA Safety Standards Series No. SSG-18, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations [A–5] and NUREG/CR-7046, Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants [A–6] in the United States of America.

The analysis of external flooding starts with the identification of all flooding mechanisms:

- Flooding due to runoff, characterized by the probable maximum precipitation;
- Flooding due to river;
- Flooding due to waves;
- Flooding due to seiche;
- Flooding due to tsunami;
- Flooding due to sudden releases of water from natural or artificial storage;
- Flooding due to ice jamming.

For Ontario's multi-unit sites, Hurricane Hazel Intensity–Duration–Frequency data and probable maximum precipitation from the Ontario Lakes and Rivers Improvement Act are used as input.

Flooding hazards analysed include heavy precipitation, waves and combination of floods with other hazards such as high wind. A plant walkdown is also performed to identify critical buildings that support emergency (ultimate) heat sink and to identify building openings with less margin compared with plant grade level. The maximum flood height is dominated by precipitation.

As an outcome of the external hazard evaluation, some flood protection barriers have been installed to protect key equipment, and a dedicated procedure to respond to severe weather conditions has been developed by utilities.

Due to the geographical location of the single Canadian deuterium uranium unit in New Brunswick province, the plant grade (14 m) has been selected with sufficient margin in comparison with the extreme high tide level (4.25 m).

The original siting assessment was evaluated by Probable Maximum Surge Flooding based on:

- Probable maximum winds and associated meteorological parameters (hurricanes);
- Tide levels and surge history;
- Surge sources;
- Wave action, wave refraction, wave run up;
- Tsunami flooding.

Flood sources considered included excessive rainfall, storm surge and tsunami. The assessment considered various tsunami related sources:

- Far-field earthquakes;
- Continental slope landslides;

— Coastal landslides;
— Near-field crustal earthquakes.

A combination of extreme high tide with a category four hurricane [Charley, 2004, Florida] was evaluated.

As an outcome of the external hazard evaluation, some flood protection barriers were installed for the access area to the secondary control room.

A–2. FINLAND

A–2.1. Procedure of external event PSA

PSA for nuclear power plants has been mandatory in Finland since the late 1980s. Seismic events, harsh weather conditions, external flooding and other off-site external events were included in the PSA models of the operating units in the 1990s, and several updates and extensions have been carried out since then. For new units, a preliminary full scope PSA, including external events, is required for obtaining a construction licence and is refined during construction. The up-to-date full scope PSA, Level 1 and 2, including all plant operating states from power to outages, is submitted as a part of the periodic safety review documents.

The Finnish environmental conditions for external hazards can be described as moderate. The seismic activity is low and there have been neither recorded destructive earthquakes nor extensive destruction because of other natural events. However, even moderate external events may result in significant risks if they are not properly considered in the design. For example, the northern climate poses some challenges in the design of nuclear power plants, which may require some adaptation of the original plant design to the local conditions. The blockage of seawater intakes by frazil ice (fast freezing of subcooled water) and the blockage of diesel generator combustion or cooling air intakes by snow are also examples of external events typical for the northern climate.

The original design basis of the operating units for external events was in some respects inadequate according to the current standards. For example, there were no seismic design requirements for nuclear power plants when the currently operating units were built in the late 1970s and early 1980s, and plant protection against extreme weather conditions was mainly based on the requirements in the national building codes. Therefore, external event PSAs have played an important role in evaluating the safety of the units and in making decisions on safety improvements. External events have been considered extensively for new units, beginning with the early design phase. As the new nuclear power plants have high redundancy of safety systems, the risk is largely determined by preparedness for external events and common cause failures.

The external event PSAs of the Finnish units follow the same general procedure with some plant and licensee specific variations: the identification of potential events, hazard evaluation, screening of events, plant modelling and risk quantification. The external events are integrated in the same PSA model with internal events and area events. Seismic PSAs have been performed following the requirements of the Finnish Nuclear Regulatory Authority and observing the IAEA and US standards for existing and new reactors in Finland.

A–2.2. PSA for other external hazards

A–2.2.1. Identification of hazards

A list of potentially significant external events has been compiled by analysing weather phenomena and human induced hazards in the vicinity of the plant. Operating experience from their own and foreign plants, lists of external hazards included in IAEA siting guides, WASH-1400 and other international publications have also been taken into consideration. Brainstorming sessions have been organized at the plants to identify external events with potential effects on the plant. Special attention has been paid to the identification of combined events consisting of two or more correlated events which cannot be treated as independent events in PSA, for example, high seawater and high wind.

A–2.2.2. Screening of identified hazards

The screening criteria vary in different external event PSAs. For example, in Olkiluoto 1 and 2, external event PSA events are screened out of further analysis according to the following criteria in Ref. [A–7]:

- The phenomenon will not exceed the plant design basis.
- If dangerous intensity of a phenomenon can be foreseen at least eight hours beforehand, only cold shut down of the reactor is considered.
- Intensity with effects on the plant is extremely improbable, cut-off frequency is 10^{-8}/a (event frequency or preliminary CDF estimate).
- The event is included in another part of the PSA.
- An event is included in a combined event if it causes risk increase in connection with some other event.
- An event is not analysed in detail if there are ongoing plant modifications to remove the risk.

Screening criteria have been developed since the early 1990s. The screening criteria described in the publication by Knochenhauer and Louko [A–8] are based on the practices in the Finnish and Swedish external event PSAs.

A–2.2.3. Current status and brief description of high wind PSA and external flood PSA

The Finnish nuclear power plant units are situated on the coast of the Baltic Sea. The Baltic Sea is a semi-enclosed basin with practically no tidal effects and fairly small variations in water level. The variations in water level are determined by wind, air pressure, seiche and the total amount of water in the Baltic Sea, which depends on the long term weather conditions in the North Sea and water flow though the Danish Straits. Extreme value distributions for high seawater level have been derived based on local observations with about a 100 year time series. These distributions are used in external event PSAs and in the evaluation of the design basis, although the uncertainties at long return periods are great.

The critical flooding levels for the nuclear power plant units have been determined by the licensees. If the water level exceeds the doorstep level of the operating units, the flooding of the basement is possible. As the critical components of safety systems and power supply are situated in the basements or on the ground level, flooding could lead to core damage with high conditional probability.

For the Olkiluoto units, the external flooding risk is assessed to be very low, and external flooding is screened out of the external event PSA. In Loviisa, the risk of flooding is much higher due to the lower elevation of the units and to the higher variations in seawater level. The CDF due to flooding is about 1.6% of the total CDF of about 2.5×10^{-5}/a; however, the uncertainty is great.

The sites have flat topography. The risk of external flooding due to exceptional rainfall is very low. As there are no rivers or other water courses in the vicinity of the sites, there is no risk of external flooding due to dam failure. Hurricane sized storms have not occurred in Finland or in the neighbouring regions and strong tornadoes are very rare. High wind could directly cause the loss of off-site power but this results only in a minor contribution to the loss of off-site power frequency used in the internal events PSA. However, high wind in combination with other correlated phenomena is a more significant risk factor. High wind is one cause for high sea water. It can also result in large amounts of algae or other impurities in sea water jeopardizing the ultimate heat sink. The boiling water reactor units Olkiluoto 1 and 2 are particularly sensitive to the total loss of AC power and of ultimate heat sink. As the emergency diesel generators are cooled by sea water, the simultaneous loss of off-site power and blockage of seawater cooling are significant risk factors. For Olkiluoto 1 and 2 the contribution of external events is about 10% of the total CDF 1.2×10^{-5}/a.

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ABBREVIATIONS

ANS	American Nuclear Society
ASME	American Society of Mechanical Engineers
CDF	core damage frequency (per reactor year)
LERF	large early release frequency
PRA	probabilistic risk assessment
PSA	probabilistic safety assessment
RF	release frequency
RG	regulatory guide
SCDF	site core damage frequency
SLERF	site large early release frequency
SSC	structure, system and component

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