

## External Events PSA for the Paks NPP

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**Abstract:** Initially, probabilistic safety assessment of external events was limited to the analysis of earthquakes for the Paks Nuclear Power Plant in Hungary. The level 1 seismic PSA was completed in 2002 showing a significant contribution of seismic failures to core damage risk. Although other external events of natural origin had previously been screened out from detailed plant PSA mostly on the basis of event frequencies, a review of recent experience on extreme weather phenomena made during the periodic safety review of the plant led to the initiation of PSA for external events other than earthquakes in 2009. In the meantime, the accident of the Fukushima Dai-ichi Nuclear Power Plant confirmed further the importance of such an analysis. The external event PSA for the Paks plant followed the commonly known steps: selection and screening of external hazards, hazard assessment for screened-in external events, analysis of plant response and fragility, PSA model development, and risk quantification and interpretation of results. As a result of event selection and screening the following weather related external hazards were subject to detailed analysis: extreme wind, extreme rainfall (precipitation), extreme snow, extremely high and extremely low temperatures, lightning, frost and ice formation. The analysis proved to be a significant challenge due to scarcity of data, lack of knowledge, as well as limitations of existing PSA methodologies. This paper presents an overview of the external events PSA performed for the Paks NPP. Important methodological aspects are summarised. Key analysis findings and unresolved issues that need further elaboration are highlighted.

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**Keywords:** PSA, External Events, Extreme Weather Conditions, Wind, Snow, Hazard Assessment, Fragility Analysis

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### 1. BACKGROUND

The Hungarian Nuclear Safety Codes [1] list the most important internal and external hazards which shall be taken into consideration during the justification of the design and safety. In particular, the Codes highlight that severe weather conditions and seismic events shall be addressed in the PSA. Initially, probabilistic safety assessment of external events was limited to the analysis of earthquakes for the Paks Nuclear Power Plant in Hungary. The level 1 seismic PSA was completed in 2002 showing a significant contribution of seismic failures to core damage risk. Although other external events of natural origin had previously been screened out from detailed plant PSA mostly on the basis of event frequencies, a review of recent experience on extreme weather phenomena made during the periodic safety review of the plant led to the initiation of PSA for external events other than earthquakes in 2009. Hungarian nuclear safety regulations prescribe that the design basis for loads from natural external hazards shall be set at  $10^{-4}$  /a hazard frequency. According to the regulations, the risk from natural external hazards beyond the design basis shall be assessed at least in the range of  $10^{-7}$  ÷  $10^{-4}$  /a hazard frequency. Therefore probabilistic safety assessment of external hazards has to be performed unless it can be shown that the design basis of the plant ensures that the plant can withstand the loads induced by a hazard with  $10^{-7}$  /a frequency. In addition to these requirements, the accident of the Fukushima Dai-ichi Nuclear Power Plant and the Targeted Safety Reassessment of the nuclear power plants located in the European Union confirmed further the importance of risk analysis for external hazards.

### 2. OBJECTIVES

In compliance with the abovementioned regulatory requirements, external events PSA for the Paks NPP has been performed. Among others, the objectives of the assessment were to quantify to the extent possible the level of risk induced by natural external hazards and to identify the main risk contributors. It was foreseeable from the beginning of the assessment that all the risk contributors from the various hazards could not be determined and quantified adequately on the basis of the available background analyses. Therefore a main further objective was to identify analysis areas that would need to be further dealt with in order to develop a full scope external event PSA, as well as to reduce uncertainties and conservatism where necessary.

Consolidated proposals on safety enhancement can only be made after resolving these analysis issues, although an objective was to identify apparently important safety concerns this assessment phase.

As to the scope of the analysis, potential hazard induced accidents in full power as well as low power and shutdown states had to be dealt with. Concerning low power and shutdown states, the plant operational states of a typical refuelling outage were looked at.

### 3. MAJOR ANALYSIS STEPS

The analysis proved to be a significant challenge due to scarcity of data, lack of knowledge, as well as limitations of existing PSA methodologies. Hereby important methodological aspects are summarized by giving an overview of every major analysis step.

The external event PSA for the Paks plant followed the commonly known steps: selection and screening of external hazards, hazard assessment for screened-in external events, analysis of plant response and fragility, PSA model development, and risk quantification and interpretation of results.

#### 3.1. Selection and Screening of External Hazards

During the first step of identifying external hazards that required detailed analysis, we made an attempt to develop a comprehensive list of potential site specific external hazards. At first we performed a review of regulatory requirements nationally and internationally. Relevant requirements of the Hungarian Nuclear Safety Codes [1] and WENRA reference levels [2] enabled to determine the vast majority of potential external hazards. In addition, use was made of the following documents to identify the initial list of potential external hazards:

- the stand-alone volume of the joint ANS-ASME PRA standard that sets forth probabilistic safety assessment methodology for external hazards [3], [4],
- a guidance document of the Swedish nuclear safety authority that builds upon the Finnish and Swedish external hazard assessment experience [5],
- the Specific Safety Guide of the International Atomic Energy Agency on level 1 PSA [6].

We applied a successive approach with combined deterministic and partially probabilistic screening of all the potential external hazards to identify the risk significant ones that needed detailed analysis to quantify the plant risk. During this screening it was found that available hazard analyses did not enable to decide if tornados and blockage of the water intake filters could be screened out or not. Additional hazard assessment has been proposed to clarify these questions.

After screening the following natural external hazards were subject to detailed analysis:

- extreme wind,
- extreme rainfall,
- extreme snow,
- extremely high and low air temperature,
- lightning,
- extreme frost and ice formation.

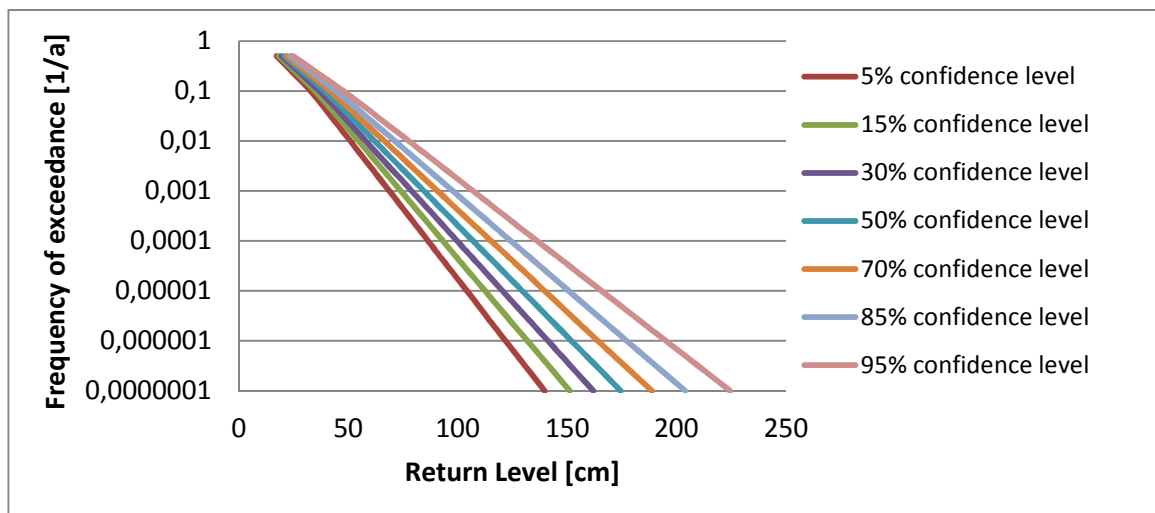
#### 3.2. Hazard Assessment

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

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

The main difficulty in determining the occurrence frequency of extreme weather conditions is the lack of observations for those events whose probability should be estimated, since data samples from experience are available for short durations only. The results include significant uncertainties irrespectively of the computational method applied. In accordance with the international practice of climatological applications, we made use of extreme value theory to characterize and quantify each external hazard. Hazard curves were established by fitting Gumbel distribution on the annual extreme values of the most up to date site specific meteorological data. Hypothesis testing was conducted to justify that the Gumbel distribution was an appropriate approximation of the hazard curves. It is noted that lightning as an external hazard required a different analysis approach because several physical properties of lightning had to be assessed in order to be able to characterise the vulnerability of plant structures and equipment.

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

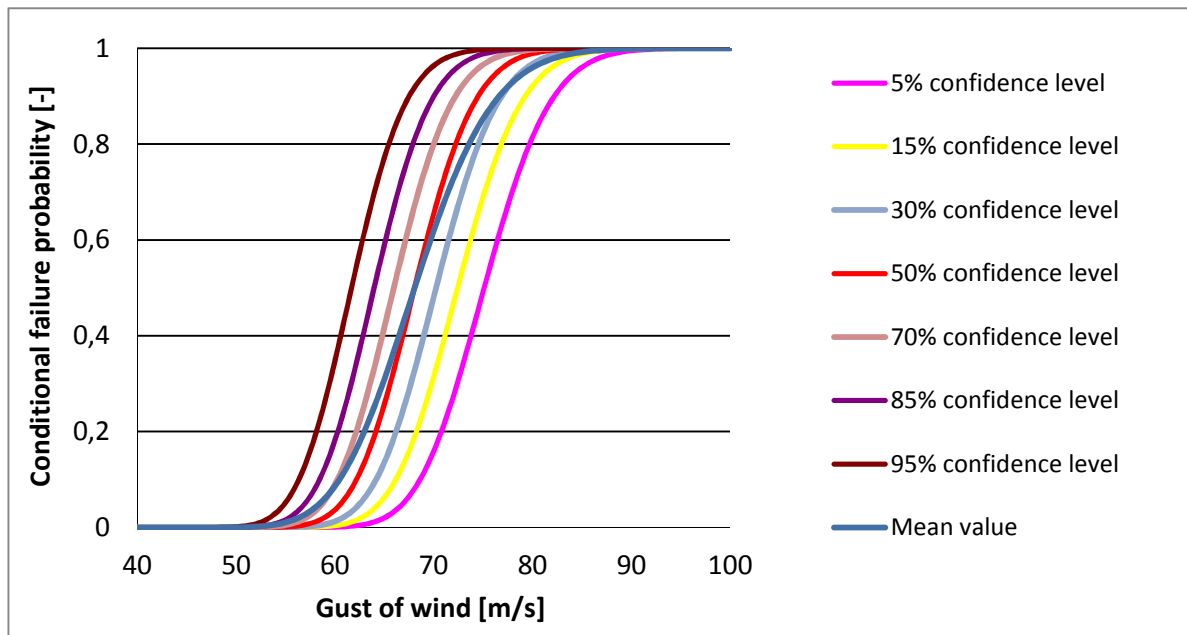


**Figure 1 Hazard curves for extreme snow**

### 3.3. Plant Response and Fragility Analysis

In the analysis of plant response to external hazards we characterized the loads induced by each external hazard on safety related systems, structures and components (SSCs) in such a form that was appropriate for use in probabilistic safety assessment. We determined the probability of loss of essential safety functions and spurious actuations for different levels of load by means of fragility curves. The methods applied to describe fragility varied among characteristic groups of external hazards.

The effects of loads from wind and snow on structures and outdoor facilities were analysed in detail for the purposes of plant response analysis. Vulnerability of power transmission lines to extreme frost and ice formation (hereafter: frost) was also taken into consideration during plant response analysis. Wind, snow and frost related fragility curves, as an outcome of the corresponding fragility analysis, were established by using a closed mathematical expression for different confidence levels. Design data were reviewed, safety margins ensured by the standards applied during structural design were assessed, and use was made of a recent large scale structural re-analysis for the plant to determine fragility. Figure 2 demonstrates the wind related fragility curves for the reactor hall as an example.



**Figure 2 Wind related fragility curves for the reactor hall**

Primarily hydraulic load assessment for the canalization system helped to evaluate how external flooding caused by extreme precipitation would impact the operability of safety related SSCs. The plant response evaluation of lightning strikes required a different methodology than the analysis of other meteorological events, because lightning could cause various failure modes depending on lightning properties that cannot be characterised by a single parameter. Accordingly, lightning related fragility was described by examining the fulfilment of the design requirements prescribed in the applicable lightning protection standards and thus by evaluating the effectiveness of the lightning protection system at the plant. Primary and secondary hazardous effects of a lightning strike were taken into consideration in this evaluation. To determine the plant response to extreme temperatures, we compared the temperature resistance of each safety related component given by the manufacturer to the expected environmental temperature at the location of the component in different plant operational states (full power, low power and shutdown states) with considerations to the applicable operational strategies in such extreme conditions and to the capacity of the connected HVAC (heating, ventilation, air conditioning) systems.

The plant response analysis proved to be the most challenging task in the PSA for external events mainly due to the lack of supporting analyses as well as data on component capacity that could be usefully and sufficiently applied in fragility assessment for PSA. Therefore, high priority was given to assemble an expert panel that could support the PSA with knowledge and experience about plant design, operation and safety analyses in relation to external hazards. Staff members of the plant had the most important role in that expert panel.

### 3.4. PSA Model Development

Based on the findings of hazard assessment and plant response analysis, core damage risk induced by extreme precipitation and lightning was found to be insignificant. However, some follow-on analyses were proposed and safety enhancement measures were conceptualised to fully underpin this conclusion. Due to lack of appropriate data and supporting analysis on the capacity of plant systems and components no PSA model has been developed yet for extreme temperatures. At present efforts are being made to enable risk quantification in relation to extreme temperatures. Consequently, PSA models have been developed for extreme wind, snow and frost hazards at this stage of the analysis. RiskSpectrum PSA Professional was applied for modelling purposes, utilizing to the extent possible the PSA models for internal events and seismic hazards developed earlier for full power as well as low power and shutdown states. Models developed for wind, snow and frost hazards are discussed in brief hereafter.

The initiating event of each PSA model is the relevant external hazard (wind, snow or frost) characterized by hazard curves (as demonstrated in Section 3.2). The loads from wind, snow or frost initiating event might cause damage to structures or outdoor facilities identified during plant response analysis. Hazard induced damage and failure forms were put into fragility groups. All the structures and equipment that were found virtually identical from the point of view of vulnerability to a specific hazard were grouped together, assuming fully correlated failures of all the components in a group, and a single set of fragility curves was assigned to each group. We determined eight wind related and nine snow related fragility groups, as well as one frost related group. Hazard induced transient initiating failures and additional system, train or component level failures and degradations were identified by a thorough examination of failure effects within each fragility group. The impact of block wall collapse on electrical cables was also taken into consideration during the identification of hazard induced failures. During this examination failures that could be caused by the simultaneous occurrences of different group failures were also identified. Based on the failures identified a list of transient initiating failures that could potentially occur due to a hazard was established. It was found that the plant responses to and the mitigation process for the identified single transient initiating failures were virtually the same for random (internal) initiating events and for transients induced by external hazards. The scope of safety functions that should be fulfilled following the occurrence of multiple transient initiating failures is assumed to be a union of the safety functions modeled for single transient initiating failures, taking into account the external hazard induced failures of the mitigation systems.

A so-called generic event tree was built up for each hazard in every plant operational state to identify hazard-induced core damage sequences. This event tree models both single and multiple hazard-induced transients together with the associated consequences on plant and human responses. On one hand each potential hazard induced transient is represented by a single dedicated event tree header in the generic event tree and on the other hand the last header in the tree combines all the core damage event sequences from all the single transient initiating failures that may occur. A simple reading of the event tree is that upper branches represent (as usual) the success of the given event tree header (the associated transient initiating failure does not occur), while lower branches represent failure of the given event tree header (occurrence of the given transient initiating failure). By setting the appropriate boundary condition sets on each event sequence, the last header represents all the mitigation functions and systems for the transients modelled in the corresponding event sequence.

A lot of failure modes considered in the PSA for internal events can be induced by an external hazard, too. As a first modelling step the failure modes that were found sensitive to the effects of external hazards were listed. Thus a failure mode included in this list can occur as a consequence of an external hazard or due to random, non-hazard related effects. For these failure modes the basic events of the PSA model for internal events were transferred into an OR gate that defined the connection logic between the two types of failure causes (i.e. hazard and non-hazard related ones).

Pre-initiator (type A) human actions considered in the PSA for internal events are included in the external event PSA without any modification because these actions are independent of the nature of the initiator. Initiator (type B) human actions that contribute to the development of a plant transient are generally not considered in the external event PSA where the external hazard is the only (common cause) initiator, although the occurrence of plant transients initiated by snow load can be prevented if snow is removed from some designated areas in a timely manner. To model this effect failure to remove snow from the roofs of some technological buildings and other facilities in time was taken into account as a contributor to the development of snow related transients. Most post-initiator (type C) actions considered in the PSA for internal events are identically included in the external event PSA. However, in the external event PSA no credit is given to a type C action, if major structural or equipment failures incapacitate the personnel to successfully interact either in the control room or by means of local actions.

During data assessment for PSA quantification the hazard potential was characterised by a family of continuous hazard curves, while hazard-induced equipment and structural failures were described by continuous fragility curves within the hazard levels of interest. This approach was preferred to defining discrete hazard ranges. The reliability data for random equipment failures were taken from the PSA for internal events.

### 3.5. Risk Quantification and Interpretation of Results

As stated above, for risk quantification purposes we used a family of continuous hazard and fragility curves, rather than using discrete values for different hazard magnitude ranges. The occurrence frequency of a minimal cutset induced by a specific external hazard ( $f(MCS)$ ) was determined partly by convoluting the input hazard curves with the relevant family of fragility curves, as well as by taking into account the probability of random equipment failures using the following formula of approximation:

$$f(MCS) = FP(NEBE_1) \cdot \dots \cdot FP(NEBE_{NE}) \cdot \sum_{i=1}^{160} (FF_i(EBE_1) \cdot \dots \cdot FF_i(EBE_E) \cdot h_i)$$

where:

- $NEBE_j$  denotes basic events for random failures in the minimal cutset, i.e. failures that occur independently of the external hazard ( $j = 1, 2, \dots, NE$ );
- $FP(NEBE_j)$  is the probability of a random failure in the minimal cutset;
- $EBE_k$  is a basic event in the minimal cutset representing a failure due to an external event ( $k = 1, 2, \dots, E$ );
- $FF_i(EBE_k)$  is the mean conditional fragility probability for external hazard range “i” of a basic event in the minimal cutset representing a failure due to an external event;
- $h_i$  is the mean occurrence frequency of the external hazard range “i”.

The conditional probability of core damage ( $CCDP(MCS)$ ) in relation to a minimal cutset can be assessed as:

$$CCDP(MCS) = \frac{f(MCS)}{\sum_{i=1}^{160} h_i}$$

The frequency of core damage induced by an external hazard ( $CDF$ ) is determined as follows:

$$CDF = \left( 1 - \prod_{n=1}^{N_{MCS}} (1 - CCDP(MCS_n)) \right) \cdot \sum_{i=1}^{160} h_i$$

The dominant core damage minimal cutsets of failures induced by external hazards were determined in the first place by using the RiskSpectrum PSA Professional software applied generally to model development and quantification in the Paks PSA. Since RiskSpectrum cannot be used to perform the numerical approximation of the convolution integral, following the generation of minimal cutsets, separate, stand-alone computer codes were applied to determine cutset frequencies, calculate the overall core damage frequency, and perform uncertainty and sensitivity analyses.

For risk characterisation, the point estimate of core damage frequency and the annual core damage probability were determined for the different external hazards in each plant operational state. By summing up the core damage probabilities for the various plant operational states, we calculated the cumulative plant risk (annual core damage probability) induced by the different external hazards. We used qualitative analysis to identify and explain the minimal cutsets that were found dominant contributors to the cumulative plant risk.

Importance and sensitivity analyses were used to calculate the following measures for each fragility group in relation to the cumulative plant risk:

- Fussel-Vesely importance (fractional contribution - FC);
- Risk reduction worth (risk decrease factor - RDF);
- Sensitivity measures ( $S_U, S_L, S_{U/L}$ ).

Sensitivity measures for each fragility group were determined by assuming a higher and a lower value of HCLPF<sup>1</sup> for the group. These higher and lower values were selected so that they represented one order of magnitude change in the hazard occurrence frequency. Moreover, we assessed the expected decrease in the

<sup>1</sup> High Confidence on Low Probability of Failure

cumulative annual core damage probability if the HCLPF of those fragility groups that have lower resistance than the design basis of the plant was increased up to the design basis value. The results of these analyses enabled the characterisation of expected risk reduction if certain safety improvements were made.

The complete set of the hazard curves for an external event and the full range of fragility distributions for each structure and component representing different confidence levels were combined through a convolution integral to develop true uncertainty distributions for external hazard induced failure frequencies. Also, uncertainties in hazard induced failures were combined with uncertainties in human error rates and non-hazard related equipment failures using Monte Carlo simulation. As a result the probability density function and the cumulative probability distribution function of the core damage frequency were obtained. Quantification was done by using a spreadsheet application developed earlier in support of the seismic PSA.

#### 4. FINDINGS

The development of external events PSA for the Paks NPP was completed by the end of 2012. Hereby we summarize the quantified core damage risk induced by natural external hazards and the identified main risk contributors. In addition, we highlight some of the most important analysis areas that need to be further dealt with in order to develop a full scope external event PSA, as well as to reduce uncertainties and conservatism where necessary.

##### 4.1. Core Damage Risk

A detailed logic model was developed for extreme wind, snow and frost hazards and therefore core damage risk was only quantified for these hazards due to the following reasons:

- Risk induced by extreme rainfall and lightning was found insignificant on the basis of design characteristics and corrective actions that the plant management has already made commitment to in order to enhance safety.
- The assessment for extremely high air temperature was limited to an initial and rough estimation of the conditional core damage probability if loss of off-site power was assumed in hot weather conditions. Among others, this limitation is attributable mostly to the uncertainties in operational strategy under harsh weather conditions and to the uncertainty in assessing the impact of high temperature on the off-site power system.
- Currently no solid assessment of core damage risk due to extremely low air temperature could be made. This is in the first place due to the uncertainties in operational strategy under harsh weather conditions and uncertainties in hazard assessment. Moreover there is a need for performing further analyses to enable an appropriate quantification of the temperature related fragility of some systems and components.

Based on the results of PSA model quantification, the point estimate approximation of the annual core damage probability induced by external hazards is:

- $1,24 \cdot 10^{-5}$  from extreme wind;
- $5,20 \cdot 10^{-6}$  from extreme snow;
- $2,78 \cdot 10^{-6}$  from extreme frost.

These figures include the contributions of all the plant operational states analysed. The results show that the risk from extreme weather phenomena is important in comparison to the risk originated from other types of initiating events analysed in the PSA for the Paks plant.

Some results of the uncertainty analysis are indicated in Table 1 below. The figures witness large uncertainties in the risk estimates.

	5 %	Median	95 %
extreme wind:	$1,23 \cdot 10^{-7}$	$4,75 \cdot 10^{-6}$	$1,84 \cdot 10^{-4}$
extreme snow:	$4,68 \cdot 10^{-8}$	$1,17 \cdot 10^{-6}$	$2,91 \cdot 10^{-5}$
extreme frost:	$1,43 \cdot 10^{-7}$	$2,61 \cdot 10^{-6}$	$4,77 \cdot 10^{-5}$

**Table 1 Uncertainties in annual core damage probability estimates for different external hazards**

The main contributors to core damage risk from extreme wind were found to be the structural failure of the longitudinal electrical gallery (part of the main building complex), failure in the power lines of the off-site power system and the human failure event to establish plant operation in island-mode. Regarding extreme snow the main risk contributors are failure to remove snow from the roofs of safety related buildings, structural failure of the turbine building and structural failure of the on-site substation control building located at the switchyard. The ultimate contributor to frost induced risk is the failure of power lines in the off-site power system and in the switchyard.

#### 4.2. Unresolved issues

We proposed numerous follow-on efforts and corrective actions based on lessons learned from the different PSA analysis steps, as well as on the results of risk quantification and the associated sensitivity studies. These proposals can be grouped into the following major categories:

- Those that can reassure the adequacy of the technical basis to screen out hazards considered negligible from risk point of view (e.g. tornado, blockage of water intake system, extreme rainfall, lightning);
- Those that can enable risk assessment for hazards not characterized quantitatively yet (e.g. extreme air temperatures, hazards currently considered insignificant);
- Those that can, by means of reducing uncertainties, establishing a better technical basis of the applied analytical assumptions, or decreasing unnecessarily high conservatism, enable a more accurate assessment of risk from hazards already quantified (extreme wind, snow, or frost).

Some of the proposals belong to more than one of the above-mentioned categories. Based on the results of the current study, competent members of the plant management have defined their position as follows:

1. Safety enhancement measures already in preparation and follow-on analyses in order to ensure a refined and more complete risk assessment have to be performed first.
2. If the refined assessment shows an unacceptable level of core damage risk, then, among other risk reduction measures, it might be necessary to set-up a detailed operational and transient mitigation strategy to follow in case of extreme meteorological conditions, similarly to the seismic safety concept elaborated earlier at the plant.

On the basis of the current analysis, it has already been pointed out that the detailed strategy referred to in item 2 above could significantly lower the risk from external hazards and the probability of human errors in severe weather conditions.

The most important area of follow-on analyses regarding extreme wind is the need to review the available structural analyses of the plant more thoroughly in order to better assess structural fragilities and subsequently reduce assumed conservatism in risk assessment to the extent possible. Moreover the reliability of establishing plant operation in island-mode in case of loss of off-site power could be enhanced since the failure of the power grid proved to be a significant risk contributor due to its less stringent design criteria.

With respect to extreme snow, the potential snow induced blockage of air intake systems to the diesel generators and to the demineralised water storage tanks needs to be further studied. Also, modification of the relevant plant procedure on removal of snow deposits from building roofs has been proposed together with identification and allocation of human and equipment resources to enhance the effectiveness of actions aiming at the prevention of transient initiating failures and thus to lower core damage risk. Furthermore a more detailed review of the available structural analyses of the plant has also been proposed in order to better assess structural fragilities and subsequently reduce assumed conservatism in risk assessment to the extent possible. Regarding extreme frost, complementary assessments are needed to decrease conservatism by assessing the safety margin of relevant components and power lines at the switchyard beyond the design basis.

To fully justify that plant risk imposed by extreme rainfall and lightning is insignificant some unresolved issues need to be clarified. A reassessment of the response of the canalisation system to hydraulic loads is needed with modified boundary conditions in comparison to the existing analyses. It may become necessary to establish controlled flooding of the diesel generator building as a result of this reassessment. Although controlled flooding cannot prevent the rooms inside the building from flooding, it can ensure the



functionality of all safety related components if a few components are installed at higher elevation. In addition, it is seen necessary to examine whether extreme rainfall could lead to the damage of safety related components due to flooding through underground structures (e.g. cable tunnels).

Concerning the risk from lightning, protection of safety related components against lightning is currently subject to a review at the plant with focus on the secondary effects of lightning in particular. Protection of components will be improved where necessary.

The risk assessment for extremely high and low air temperatures proved to be the most challenging task. Therefore it requires the most significant follow-on efforts. Detailed analysis is needed to evaluate the effectiveness and reliability of the plant HVAC systems during harsh weather conditions. Temperature limits for the safe operation of all components with considerations to the actuation of temperature related protection need to be determined in order to assess the sequence of equipment trips during harsh temperature conditions. Temperature resistance of electrical, control and instrumentation components located outside of the plant buildings should be assessed in detail to determine the safety margin beyond design basis and to underpin fragility analysis. The vulnerability of mechanical components to extreme temperatures needs to be reviewed. Fragility assessment regarding extreme temperatures needs to be conducted for the off-site power system to quantify core damage risk in an appropriate manner. It should be analysed whether safe stable plant conditions can be ensured by using power supply from the emergency diesel generators in lack of off-site power during extremely high and low air temperature conditions.

## 5. CONCLUSION

Development of external events PSA for the Paks NPP was completed by the end of 2012. The analysis followed the commonly known steps: selection and screening of external hazards, hazard assessment for screened-in external events, analysis of plant response and fragility, PSA model development, and risk quantification and interpretation of results. The risk of core damage induced by natural external hazards was quantified to the extent seen feasible. In addition to risk quantification, unresolved issues and necessary follow-on analyses were identified and proposed. At present an action plan is being developed for these analyses.

Core damage risk has been assessed quantitatively for wind, snow and frost hazards. Detailed importance, sensitivity and uncertainty analyses were conducted. Moreover the main risk contributors induced by these external events were also identified. Additional follow-on analyses were proposed to enable an improved risk quantification by means of reducing uncertainties, establishing a better technical basis for the applied analytical assumptions, or decreasing unnecessarily high conservatism.

Based on the findings of hazard assessment and plant response analysis, the core damage risk induced by extreme rainfall and lightning was found to be insignificant. However, some follow-on analyses were proposed and safety enhancement measures were conceptualised to fully underpin this conclusion. Due to lack of appropriate data and supporting analysis on the capacity of plant systems and components no PSA model has been developed yet for extreme temperatures. Follow-on analyses necessary for quantifying the risk of core damage induced by extreme temperatures have been identified.

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