Assessing the Impact of Combined External Events on the Safety of NPP Paks

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Abstract: Originally, mostly single external hazards were considered in the definition of the design basis of the Paks nuclear power plant (NPP) in Hungary. Accordingly, the analysis and evaluation of plant resistance against design basis loads as well as the probabilistic safety assessment (PSA) of the plant have been limited to these single external hazards. However, some specific requirements of the Hungarian Nuclear Safety Codes, international recommendations and lessons learned from the Fukushima Dai-ichi NPP accident pointed out the need for systematically assessing the combinations of external hazards for the Paks NPP so that their impact on plant safety can be determined, understood and evaluated. The assessment has lately been completed by following the commonly exercised steps in this domain: hazard selection and screening, hazard assessment, evaluation of plant protection, plant response and fragility analysis, development of event sequence models for hazard initiated plant transients, and risk quantification and evaluation of results. The analysis proved to be a significant challenge due to scarcity of data, lack of knowledge as well as limitations in existing PSA methodologies. Detailed assessment was performed for the following combinations of external hazards: handling of dangerous substances in severe weather conditions; multiple accidents in nearby industrial facilities due to a common initiator of natural origin; an earthquake that occurs when the ambient temperature is extreme; storm; extreme wind and snow; extreme low or extreme high ambient temperature. Risk induced by the combinations of extreme wind and snow as well as earthquakes occurring in extreme warm weather was quantified using either dedicated PSA modeling or a bounding assessment, as shown appropriate. This paper presents an overview of systematically considering combinations of external events in the design basis and in the PSA of NPP Paks. Important methodological aspects as well as key analysis results and findings are summarized.

1. INTRODUCTION

Originally, mostly single external hazards were considered in the definition of the design basis of the Paks nuclear power plant (NPP) in Hungary. Accordingly, the analysis and evaluation of plant resistance against design basis loads and the probabilistic safety assessment (PSA) of the plant have been limited to these single external hazards. However, the Hungarian Nuclear Safety Codes (NSC) as high level safety regulations require the inclusion of combined external hazards in the safety demonstration of a nuclear power plant in a site specific manner. This requirement as well as international recommendations and lessons learned from the Fukushima Dai-ichi NPP accident pointed out the need for systematically assessing the combinations of external hazards for the Paks NPP so that their impact on plant safety can be determined, understood and evaluated.

As a preparatory step, the available methodologies were studied and evaluated to underpin the treatment of combined external events in the design basis and in the PSA for the Paks NPP. Also, the corresponding analysis practices applied in Hungary were reviewed in support of this task. A comparison of the current practices with applicable regulatory requirements as well as with Hungarian and international regulatory recommendations was the basis of this review. Eventually, a proposal was prepared for the technical tasks and the schedule thereof to identify combinations of external hazards and for assessing the effects of such hazards on NPP safety. This proposal included a high level methodology for hazard selection and screening, hazard assessment, evaluation of plant protection, plant response and fragility analysis, development of event sequence models, and risk quantification. Paper [1] presents an overview of the preparatory study performed for the Paks NPP.

2. OBJECTIVES

In line with the proposed work plan, the assessment of combined external hazards for the Paks NPP was completed in 2021. The main objectives of the assessment were to identify combinations of external hazards and assess the effects of such combinations on NPP safety. Specifically, the relevant load combinations were to be identified and characterized, the protection of the plant against these hazard combinations was to be assessed to help conclude on the adequacy of protection, the residual risk due to beyond design basis load combinations was to be quantified and the main risk contributors were to be identified. A further objective was to identify important safety concerns, if any.

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

3. MAJOR ANALYSIS STEPS

As an initial step, it was found necessary to systematically categorize and interpret hazard combinations, since there appears to be a lack of consensus internationally in this respect.

The following basic types of combined external hazards have been defined and used in the analysis:

- Combination of dependent hazards: there is a causal connection between and among the hazards that constitute the hazard combination. Further subcategories are:
  - Consequential hazards: the combination is based on cause-effect relation, i.e. one hazard triggers another (or more) hazard(s), differentiating as:
    - A may cause B: event A may trigger event B, but event B may occur due to other reasons too;
    - A is a prerequisite of B: event A may trigger event B, but event B cannot occur due to other reasons.
  - Non-consequential connected hazards (hereinafter referred to as correlated hazards): the hazards in the hazard combination occur as a result of a common root cause.
- Combination of independent hazards: the simultaneous occurrence of such hazards that have no causal connection. In general, the occurrence frequency of such combinations is very low, so combinations of independent hazards have to be considered, if:
  - independent events have a high occurrence frequency, or
  - at least one of the events is long-lasting and usually rare.

Similarly to the assessment of single hazards, the development of PSA for combinations of external hazards for the Paks NPP followed the commonly known steps, i.e.:

1. Selection of combined external hazards;
2. Screening of combined external hazards;
3. Detailed assessment of screened-in event combinations:
   a. Hazard assessment;
   b. Plant response and fragility analysis;
   c. Event logic modeling and risk quantification.

The following analysis tasks have been completed to identify the combined hazards to be included in the design basis and to assess the protection against these events:

1. Selection of combined external hazards;
2. Screening of combined external hazards;
3. Definition of design basis load combinations;
4. Evaluation of plant protection and specification of protective measures, as necessary.

The analysis proved to be a significant challenge due to scarcity of data, lack of knowledge as well as limitations in existing PSA methodologies. Hereby important methodological aspects are summarized by giving an overview of every major analysis step. The analysis related to the identification and characterization of hazard combinations to be considered as part of the design basis are not discussed separately, since the analysis steps performed in PSA are more comprehensive and cover most of the analysis steps that had to be performed to assess the protection of the plant against design basis loads.

3.1. Selection of Combined External Hazards

An initial, broad list of site specific combined external hazards was developed first in the following steps:

- Development of an intendedly exhaustive list of potential single external hazards
  Use was made of site characteristics, national regulatory requirements and international recommendations (e.g. [2,3]), PSA standards (e.g. [4]), guidance documents (e.g. [5]) and relevant international practice (e.g. [6]).
- Screening of single hazards with respect to hazard combinations
  Although the comprehensive list of single hazards was the basis of identifying hazard combinations, the following initial screening criteria were used at this stage:
  - Screening by relevance: single hazards that cannot occur at the site were screened out from further analysis of hazard combinations;
  - Frequency based screening: a single hazard was screened out, if the occurrence frequency thereof, regardless of the load intensity, is less than a frequency threshold of 10^{-7} /a.
- Evaluation of the dependence among the hazards
  A table form was applied to facilitate the identification of hazard combinations by placing the various single hazards from the general list of single hazards, screened by relevance and frequency earlier, into the rows and the columns of the table. The inner cells of the cross-correlation chart represent the event combinations from hazards in the corresponding rows and columns. In all the cells, i.e. for all the possible hazard combinations, the possible relationship type between the hazards was identified and marked with a predefined symbol. The following possible types of relationship between the hazards were used:
  - one hazard is a prerequisite of the other hazard;
  - one hazard may cause the other hazard, the impact mechanisms of the single hazards are similar or the same;
  - one hazard may cause the other hazard, the impact mechanisms of the single hazards are different;
  - correlated hazards, the impact mechanisms of the single hazards are similar or the same;
  - correlated hazards, the impact mechanisms of the single hazards are different;
  - independent hazards, the impact mechanisms of the single hazards are similar or the same;
  - independent hazards, the impact mechanisms of the single hazards are different;
  - mutually exclusive hazards.

  This approach ensured mapping of numerous hazard combinations (666 in total) consisting of two hazards. However, further considerations were needed to identify hazard combinations of more than two hazards. On one hand, the rows and columns of the cross-correlation chart corresponding to the different hazards were studied. In addition, an attempt was also made to map root causes that can trigger combinations of more than two hazards.

3.2. Screening of Combined External Hazards

A successive approach with combined deterministic and partially probabilistic screening of all the potential combinations of external hazards was applied to identify the risk significant combinations that needed further detailed analysis and risk quantification. In general, the same screening criteria were considered applicable to hazard combinations as those that had been used for single hazards before. It was recognized that the relationship between the impact mechanisms of the single hazards in a combination has a significant role. If the impact mechanisms of the single hazards are similar or the same, then they affect the same SSCs amplifying one another's effects. In such cases, the resistance against the combined load was assessed. If the impact mechanisms of the single hazards are different, then these hazards do not affect the same SSCs, or they affect at least with different, independent impact mechanisms. In both cases, the main aim of impact screening was to determine whether the hazard combination would generate a plant transient or not.

In addition to the screening criteria applied to single hazards, the following criteria were also considered for screening hazard combinations:

- The hazards are mutually exclusive;
- The definition of a single hazard covers the other single hazard included in the combination;
- The impact of the hazard combination is not more severe than the effect of the more powerful hazard.

Detailed screening of hazard combinations was performed considering the following hazard categories:

- hydrological hazards;
- man-made external hazards;
- riverine events endangering the water intake facility;
- hazards related to the relevant areas of geosciences;
- meteorological hazards.

Firstly, combinations of hazards belonging to the same category were analyzed and evaluated. Subsequently, hazard combinations of hazards related to different categories were looked at. For the sake of traceability and transparency, it did not seem reasonable to go through all the identified 666 hazard combinations on a case-by-case basis (supported also by the fact that hazard assessment for single hazards at the Paks NPP is not in full compliance with the definitions of the intendedly exhaustive list of potential single external hazards developed for hazard combination selection purposes). Hence, lessons learned and conclusions drawn from the analysis were summarized expansively for each hazard category.

It should be noted that the assessment of single hazards incorporates potential hazard combinations to some extent, namely:

- With respect to external hazards endangering the blockage of water intake from the river Danube, the identification of relevant event sequences leading to loss of water intake, i.e. the assessment of critical consequences due to man-made hazards or natural phenomena considered possible combinations of the single events.
- The characterization of extreme hydrological conditions, i.e. the assessment of floods and low water levels with extreme occurrence frequencies included all possible combinations of single hydrological events.
- In the Hungarian practice all seismological conditions and hazards are assessed in conjunction with other relevant hazards looked at in geoscience, i.e. geotechnical, geological and tectonic conditions and hazards. So the cross-correlations of these phenomena are assessed in an appropriate manner too. However, these hazards are not assumed simultaneously with other hazards that are not covered by geosciences.

After screening, the following combinations of external hazards were selected for detailed assessment (the combinations covered by the assessment of single external hazards are not listed):

- handling of dangerous substances in severe weather conditions;
- multiple accidents in nearby industrial facilities due to a common initiator of natural origin;
- earthquake occurring when the ambient temperature is extreme (independent hazards);
- storm: high wind, extreme precipitation and thunder;
- snowstorm and accumulated snow and strong wind: extreme wind and snow;
- extreme warm weather: extremely high air temperature and high Danube temperature;

- extreme cold weather: extremely low air temperature and surface ice on the Danube (and icing and snow).

3.3. Hazard Assessment

The objective of probabilistic hazard assessment in this case was to determine the exceedance frequency-magnitude relationship for different magnitudes of the parameter combinations which represent best the loads induced by the external hazards in a given combination. Besides, load combinations that should be considered in the design basis of the Paks NPP were determined during hazard assessment. Both probabilistic and deterministic approaches have been used in hazard assessment for combinations of external hazards.

The meteorological conditions can have a significant impact on the dispersion and spreading of dangerous substances as well as on the effects of fires that had not been fully assessed earlier. A large number of dedicated deterministic analyses have been performed to determine whether an accident during handling dangerous substances in severe weather conditions can challenge the safety of the Paks NPP with an exceedance frequency above the predefined threshold (i.e. 10^{-7} /a) or not. The analysis results pointed out that such accidents do not pose more significant impact on the NPP safety in severe weather conditions than in moderate conditions assessed earlier, hence these were screened out from further assessment.

As an effect of a common initiator of natural origin, e.g. earthquake or high wind, multiple accidents may simultaneously occur in nearby industrial facilities that handle dangerous chemical substances. Further considerations were given to assess whether such multiple accidents can have a considerable effect on the safety of the Paks NPP with an exceedance frequency above the predefined threshold (i.e. 10^{-7} /a) or not. It was concluded that due to the distance between the hazard sources and the NPP, the direction of the sources relative to the NPP and the different types of effects of the various sources, multiple accidents in nearby industrial facilities do not pose a significant challenge to the NPP safety, hence this combination was also screened out from further assessment.

A method was developed to assess the simultaneous occurrence of multiple independent hazards (see [1] for details). According to this method, the joint hazard occurrence frequency depends not only on the occurrence frequencies of the relevant single hazards, but also on the duration of each hazard as well as on the relative duration when the relevant hazards can occur simultaneously (e.g. due to seasonality). This method was applied to an earthquake that occurs when the ambient temperature is extremely high or low. The duration of an earthquake was regarded as limited to a relatively narrow time window, and a period of one week was considered for the extremes of ambient air temperature. The value pairs of peak ground acceleration and ambient temperature that should be considered in the design basis (i.e. corresponding to 10^{-4} /a exceedance frequency) have been determined. Moreover, hazard surfaces related to these quantities have also been assessed for the purposes of PSA. Figure 1 shows the results of probabilistic hazard assessment for these hazard combinations.

As far as storm, and the combination of accumulated snow and strong wind are concerned, hazard surfaces have been assessed based on the data collected by the Hungarian Meteorological Service at station Paks during the past few decades and by using a methodology developed for such purposes earlier [1]. The joint distribution functions of the hazards were established in the form of a bivariate extreme value distribution considering the dependence (or correlation) between the hazards in a combination by a logistic dependence model and the extreme value distribution functions of the single hazards as marginal distributions. Figure 2 represents the results of hazard assessment for storm, and for the combination of accumulated snow and strong wind.

Snowstorm was characterized by the relative frequency of strong winds during intensive snowfalls, as it deemed appropriate for the purposes of PSA. Full correlation was conservatively assumed between the extreme values (i.e. the return values corresponding to the same occurrence frequency) of extremes of high instantaneous, daily and weekly air temperatures, and high cooling water temperature. A similar approach was used for the load parameters of extremely low ambient air temperature.

Figure 1: Hazard Surfaces for Earthquakes Occurring When Ambient Temperature is of Extreme Values

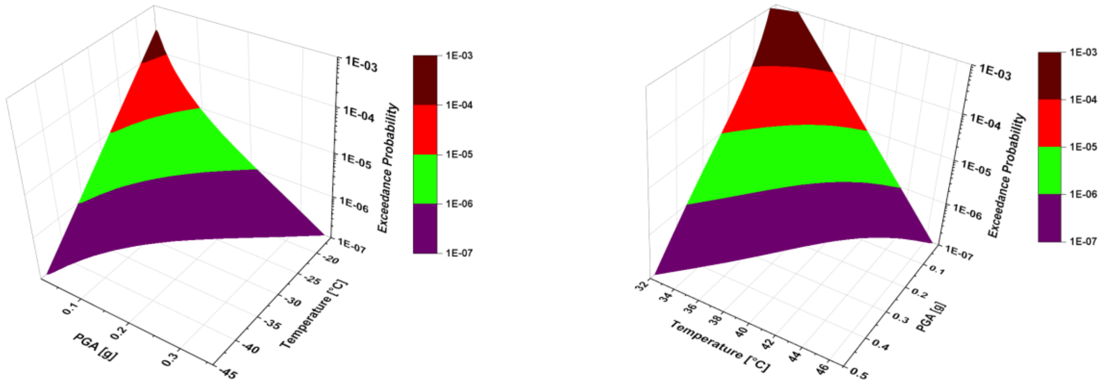
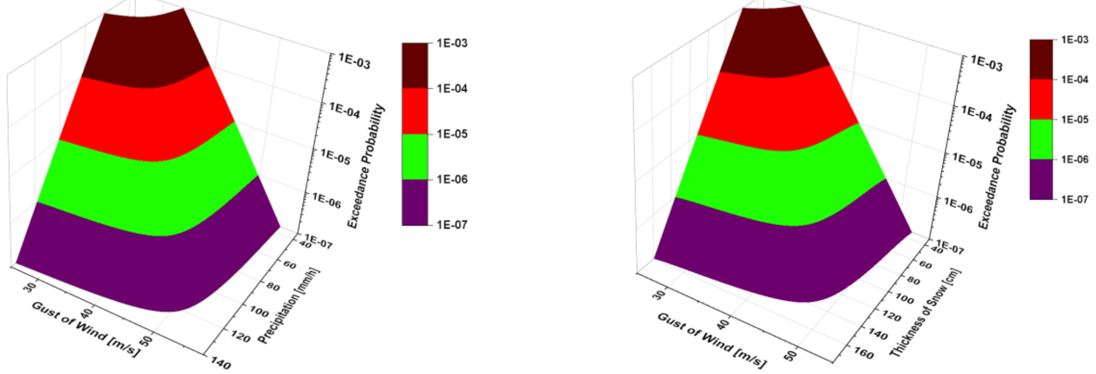


Figure 2: Hazard Surfaces for Storm, and Accumulated Snow and Strong Wind



3.4. Plant Response and Fragility Analysis

The main aim of the plant response and fragility analysis for the combinations of external hazards was to determine which safety related SSCs are challenged if the combined external events in question occur and to characterize the vulnerability of these SSCs to the combined loads in such a form that is appropriate for use in PSA. Accordingly, the plant response was described first by identifying the scope of the SSCs that may fail due to the combinations of external hazards. The probability of these SSC failures was determined in the next analysis step.

According to the results of the plant response analysis for an earthquake that occurs when the ambient temperature is extreme, those accident sequences are important from the point of view of hazard combinations that include the failure of the HVAC (heating, ventilation, air conditioning) systems induced by seismic events occurring during a period of moderately extreme ambient temperature. In these scenarios, hazard intensities lower than the design basis loads for single hazards can induce failures that lead to significant consequences. Other failures and event sequences induced by an earthquake that occurs when the ambient temperature is extreme are bounded by the consequences of single hazards, since significant failures can only be induced by loads that exceed the design basis for single hazards and the exceedance frequency for combined hazards is orders of magnitudes lower than that for single hazards.

An earthquake can cause the failure of the HVAC system of the plant by means of the following processes:

- direct, seismic-induced failure of the room cooling or heating system components;

- loss of the normal power supply system leading to loss of the power supply to the room cooling and heating system;
- seismically induced reactor scram leading to loss of heating steam necessary to the operation of the room heating system.

These failures were analyzed in detail and the respective fragility curves were developed to characterize the failure probability of the HVAC system.

It was justified in the study that the plant is sufficiently protected against the design basis load combinations of an earthquake that occurs when the ambient temperature is extremely high. Moreover, the combinations of earthquakes and extremely low ambient temperature were screened out from detailed risk assessment, since a safe, stable plant state can be reliably ensured even if an earthquake with non-negligible damage potential occurs when the ambient temperature is the lowest considered for such an earthquake. On the contrary, load combinations of earthquakes and extremely high ambient temperature could not be screened out from further assessment.

As far as storm is concerned, loss of off-site power induced by high wind or lightning with simultaneous extreme precipitation was in the focus of the analysis, as in this case the operation of the diesel generators is necessary and the cooling water thereof are discharged to the same canalization system that is used for rainwater discharge. Recently, two additional pipelines have been implemented near the diesel generator stations to reduce the loads on the critical subparts of the canalization system. As a result of this upgrade, the canalization system is capable of draining water from extreme precipitation together with the cooling water of one diesel generator at each unit. Consequently, the plant is sufficiently protected against the effect of the design basis storm and the risk attributable to storm is also negligible.

In view of the high task complexity and the significant resource needs, no dedicated, detailed structural analysis was performed for the safety related buildings of the plant by considering load combinations from accumulated snow and strong wind. However, a thorough review of the already available structural analyses led to a conclusion that the fragilities assessed for single hazards appeared appropriate for describing fragilities for the simultaneous occurrence of snow and wind loads. On one hand, advantage was taken of the fact that some designated load combinations had been considered during a recent large scale structural re-analysis. On the other hand, it was found out that the most dominant structural components in the fragility for wind and for snow as separate single hazards do not coincide. Consequently, the safety related plant buildings are sufficiently protected from design basis load combinations of accumulated snow and strong wind, and the risk attributable to single hazards covers the risk that is associated with beyond design basis load combinations. Whilst all safety related plant buildings could be screened out from detailed assessment considering accumulated snow and high wind, loss of normal power supply due to high wind during heavy snowfall needed to be further analyzed in PSA, since loss of off-site power due to snow had not been considered in the snow PSA earlier. The fragility parameters of the off-site power grid can be characterized by the parameters of wind fragility, since the snow fragility of the power grid is negligible compared to its wind fragility.

As there is no plant specific experience on the accumulation of a critical, airtight snowpack on the air intake filters, it was conservatively assumed on the basis of expert judgement that the conditional blockage probability of the air intake system to the diesel generators in case of a heavy snowfall is 0.1 (if no operator action is assumed). The potential time delays in the blockage of the air intake system of the individual diesel generators as well as the consequences thereof were conservatively not considered.

As far as extreme warm weather and extreme cold weather as hazard combinations are concerned, it is to be noted that the plant response to the extremes of ambient temperature is almost the same as the plant response to extreme high or extreme low ambient temperature as single external hazards that have been assessed earlier. For example the temperature of the Danube river was considered in the analysis of extremely high ambient temperature, as single hazard. However, the analysis of these hazard combinations pointed out that a critical amount of frost and ice may accumulate, if the ambient temperature is extremely low. Extreme low and extreme high ambient temperature was not assessed further in the study as they will be addressed in the PSA for single hazards.

3.5. Event Logic Modeling and Risk Quantification

Based on the findings of (1) selecting and screening combinations of external hazards, and (2) hazard assessment and plant response analysis performed for the screened-in hazard combinations, it could be concluded that core damage risk attributable to the combinations of earthquake occurring in extreme warm weather as well as extreme wind and snow were in need of quantification. All other combinations of external hazards could be screened out from further assessment, as either the risk attributable thereto was found negligible or their risk implications had already been considered in the risk assessment for single external hazards.

3.5.1. Earthquake Occurring in Extreme Warm weather

According to the results of the plant response analysis, a moderate earthquake may lead to the failure of the HVAC system of the plant and subsequently, in moderately extreme warm weather, safety related components may be critically overheated. Consequently, an event logic model was developed for earthquakes occurring in extreme warm weather and the risk attributable to such hazard combinations was quantified. On one hand, the elaboration and quantification of a detailed PSA model for the hazard combinations of interest was not feasible by using commercial PSA software. On the other hand, this kind of PSA model development and quantification did not appear necessary either. The underlying reasons are as follows:

- risk assessment tools are generally not capable of adequately handling the assessed input data and the characteristics of the continuous hazard and fragility curves established for the purpose of the analysis;
- event sequences and the relevant failure combinations deemed easy to determine;
- temperature fragilities necessary for risk quantification were available only to a limited extent.

In the first step, the load combinations to be considered within the scope of the assessment were selected and the exceedance frequencies corresponding to 50% confidence levels were assigned thereto. It is noted that the hazard potential was characterized by continuous hazard surfaces, as opposed to defining discrete hazard combination ranges, in order to simplify the use of fragility surfaces and make risk quantification straightforward.

In the next step, those event sequences and the corresponding failure modes were identified that can lead to core damage if an earthquake occurs in extreme warm weather. Again, those accident sequences are important from the point of view of hazard combinations that include the failure of the HVAC systems induced by seismic events occurring during a period of moderately extreme ambient temperature. All the event combinations, i.e. seismic failures, were identified that represent such scenarios.

In the third step, the applicability of the available fragility data relevant to single external hazards was analyzed and evaluated considering the input data needs of the PSA for earthquakes occurring in extreme warm weather. As the impact mechanisms of earthquakes and extremely high ambient temperatures (as single hazards) are different, it was found that the fragility curves for the two respective single hazards could be used in the assessment. In order to enable risk quantification, the conditional core damage probability for different extreme warm weather situations characterized by instantaneous maximum ambient temperature when the HVAC systems are unavailable was estimated based on conservative expert judgement.

The conditional seismic failure probability of each component group of the plant room cooling system ($FP_j(EQBE_k)$) was determined for each temperature value between 32 °C and 47 °C by convoluting the seismic hazard curve derived from the hazard surface characterizing the hazard combination for the given temperature value with the relevant mean fragility curve of the seismic fragility group in question using the following approximate formula:

$$FP_j(EQBE_k) = \frac{\sum_{i=1}^{30}\left(FF_i(EQBE_k)\cdot h_{i,j}\right)}{H_j} \tag{1}$$

where:

- $EQBE_k$ denotes a basic event in the minimal cut set representing a seismic failure (k = 1, 2, … 16);
- $FF_i(EQBE_k)$ is the mean conditional failure probability (fragility) for seismic range "*i*" of a basic event in the minimal cut set representing a seismic failure*;*
- $h_{i,j}$ is the mean occurrence frequency of the seismic acceleration range "*i*", corresponding to the lowest value of temperature range "*j*";
- H_j is the mean occurrence frequency of extreme warm weather as a single external event corresponding to the lowest value of temperature range "*j*".

The core damage frequency attributable to a fragility group was assessed by the following formula, considering the conditional seismic failure probability of a given component group of the plant room cooling system and the conditional core damage probability given the loss of the room cooling system of the plant:

$$f(CD_k) = \sum_{j=1}^{16}\left(FP_j(EQBE_k)\cdot \ldots \cdot FP_j(TBE)\cdot h_j\right) \tag{2}$$

where:

- $FP_j(TBE)$ is the conditional core damage probability assuming loss of the room cooling system of the plant, corresponding to the lowest value of temperature range "*j*"*;*
- h_j is the mean occurrence frequency of the temperature range "*j*".

A separate, stand-alone spreadsheet application was applied to determine cut set frequencies, calculate the overall core damage frequency, and perform sensitivity analyses.

3.5.2. Extreme Wind and Snow

The effects of accumulated snow and strong wind as well as snowstorm on nuclear safety are in the focus of the risk assessment for the simultaneous occurrence of extreme wind and snow. Consequently, these two combinations of external hazards with different impact mechanisms were included in the definition of extreme wind and snow.

Similarly to the assessment of earthquakes occurring in extreme warm weather, in the first step, the load combinations to be considered within the scope of the assessment were selected and the exceedance frequencies corresponding to 50% confidence levels were assigned thereto. Also, the hazard potential was characterized by continuous hazard surfaces in this case too.

On one hand, loss of off-site power due to extreme wind occurring during extreme snowfall had to be analyzed in the PSA for hazard combinations, as loss of off-site power due to snow had not been considered in the snow PSA earlier. On the other hand, blockage of the air intake system of the diesel generators due to snowstorm was also considered in the assessment. Basic events representing the following failures were newly introduced into the PSA model: wind induced loss of off-site power during extreme snowfall; wind induced switchyard failures leading to loss of normal power supply during extreme snowfall; loss of the diesel generators due to snowstorm induced blockage of air intake systems. It did not seem reasonable to take those accident sequences into account in the assessment of hazard combinations that represent wind induced failures in the external power grid or in the switchyard without any snow induced failures (wind induced and random failures lead to core damage), since these scenarios are covered by the risk assessment for extreme wind as a single external event. Consequently, the occurrence frequency of such scenarios was to be assessed under the condition that extreme wind induces loss of off-site power as a result of grid related or switchyard failures and further snow induced plant failures also occur simultaneously (e.g. failure of the diesel generators due to the collapse of the diesel generator building by accumulated snow on the roof or blockage of air intake filters due to snowstorm). Moreover, snow induced switchyard failures and blockage of the air intake filters to the diesel generators were to be considered in the assessment.

The event tree developed for extreme snow as a single hazard was considered as the basis of event logic modeling for the combination of extreme wind and snow. This even tree was modified to enable an adequate quantification. In order to consider scenarios when at least one snow induced transient or mitigation system failure occurs (except for switchyard failures due to snow) in conjunction with wind induced loss of normal power supply, those event sequences were selected from the event tree for extreme snow that represent snow induced transients (except for snow induced loss of normal power supply) or other failures but leading to a safe, stable plant state. Dedicated event trees describing wind induced loss of normal power supply were linked to the success event sequences of the event trees for extreme snow. Besides, basic events representing the failure of the diesel generators due to blockage of the air intake systems by snowstorm were built into the fault tree related to the event tree header of snow induced switchyard failures.

Pre-initiator (type A) human actions considered in the PSA for internal events are included in the PSA for extreme wind and snow 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 events PSA where the external hazards are 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 PSA for extreme wind and snow. However, in the PSA for extreme wind and snow 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.

It was concluded that the event logic model for the combination of extreme wind and snow could be based on the PSA model for snow, and all snow fragility groups had to be considered, whilst, only wind induced loss of off-site power and switchyard failures needed to be included from among the wind fragility groups. In order to enable efficient and simple risk quantification, the conditional failure probability of the loss of off-site power or switchyard failures due to wind was assessed for each snow load with the following formula:

$$FP_j(WBE_k) = \frac{\sum_{i=1}^{300}\left(FF_i(WBE_k) \cdot h_{i,j}\right)}{H_j} \tag{3}$$

where:

- WBE_k denotes a basic event in the minimal cut set representing a wind induced failure (loss of off-site power or switchyard failure, k = 1, 2);
- $FF_i(WBE_k)$ is the mean conditional failure probability (fragility) of a wind fragility group for wind range "i";
- $h_{i,j}$ is the mean occurrence frequency of the wind range "i", corresponding to the lowest value of snow range "j";

- H_j is the mean occurrence frequency of extreme snow as a single external event corresponding to the lowest value of snow range "*j*".

Accordingly, all fragility groups, including the wind induced failures too, were characterised as a function of snow load. Therefore, the same quantification approach could be followed as in the PSA for snow as a single hazard, using families of continuous hazard curves from the snow PSA and the relevant wind fragility curves as a function of snow load.

4. FINDINGS

The core damage risk attributable to the combinations of earthquake occurring in extreme warm weather as well as of extreme wind and snow was quantified. All other combinations of external hazards were screened out from detailed assessment, since either the risk attributable thereto was found negligible or their risk implications have already been considered in the risk assessment for single external hazards.

Based on the results of quantification, the point estimate of the core damage frequency attributable to earthquake occurring in warm weather is $1.74 \cdot 10^{-7}$ /a. As the same seismically induced component failures occur in warm weather in full power operation as well as in low power and shutdown states, the risk level can be considered as constant throughout the year, regardless of the plant operational state. It is noted that the conditional core damage probability for different extreme warm weather situations assuming loss of the HVAC systems was estimated on the basis of a rough conservative expert judgement. Therefore the risk estimate has considerable uncertainties and should be rather regarded as an upper bound value in all PSA applications. Although the results can be regarded as reasonably conservative, symmetric sensitivity analyses have been performed. The sensitivity studies showed that if all conditional failure probabilities estimated by experts are assigned to a higher or lower temperature value by 1 °C, the risk results double or decrease to 50%. It was concluded that the risk attributable to earthquakes occurring in warm weather is in the order of magnitude 10^{-8} /a – 10^{-7} /a. The results of importance analysis pointed out that the fans and heat exchangers of the HVAC system as well as the seismically unqualified relays and cabinets are the dominant risk contributions.

According to the PSA results, the point estimate of the annual core damage probability attributable to extreme wind and snow is 2.06E-08. The most dominant event sequences include (1) the loss of off-site power due to high wind and the blockage of the air intake system of the diesel generators due to snowstorm; (2) the wind induced failure of the switchyard, subsequent failure of plant operation in island mode and the blockage of the air intake system of the diesel generators due to snowstorm. These event sequences are similar in each plant operational state. Consequently, random failures and characteristics of different plant operational states do not have a significant effect on the risk results, hence the risk in the different plant operational states do not differ considerably. Although it was not found feasible to quantify the uncertainties in the results of hazard assessment and in the blockage probability of the air intake system of the diesel generators, the limited scope parametric uncertainty analysis that was performed still showed remarkable uncertainties in the risk estimate due to the large uncertainties in the snow removal from the roofs of the safety related buildings.

Several safety enhancement measures were proposed on the basis of the assessment. The most important ones are listed hereby:

- The application of the severe accident management diesel generators to ensure power supply to the consumers of the cooling system of plant rooms should be proceduralized and the training programs should be complemented accordingly.
- The reliability of establishing plant operation in island-mode in case of loss of off-site power should be enhanced, as the failure of the power grid proved to be a significant risk contributor due to its less stringent design criteria.
- Modification of the relevant plant procedure on removal of snow deposits from the roofs of safety related buildings has been proposed together with the identification and allocation of the

necessary 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.

- Although the risk attributable to extreme wind and snow appears moderate, a proposal was made to implement administrative and/or technical measures to mitigate the blockage of the air intake system of the diesel generators with high confidence by switching to the use air from within the room.

5. CONCLUSION

Originally, the analysis and evaluation of plant resistance against design basis loads as well as the PSA of the plant were limited mostly to single external hazards. An assessment of combined external hazards for the Paks NPP has lately been completed. The relevant load combinations have been identified and characterized; the adequacy of protection against these hazard combinations has been justified. Moreover, the residual risk due to beyond design basis load combinations has been quantified and the main risk contributors have been identified. The assessment followed the commonly exercised steps in this domain: hazard selection and screening, hazard assessment, evaluation of plant protection, plant response and fragility analysis, development of event sequence models for hazard initiated plant transients, and risk quantification and evaluation of results.

Detailed assessment was performed for the following combinations of external hazards: handling of dangerous substances in severe weather conditions; multiple accidents in nearby industrial facilities due to a common initiator of natural origin; an earthquake that occurs when the ambient temperature is extreme; storm; extreme wind and snow; extreme low or extreme high ambient temperature. The risk induced by the combinations of extreme wind and snow as well as by earthquakes occurring in extreme warm weather was quantified using either a detailed PSA model or a bounding assessment, as shown appropriate. All other combinations of external hazards were screened out from detailed assessment, since either the risk attributable thereto was found negligible or their risk implications have already been considered in the risk assessment for single external hazards. The core damage risk attributable to these hazard combinations was found moderate ($\sim 2 \cdot 10^{-7}$ /a) being two orders of magnitude lower than the risk originating from single external hazards other than earthquake ($\sim 2 \cdot 10^{-5}$ /a). To sum up, it can be concluded that the Paks NPP is sufficiently protected against the combinations of external hazards.

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