NON-SEISMIC EXTERNAL EVENT LEVEL 1 PSA FOR THE WWER440 TYPE REACTORS

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The objective of the non-seismic external event PSA is to quantify the core damage frequency for all operating modes and to understand the overall risk from external events (natural events other than seismic events), identify the dominant contributors to the risk, determine the external event loads which dominate the plant risk, compare external event risk to risk originating from internal events and other events and propose safety measures to improve the plant safety. The basic inputs used for modeling of the plant are the results of the external event hazard analysis of the site (hazard curves), the fragility analysis of the plant structures, systems and components (fragility curves) and the existing level 1 full power and shutdown PSA model for internal initiating events. The impact of extreme meteorological conditions on safety of WWER440 reactors is being evaluated in the light of Fukushima accident. Only extreme meteorological conditions can have impact on the plant safety. The nuclear power plants are protected against all meteorological conditions that are likely to experience within the projected life time. The challenge is to estimate the frequency of such meteorological conditions which has potential to damage the plant.

I. INTRODUCTION

Based on the detailed analyses the following extreme meteorological conditions were included into the non-seismic external event PSA for the Slovak nuclear power plants: extreme wind, tornado, extreme snow, extreme rain, extremely high and extremely low air temperature, icing and lightning. Internal initiating events were identified from PSA for internal events, which can be induced by extreme meteorological conditions. The man-made external events with frequency of occurrence less than 1.0E-7/year were excluded from further analysis in coincidence with the methodological guidelines.

External events in the form of extreme weather conditions can occur as single events or as combinations of two or more external events. The potentially combined events are two or more external events having a conditional probability of simultaneous occurrence, e.g., strong winds occurring at the same time as precipitation and extreme snow.

The paper describes the external event PSA of the J. Bohunice V2 plant [1]. Following the introduction, the initiating events are identified in the second part of the paper. In the third part of the paper the definition and modeling of accident sequences is described. The topic of the fourth part is fault tree development. The fifth part describes the data analysis. The sixth part is focused on the results. The conclusions are presented in the seventh part of the paper.

II. IDENTIFICATION OF THE INITIATING EVENTS

This section describes the initiating events induced by the non-seismic external events. Accident initiating events (from the list of internal events PSA) induced by extreme wind are the following:

- Loss of essential service water (paths 1,2,3) induced by damage of turbine hall, essential cooling towers, central pumping station or building 805. Piping and tanks of essential service water system are damaged (the tanks of essential service water system are located in the building 805, level 31m) after collapse of the outside walls and windows,
- Opening of all steam dump stations to the atmosphere or SG safety valves due to damage of building 805 (mechanical damage of steam lines with steam line breaks after failure of outside walls),
- Closing of all quick closing valves on the steam lines after failure of outside walls of building 805 (mechanical damage of steam lines with isolation of main steam flow),
- Loss of offsite power due to damage of turbine hall, mechanical damage of plant transformers, self consumption transformers and auxiliary transformer,
- Loss of circulating cooling water for damage of central pumping station (outside walls and windows),

- Loss of feedwater supply due to damage of turbine hall (outside walls and windows).

Dominant type of damage is collapse of outside walls of the building due to strong wind. The analyses suppose:

- collapse of outside wall structures,
- potential failure of steel covering,
- failure of outstanding panels from the walls and
- failure of operational and safety systems and equipment leading to the occurrence of initiating events in the buildings with large openings and windows.

Accident initiating events induced by tornado are the same as for the extreme wind. Missiles produced by tornado can damage buildings with window openings but also the structure of the buildings. Possible sources of missiles in the tornado are cars in the site, unprotected or weak anchored pipelines, lamp pillars, steel structures and equipment coverings, fire hydrants, etc. Car size missiles can roll in extreme wind and eventually collide with near building structures. The Slovak Hydro-meteorological Institute (SHMU) does not register any tornado in Slovakia until now. Therefore, generic tornado data valid in Europe were used for the purpose of the project.

Accident initiating events induced by extreme snow are the same as for extreme wind. So, extreme snow induces damage of the same buildings as extreme wind (turbine hall, essential cooling towers, central pumping station or building 805).

Accident initiating events induced by extreme rain are as follows:

- Loss of essential service water (paths 1,2,3) induced by damage of turbine hall, central pumping station, and
- Loss of circulating cooling water induced by damage of turbine hall, central pumping station

Accident initiating events induced by extremely high air temperature is inadvertent reactor trip due to limiting conditions of operation (ESFAS and category I uninterruptible power supply are becoming unavailable).

Accident initiating events induced by extreme low air temperature is loss of essential service water system due to freezing of water in the pump suctions.

Accident initiating event is loss of offsite power due to loss of electrical lines under the weight of icing.

Accident initiating event is loss of offsite power after lightning strike into the turbine hall, self consumption transformers or unit transformers.

Frequency of aircraft crash into Unit 3 of J. Bohunice V2 NPP was estimated. Frequency of occurrence is less than 1.0E-7/year. Thus the aircraft crash is excluded from further analysis. Similarly, influence of neighboring industry and other external influences were estimated and excluded from further analysis. The analyses are performed using the approaches involved in the WENRA and IAEA guidelines [2,3].

III. ACCIDENT SEQUENCE DEFINITION AND MODELING

The main objective of the accident sequence definition and modeling is to modify the event trees, developed earlier within the internal event PSA (if they are applicable for the external event PSA), to construct the event trees for the specific external event-induced initiating events that reflect the plant response to external events and to construct a generic event tree that integrates these event trees to external event PSA model and provides possible combination of single initiating events.

An example of systemic event tree, constructed for initiating events induced by extreme meteorological conditions, is described. Extreme meteorological conditions can destroy buildings. Spatial correlation of events associated with building damage leads also to damage of components of operational and safety systems.

The systemic event tree for consequential loss of main feedwater system (LMF-EWI) is described for illustration. This event is involved in the internal event PSA. The initiating event, initiated by extreme wind, is unavailability of all working main feedwater pumps. The probability of occurrence depends on wind speed. Given the initiating event, both TGs will be tripped due to the low pressure in the discharge header of main feedwater pumps. Then, the AO1 reactor scram will be initiated upon low steam generator (SG) level, high SG pressure or high reactor coolant system (RCS) pressure and temperature. Following the reactor scram the steam and heat removal will be performed using the steam dump stations to the condensers. The steam dump stations to the atmosphere and the steam generator safety valves are also available.

The start of auxiliary feedwater (AFW) system is assumed from low SG level. Given failure of this system, the emergency feedwater (EFW) pumps start upon SG level decrease. Given failure of the EFW system, the mobile source can be used to supply SG. Given no reactor protection system (RPS) interaction, emergency boration is performed by the operator using the emergency procedures.

Given loss of the primary to secondary side heat removal, the primary bleed and feed is initiated. It is restoration of the critical safety function by operator using the emergency procedure. One high pressure safety injection (HPSI) pump is started and a pressurizer relief valve or 1/2 safety valves is open. The RCS can be depressurized also using the severe accident management (SAM) system to depressurize RCS. Given failure of the HPSI pump, the primary bleed and feed can be performed also using the low pressure safety injection (LPSI) system. The RCS depressurization is performed using the pressurizer relief valve and 2/2 pressurizer safety valves or the SAM system to depressurize RCS.

Failure of main steam relief is negligible. Adequate redundancy exists to provide steam relief via 1/4 steam dump stations to the condensers, 2/6 steam dump stations to the atmosphere or 3/18 SG safety valves.

The event tree for LMF-EWI is presented in Fig. 1. The node LMF-EWI00 represents the initiating event. The reactor will be tripped upon high SG pressure, low SG level, high RCS pressure or temperature or emergency boration. It is represented by @RP-LMF00 top event. The primary to secondary side heat removal can be performed in natural or pumped circulation. The 6 available SG can be supplied by AFW or EFW system or mobile source. The node @AF(LMF)00 represents the primary to secondary side heat removal in pumped or natural circulation when the SG are supplied by AFW pumps and adequate steam relief is provided. The node @EF00 represents the primary to secondary side heat removal in pumped or natural circulation when the SG are supplied by EFW pumps or mobile source and adequate steam relief is provided.

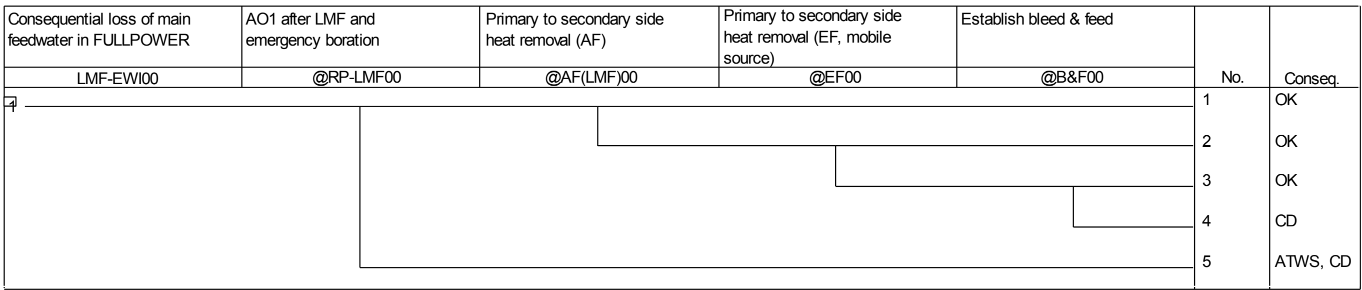

Fig. 1 Event tree for LMF-EWI

Given loss of the primary to secondary side heat removal primary bleed & feed is initiated. This is represented by the top event @B&F00.

There are the following sequences in the event tree:

Sequence 1: This is a successful sequence. After reactor trip, the primary to secondary side heat removal is performed using AFW pumps to supply SGs and adequate steam relief is provided.

Sequence 2: This is a successful sequence. After reactor trip, the primary to secondary side heat removal is performed using EFW system or mobile source (the AFW system is failed) to supply SGs and adequate steam relief is provided.

Sequence 3: This is a successful sequence. After reactor trip, the primary to secondary side heat removal is failed, but primary bleed and feed is initiated.

Sequence 4: After reactor trip, the primary to secondary side heat removal is failed and no primary bleed and feed is performed. It causes core damage.

Sequence 5: This is an anticipated transient without scram (ATWS) event leading to core damage with no RPS response and no emergency boration.

There are the following top events in the event tree:

@AF(LMF)00 - failure of the primary to secondary side heat removal in pumped or natural circulation using AFW pumps with possibility to supply 6 SG. Adequate steam relief is provided via steam dump stations to the condensers, steam dump stations to the atmosphere or SG safety valves.

@B&F00 - failure of primary bleed & feed.

@EF00 - failure of the primary to secondary side heat removal in pumped or natural circulation using EFW or mobile source with possibility to supply 6 SGs. Adequate steam relief is provided via steam dump stations to the condensers, steam dump stations to the atmosphere or SG safety valves.

@RP-LMF00 - no reactor trip (AO1) signal from high SG pressure or low SG level or high RCS pressure or temperature and no emergency boration.

A generic event tree is constructed for the plant to model simultaneous occurrence of initiating events during an external event. The initiating events (see section II.) are involved in the heading of the generic event tree.

Simultaneous occurrence of initiating events is possible in any combination during an extreme wind. The generic event tree was not developed by a mechanistic approach. If the generic event tree would have been built up mechanistically then the number of the event sequences would be 2N, where N is the number of potential initiating events (6 in our case). This would have resulted in 64 accident sequences. However, it is possible to reduce the number of accident sequences in the generic event tree to the acceptable level by leaving out unnecessary or meaningless combinations of initiating events.

The generic event tree is constructed using the hierarchy between the initiating events. It allows to reduce the complexity of the event tree model. The order of this hierarchy is defined such that if one initiating event occurs, the occurrence of other initiating events further down the hierarchy is of no significance in terms of the plant's response. Thus, for example, if a loss of offsite power occurs, we are not concerned whether a loss of circulating cooling water or loss of feedwater supply occurs. Plant's response requirements will be dictated by the need to mitigate the loss of offsite power.

The following considerations were made that helped to reduce the complexity of the generic event tree:

1. Inadvertent opening of all steam dump stations to the atmosphere or all SG safety valves (SDTA-SGSVALL-EWI) in combination with closing of all quick closing valves on the steam lines (QCV-ALL-EWI) has no impact on the plant response. Therefore, the tree does not branch off after SDTA-SGSVALL for QCV-ALL-EWI.
2. Loss of circulating cooling water (LOCW-EWI) leads to loss of main feedwater (LMF-EWI). So, the tree does not branch off after LOCW-EWI for LMF-EWI. Simultaneous occurrence of the both initiating events has the same response on the plant as a single initiating event (LOCW-EWI).
3. Loss of all operational service water trains LOSW(1,2,3)-EWI leads to loss of high pressure safety injection system. Simultaneous occurrence of this initiating event with opening of all steam dump stations to the atmosphere and all SG safety valves leads to core damage because loss of coolant is not compensated after undercooling of the reactor.

The generic event trees were constructed for extreme wind, tornado, extreme snow, extreme rain, extremely high and low temperature, icing and lightning. An example of the generic event tree is presented in Fig. 2 for extreme wind during full power operation.

VI. FAULT TREE DEVELOPMENT

The fault trees are constructed to adequately describe the logical combinations of equipment failures and human errors leading to the failure of safety systems to fulfill their intended functions. The system models of the internal event PSA are a good starting point for developing fault trees for the external event non-seismic PSA. These existing systemic fault trees are extended and modified for the purposes of the external event PSA.

The following tasks are performed to develop system fault trees so that they meet the requirements of the external event PSA:

1. addition of external event-induced causes for component failure modes that are included in the PSA models for internal events,
2. addition of new external event-induced component failure modes that are not included in the PSA models for internal events due to their low probability of occurrence,
3. modeling of failures for buildings and facilities due to spatial system interactions.

The first two steps above are concerned with supplementing the PSA model with "new" component failure events, while the last with modeling of equipment failures due to the collapse of buildings, where facilities are located. Failures may occur as a result of the impact of external events or influence of random effects (not due to external events). Fault tree development procedure is analogous to that of the seismic PSA. Thus a failure mode included in this list can occur as a consequence of an external event or due to random effects. These failure modes are transferred into an OR gate (see Fig 3).

V. DATA ANALYSES

The input data set necessary for internal event full power PSA are the following:

1. initiating event frequencies,
2. component failure rates and failure probabilities,
3. time date related operation, testing, repair and maintenance (mission time, repair time, test interval, test duration),
4. common cause failure probabilities, and
5. human error probabilities.

Additional data are required for the external event PSA. The initiating event frequency is calculated from the hazard curves of each external event. The external event induced failure probabilities are calculated using the fragility analysis. The correlated component failures are calculated using the correlation coefficient. Probabilities of human errors from the internal events PSA are recalculated for the purpose of external event PSA.

The frequency of an external event is characterized by the hazard curves that show the annual frequency of exceedance at various levels of load and at different levels of confidence. For the convenience of calculation the hazard curves are decomposed into a number of discrete load ranges. The calculations are performed for these discrete ranges, characterized by the mean frequency of the load for each range. The hazard curves are considered as input information for the external event

PSA. The hazard curve for extremely low temperatures is presented in Fig. 4 for the of the Unit 3 of J. Bohunice V2 NPP. Table I. presents the input data for the hazard curves from the SHMU measurements on the site. The curves are constructed using the Gumbel distribution.

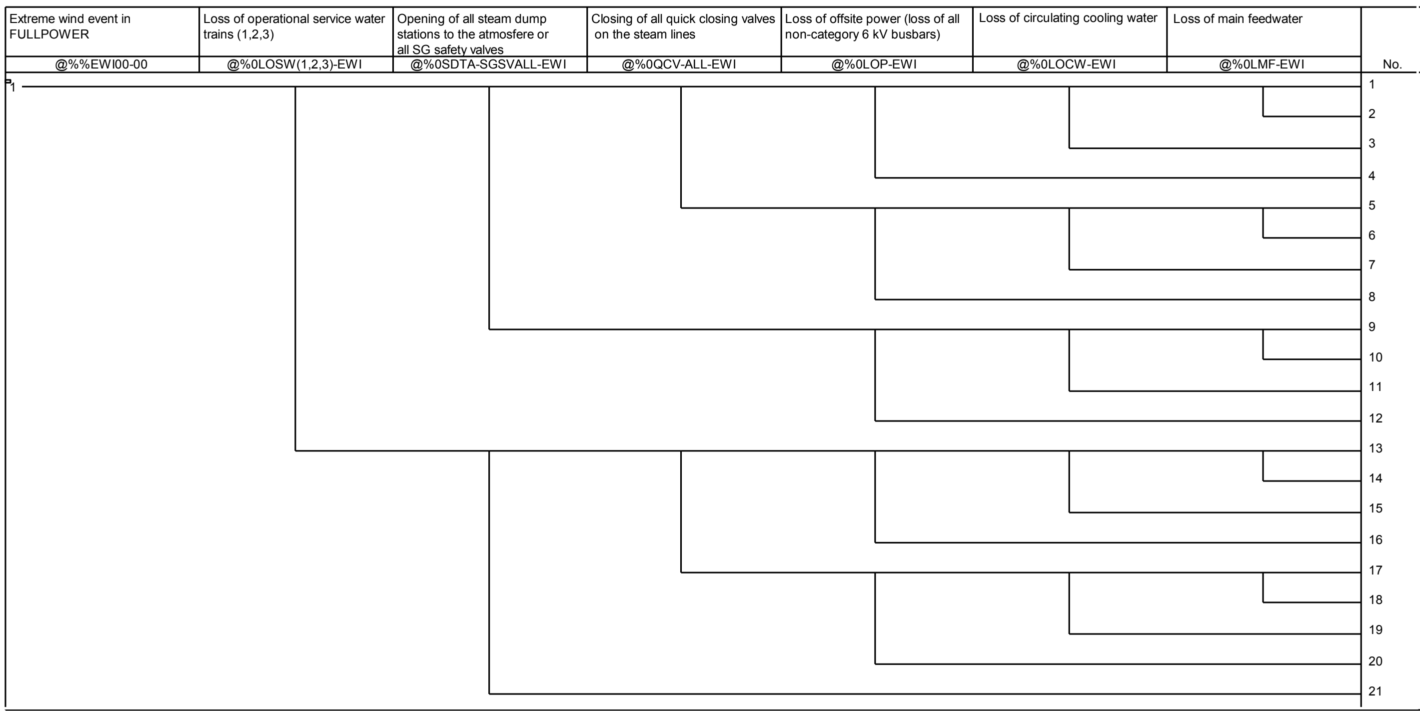

Fig. 2 Generic event tree for extreme wind

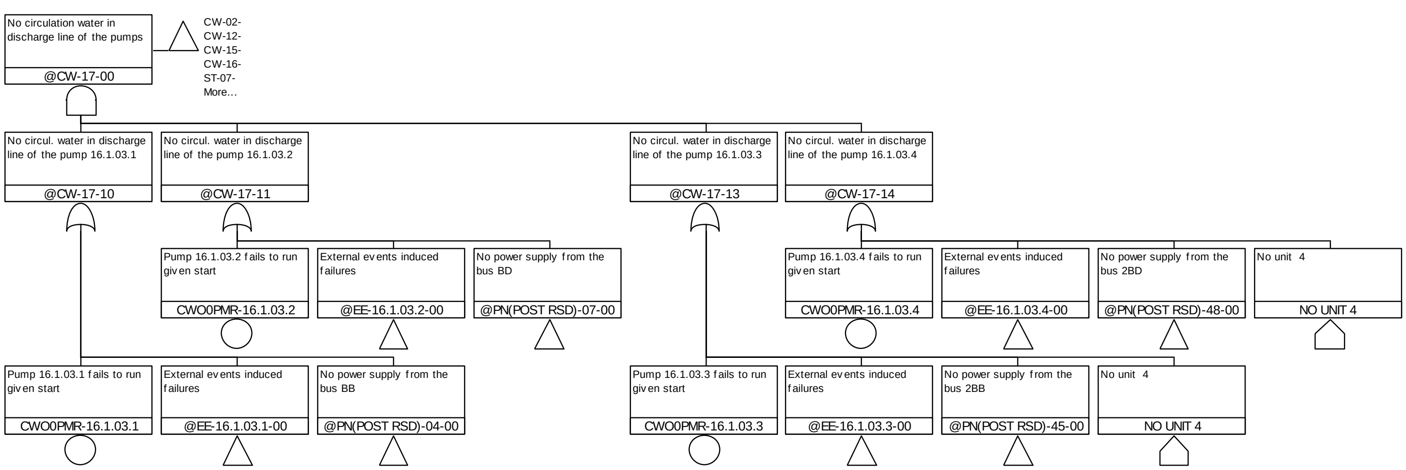

Fig. 3 Fault tree development for external events

TABLE I. Daily minimum temperature data from the meteorological station

Winter		1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989
T_{min}	**[°C]**	-13.8	-24,0	-16.6	-26.1	-10.7	-10.6
Winter		1989-1990	1990-1991	1991-1992	1992-1993	1993-1994	1994-1995
T_{min}	**[°C]**	-12.3	-15.5	-12.6	-19,0	-12.6	-17.6
Winter		1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001
T_{min}	**[°C]**	-18.4	-20.7	-13.6	-14.1	-14.6	-10.1
Winter		2001-2002	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007
T_{min}	**[°C]**	-20.1	-16.1	-15.3	-16.2	-19.6	-8.8
Winter		2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	2012-2013
T_{min}	**[°C]**	-11.7	-17.7	-17.5	-18.1	-15.1	-13.3

Failures of equipment and structures, induced by external event, including initiating events and mitigating system failures, are modeled by different basic events within the different load ranges. The probabilities of these non-seismic failures are determined by the fragility analyses for each external event. Each fragility analysis quantifies the likelihood that a component or structure may fail, as a function of the external event load. The fragility analyses explicitly account for the effects from randomness of the characteristics and uncertainty in the component response to a particular input load. Therefore, the fragility of each component is specified by a family of continuous curves that extend over the full range of input loads. The likelihood that the component may fail during a specific, by external event induced, initiating event is determined by convolution of the family of fragility curves with the input hazard curves, over the specified initiating event load range. Thus, the resulting mean failure fraction accounts for both the uncertainty in the hazard and the uncertainty in the component fragility over the input range of loads. The fragility curves are specified as continuous functions that extend from a zero failure probability to a maximum considered failure probability. In practice, a lower limit is typically assigned to the fragility for each component, below which the likelihood of failures is considered negligible. The lower limit is defined by the "High Confidence of Low Probability of Failure" (HCLPF) load. This value is determined by the peak load at which there is 95% confidence of less than 5% chance of failure. In practice, the HCLPF capacity is the peak load below which there is less than approximately 1% cumulative probability of component failure when the complete fragility curves are convoluted with the hazard curves. A typical set of fragility curves of the extreme wind are shown in Fig. 5 for the steel construction of the reactor hall roof.

VI. RESULTS

The contribution from non-seismic external event to the total core damage frequency is low (on the level of 1.0E-6/year for all operating modes). Dominant contribution is coming from the extreme wind and tornado.

The contribution from combination of external events is negligible.

The safety upgrades against extreme wind and tornado are proposed to decrease the risk. It is proposed to increase the resistance of glass panels and windows in the turbine hall and central pumping station (building 584) to prevent their damage due to missiles   during tornados. After implementation of the proposed changes the contribution to the total core damage frequency is decreased by one magnitude (to the level of 1.0E-7/year for all operating modes). The same is valid fuel damage frequency (FDF) in the spent fuel pool for all operating modes.

It is necessary to note, that the results are significantly dependent from correlation coefficient. It represents the probability that system components located in the buildings will fail following building damage. These coefficients are applied for extreme wind, tornado, extreme snow and extreme rain. Further research is needed in this field to eliminate or decrease uncertainties in the results.

The results are significantly impacted also by human reliability in threat category of EE02. There are three categories of threats due to external events: EE01, EE02 and EE03. In case of EE01 the human error probabilities are used from the internal event PSA. EE02 represents medium-sized deterioration of conditions for human interactions due to external events. EE03 does not suppose successful human action due to significant deterioration of conditions, initiated by external events.

In case of category EE02 such state of signalization and alarms can occur, which are not involved in the procedures. The measurement under condition of building collapse will be degraded in such a way, that incorrect values will be presented for the operator. According to this values interactions must be performed within the SB EOP (Symptom-Based Emergency Operating Procedures). However, there is high probability that these interactions will not be successful for accident mitigation. Increasing of human reliability by improvement of the procedures is not possible under such conditions. The only way how to improve the human reliability is safety upgrading of the buildings, electrical equipment and mobile sources against external events to the level where spurious signal generation is not possible and the conditions valid for category EE01 are maintained.

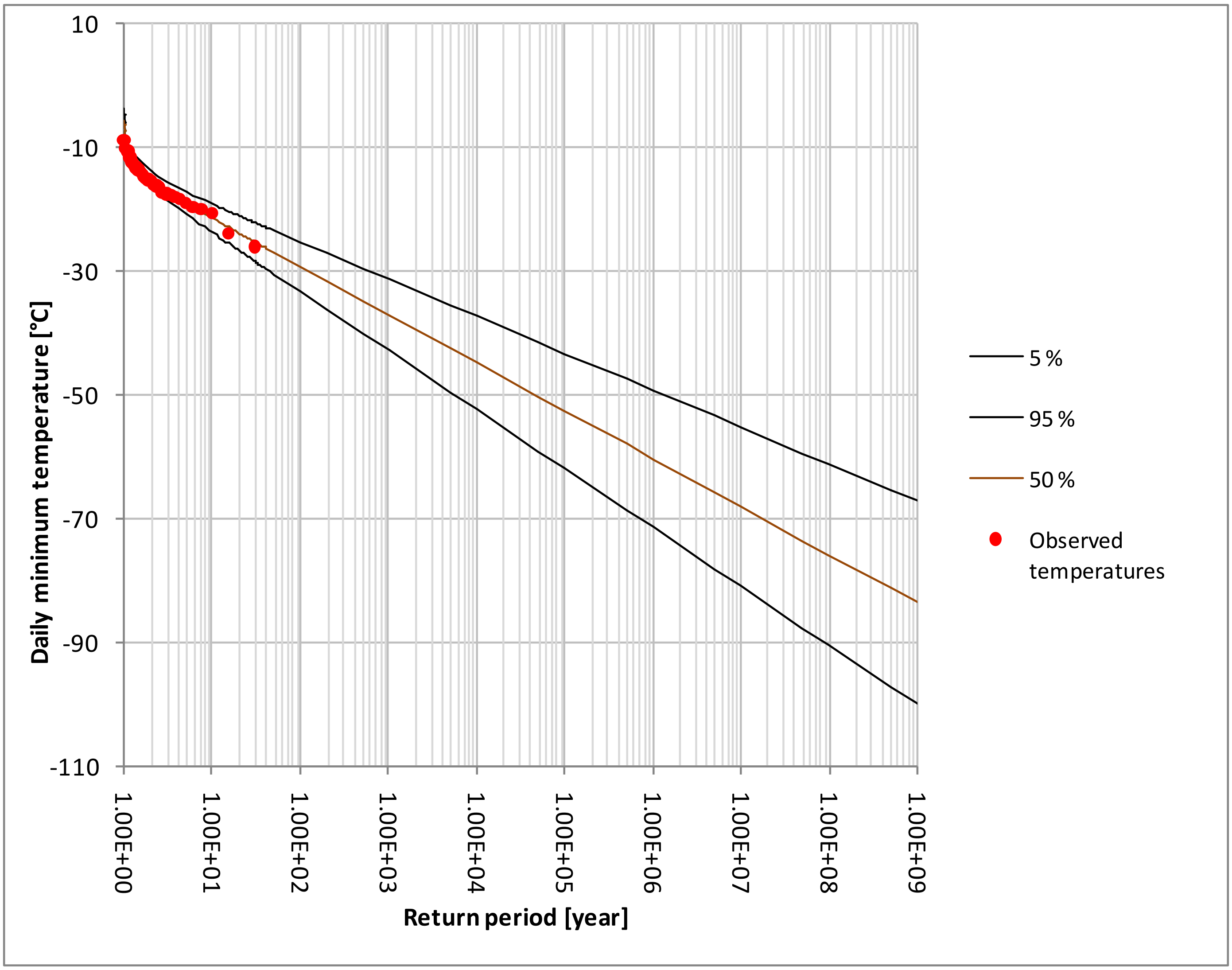

Fig. 4 Hazard curves for extreme low temperatures

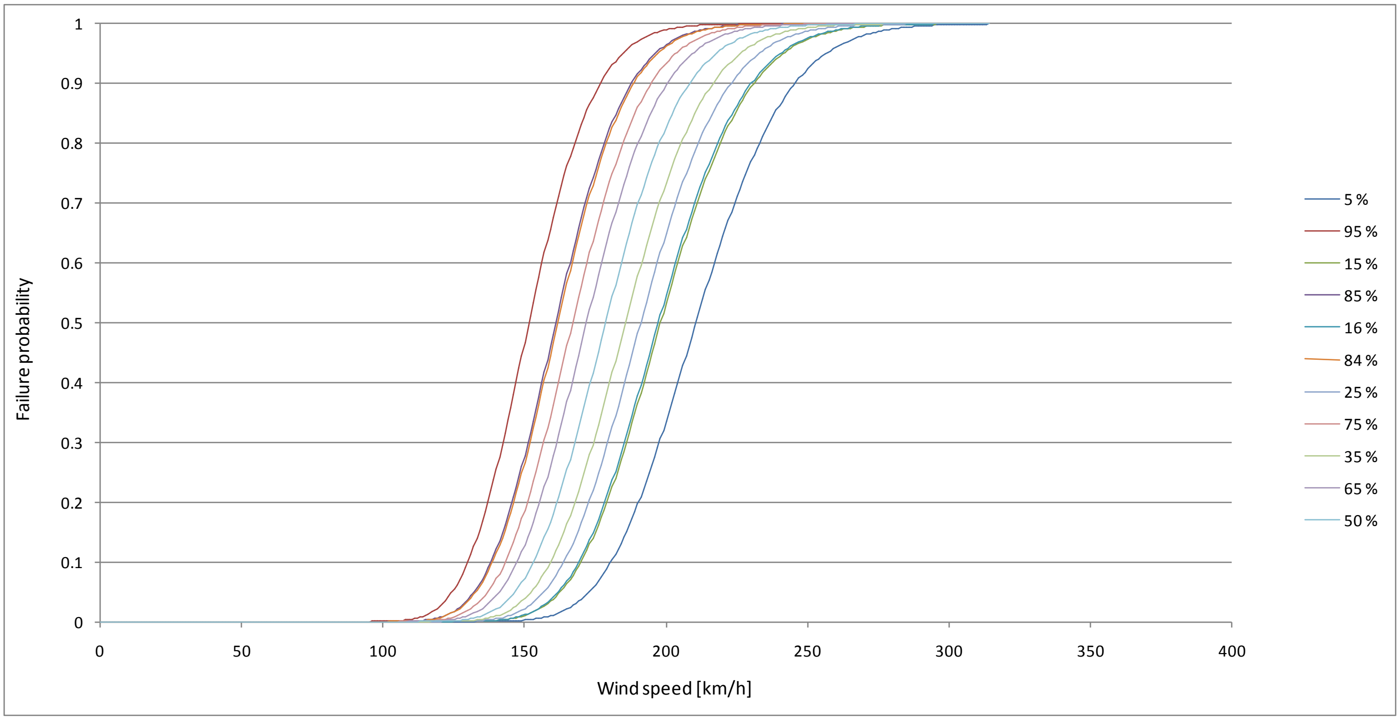

Fig. 5 Fragility curves of the extreme wind for the steel construction of the reactor hall roof

VII. CONCLUSIONS

Finally, it can be concluded that the non-seismic external event contribution to the overall CDF and FDF is low enough. However, further increasing of the safety is possible by increasing resistance against non-seismic external events (mainly extreme wind and tornado) of the selected buildings.

Combination of external events was also evaluated. Causally connected hazards (cause-effect relation) where one hazard may cause another hazard or where one hazard is a prerequisite for a correlated hazard were not identified for the Slovak sites. Associated hazards which are probable to occur at the same time due to a common root cause has negligible impact on the risk.

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