External Event Evaluations for the Design Phase PRA of Hanhikivi 1

Juho Helander*
Fennovoima, Helsinki, Finland

Abstract: Fennovoima's Hanhikivi 1 nuclear power plant will be constructed on a new nuclear power plant site. This paper summarizes the comprehensive evaluations of external events performed for the Hanhikivi site, including event identification, grouping and probability evaluations. Events were grouped into three different categories based on the safety significance, and most focus has been put on the events in the highest category in event studies, plant design and analyses. Hazard curves were evaluated for external events if measured time series from several decades were available. In other cases, event probabilities in the Hanhikivi site were evaluated based on other methods. Specific studies were conducted for example for loss of offsite power, loss of ultimate heat sink and lightning strikes. In addition to the single events, also event combinations were assessed. The information provided by the external event studies has been utilized in defining plant design values and in developing the external event PRA. Currently a preliminary version of the Hanhikivi 1 design-phase PRA has been developed, and the general approach used in the external event PRA is discussed in this paper.

Keywords: PRA, External events, External event PRA

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1. INTRODUCTION

Fennovoima is planning to construct a new nuclear power plant, Hanhikivi 1, in Northern Finland. The plant is currently under design and the construction is scheduled to begin in 2019 and electricity production in 2024. A preliminary design-phase PRA for Hanhikivi 1, which has been developed by JSC Atomproekt, was completed in 2017. The PRA will be updated in 2019 based on the updated design information of the plant.

This paper presents an overview of the external event evaluations - including event identification and categorization and probability estimation - performed for the Hanhikivi site in the design phase of the plant project. Furthermore, it is discussed how the external event studies have been used in determining external event design values and in developing the Hanhikivi 1 PRA.

2. METHODS

2.1. Guides and standards

The Finnish YVL guide B.7 "Provisions for internal and external hazards at a nuclear facility" is the main regulatory document presenting requirements related to the protection of a nuclear facility against external events. The YVL guide B.7 lists several external events that shall be considered in the plant design. However, the licensee shall compile and justify the comprehensive list of external events considered relevant in the plant site. Furthermore, in the YVL guide B.7 it is required that the occurrence frequencies of external events affecting plant safety shall be assessed. If measured time series are available, a hazard curve shall be determined for the phenomenon. When extrapolating to low probabilities, an extreme value distribution shall be fitted to the measurement data. Furthermore, the uncertainties shall be considered by evaluating separate hazard curves based on the measurement data of several different locations in the vicinity of the nuclear power plant.

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*juho.helander@fennovoima.fi

The YVL Guide B.7 requires that the plant design values against external events are determined based on the following general principles:

- The design values shall include an adequate margin to the record observations measured in the site vicinity
- The median probability of the exceedance of the design value shall be less than 10^{-5}/y
- Events exceeding the design values shall be considered as design extension conditions (DEC C events)

Furthermore, specific requirements are given regarding high sea water level:

- The design value shall be higher than the sea level with 10^{-2}/y median probability + 2 m + site-specific wave margin
- The design value shall be higher than the level corresponding to the least favorable combination of factors affecting the sea water level, including the total volume of water in the Baltic Sea, air pressure, wind, seiche and tide

The Finnish YVL guide A.7 “Probabilistic risk assessment and risk management of a nuclear power plant” presents general requirements for the PRA of a nuclear facility in Finland. As regards external events it is required that: “The frequency of events exceeding the plant design bases and their impact on safety systems as well as potential losses of safety functions shall be analyzed in the PRA”. Furthermore, it is required that “abnormal weather conditions, seismic events and other environmental factors as well as external factors caused by human activities” are analyzed as initiating events in the PRA.

In addition to the YVL guides, also the following international guides and standards provide guidance related to external event identification and analysis:

- IAEA. NS-G-1.5, 2003. External events excluding earthquakes in the design of nuclear power plants.
- IAEA. NS-G-3.1, 2002. External human induced events in site evaluation for nuclear power plants.
- IAEA. NS-R-3, 2016. Site evaluation for nuclear installations.
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- SKI. SKI report 02:27, 2003. Guidance for external events analysis.

2.2. Method description

Hanhikivi is a greenfield site; no operating nuclear power plants exist at the site. Thus, no previous information related to external events existed, and it was necessary to perform all necessary external event evaluations to provide adequate information for determining plant design values and to develop external event PRA. The general process related to external event evaluations is presented in Figure 1.

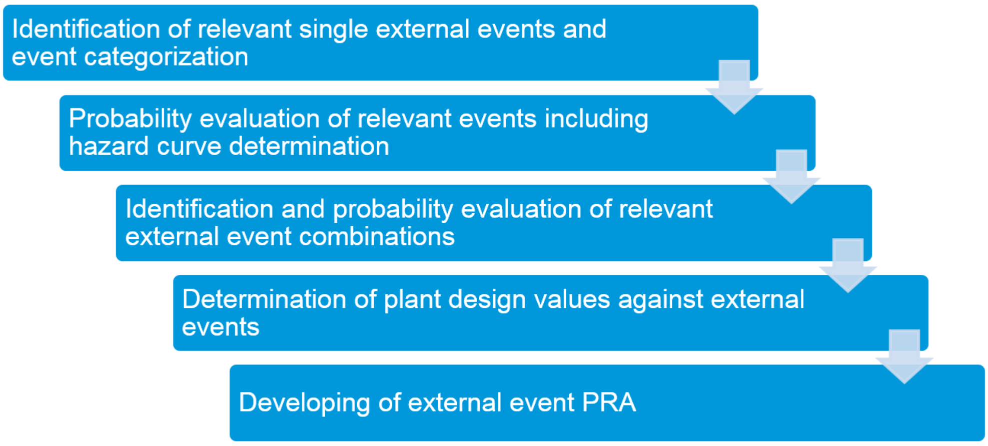

Figure 1: The general process related to external event evaluations.

The first phase in the external event evaluations includes the identification of all external events relevant from the nuclear safety perspective. To begin with, a preliminary, comprehensive list of all conceivable external events was compiled based on the Finnish YVL guide B.7 and other relevant guides and standards listed in section 2.1.

After the initial list of external events was compiled, each event was categorized into one of the following three groups based on the safety significance:

I. The event shall be considered in the plant design and it is considered significant to nuclear safety. These events may cause an initiating event or loss of safety significant system, structure or component (SSC). Most attention should be paid to these events in the plant design and analyses, such as PRA.

II. The event shall be considered in the plant design, but its significance to nuclear safety is considered low because the event is characterized by one or more of the following aspects:
  - It is considered highly improbable that the event could lead to failure of safety-significant SSC
  - Event probability is extremely small or other events leading to the same consequence are considered significantly more probable
  - The progress of the event is slow
  - The design provisions against the event are fairly simple and straightforward
  - Consideration of the event in the plant design is obvious (for example it is considered in any construction work performed in Finland)
  - The event is rather related to plant operability than safety

III. The event is extremely unlikely or not considered possible at the Hanhikivi site or its consequences are insignificant.

For the Hanhikivi nuclear power plant site, detailed probability evaluation was performed for external events belonging to the event category I. Hazard curves were evaluated based on the measurement data of the Finnish Meteorological Institute supplemented with the data of the Swedish Meteorological and Hydrological Institute. Uncertainties were considered by determining the hazard curves based on data from several different weather stations near the Hanhikivi site and also by utilizing different statistical methods (Annual Maximum and Peak-Over-Threshold) and by fitting different probability distributions to the data including Generalized Extreme Value (GEV) distribution, Gumbel, log-normal, Weibull and exponential distributions. The probabilities were evaluated from 10^{-1}/y up to the annual probability of 10^{-9}. Among the several hazard curves, the one considered the most representative for the Hanhikivi site was selected.

Based on the measurement data, the record observations close to Hanhikivi were identified. Furthermore, the effect of climate change on the occurrence probability of each event by the end of the 21st century was assessed based on climate modelling and expert judgement.

Measured time series were not available for all external events. In these cases, the probability evaluation was performed by utilizing observation reports made by people, climate modelling and operational history of power plants operating in similar conditions. Regarding earthquakes, comprehensive probabilistic seismic hazard analysis (SPHA) was performed.

Regarding external event combinations, the method presented in Figure 2 was utilized [1] [2]. For external events belonging to category I, an event matrix was compiled in order to systematically evaluate each event combination of two events. Irrelevant event combinations were excluded mainly based on seasonal variation, exclusive preconditions and similar effects on plant safety. Event combinations including two events with an identified dependency were identified and evaluated in detail. After the analysis of combinations of two events, the combinations of three or more events were identified and analyzed. Detailed evaluation of plant response can be performed only when the plant design has been frozen.

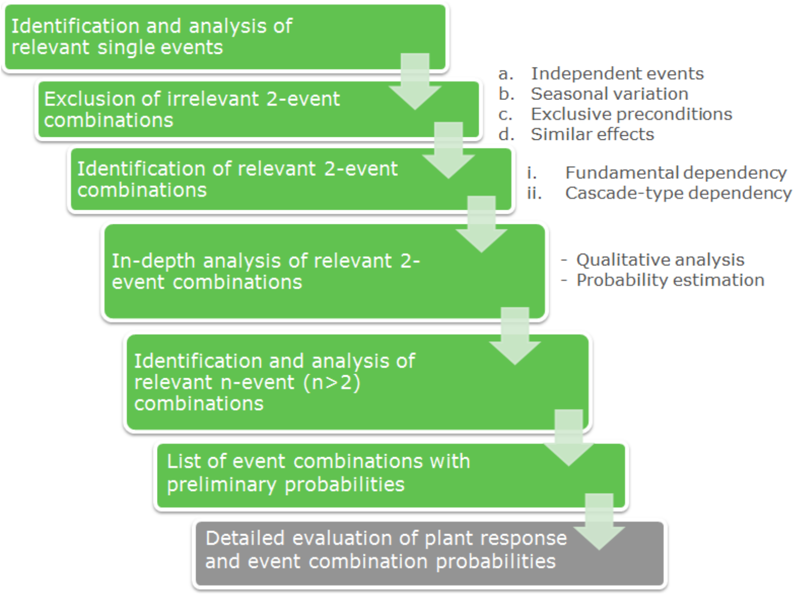

Figure 2: Identification and evaluation of external event combinations. [1] [2]

At this stage of the Hanhikivi 1 project, the event combination probabilities have been assessed with the preliminary and simple method presented in Table 1. The probability of the event combination (p_{12}) is determined by using the probability estimates of the single events (p_1, p_2). The event with a lower probability (p_1) is assumed to have occurred and the conditional probability of occurrence of the second event is assumed to range from 1 % to 50 %. In certain specific cases, the conditional probability may be re-evaluated based on expert judgement. This simple method for evaluating event combination probabilities can be considered conservative, and more sophisticated methods will be used during the PRA development in the construction phase of the plant.

Table 1: Determination of event combination probabilities.

	No strong dependency	Strong dependency
$p_2 / p_1 < 100$	$p_{12} = 0.01 \cdot p_1$	$p_{12} = 0.1 \cdot p_1$
$p_2 / p_1 \geq 100$	$p_{12} = 0.05 \cdot p_1$	$p_{12} = 0.5 \cdot p_1$

The design values for the Hanhikivi 1 plant were determined for all events for which hazard curves could be developed. In accordance with the Finnish YVL Guide B.7 (“Provisions for internal and external hazards at a nuclear facility"), the starting point for the design value determination was the 10^{-5}/y median value given by the hazard curve evaluated the most representative for the Hanhikivi site. In addition, the sensitivity analyses based on different statistical methods and distributions, the anticipated effect of climate change and the record observations were taken into account. Similarly, the design extension condition (DEC C) values were determined based on the 10^{-7}/y median values.

In the external event PRA, the single external events grouped into category I and the relevant event combinations identified according to Figure 2 were considered possible initiating events. The effects on plant safety were evaluated at different hazard levels:

- below the design values (probability > 10^{-5}/y)
- above the design values (probability between 10^{-5}/y and 10^{-7}/y)
- above the DEC C conditions (probability < 10^{-7}/y).

Seismic PRA was developed according to international guidelines, such as [3] and [4]. Only generic seismic fragilities of SSC can be used in the design-phase PRA, whereas plant specific fragilities can be evaluated later during plant construction.

3. RESULTS

3.1. Event identification and grouping

The initial, comprehensive list of external events included in total 73 external events related to meteorology, ground, water bodies and human actions (only accidental events were considered). Table 2 presents those 18 events grouped into category I, which includes events that are most significant to nuclear safety.

Table 2: Most significant external events grouped into category I.

Meteorological events	**Events related to sea**	**Other events**
Enthalpy	Algae or other organic material	Airplane crash
Freezing rain	Frazil ice	Chemical, liquid and gas releases, explosions and fires
High or low air temperature	High sea water level, including waves and meteotsunamis	
Lightning		Earthquakes
Rain	High sea water temperature	
Snow load and snow depth	Low sea water level	
Snow storm	Oil or chemical spill	
Wind, tornado and downburst	Sea ice and pack ice	

Several meteorological events were considered significant to safety. High air enthalpy, referring to conditions with high air temperature and humidity, could be considered also an event combination. However, because hazard curve for enthalpy can be determined, it was regarded as a single event. Snow storm is also a combination of events (strong wind and heavy snowfall) and it was analyzed in connection with event combinations (see Section 3.4).

As regards the sea-related hazards, specific focus has been put on the high sea water level as the Hanhikivi nuclear power plant is located close to the sea shore and external flooding could result in severe cliff-edge effects that simultaneously cause the unavailability of several safety systems. Other events related to sea could cause the loss of sea water cooling (i.e. loss of ultimate heat sink) due to blockage of sea water intake or screens, high sea water temperature or low sea water level.

The crash of a small airplane and a large commercial aircraft shall be considered in the plant design in accordance with the YVL guide A.11 "Security of a nuclear facility" regardless of the event probability.

Accidents related to dangerous chemicals, liquids and gases outside the site area and not related to the plant operation were evaluated insignificant as there are no major industrial or storage facilities or transportation routes nearby. However, the accidents related to substances stored and used within the site area, such as emergency diesel fuel, need to be considered. Earthquakes are considered significant events; although Finland is located in a seismically quiet intraplate area, the possibility of a strong earthquake cannot be excluded.

Additional 19 events listed in Table 3 were grouped into category II. Also these events shall be considered in the plant design, and it shall be ensured that the events do not lead to the failure of safety-significant systems, structures and components.

Table 3: External events grouped into category II.

Meteorological events	**Events related to sea**	**Events related to ground**	**Other events**
Air pressure (high/low/fluctuations)	Corrosion of underwater structures	Ground water level changes	Electromagnetic interference caused by solar flares or human activity
Atmospheric moisture (high/low/fluctuations)	Low sea water temperature	Land rise	
Drought	Growing of mussels, plant life and other organisms or accumulation of sediments in the sea water system	Soil frost	
Fog			External fires (wildfires and forest fires)
Hail			Birds, insects, rodents and other animals
Rime ice		Tunnel collapses	
Snow melting	Splashes from sea		Tree leaves

The remaining 36 events not listed in Table 2 or Table 3 were grouped into category III. It was evaluated that it is not necessary to explicitly consider these events in the plant design or analyses since the events are either extremely improbable or designing the plant against the events in categories I and II already provides adequate protection against category III events.

3.2. Hazard curves

Based on the comprehensive measurement data available from Finland (and Sweden), hazard curves were determined for the following external events: high enthalpy, high and low air temperature, lightning stroke peak current, precipitation, snow load, snow depth and wind, high and low sea water level and high sea water temperature. The hazard curves are documented in project specific reports that are not publicly available. Figure 3 presents an example of a hazard curve illustrating the return levels of cumulative daily precipitation (median and 90 % confidence interval) based on 134 years of data from a Swedish weather station close to Hanhikivi. Also the observations are shown in the figure.

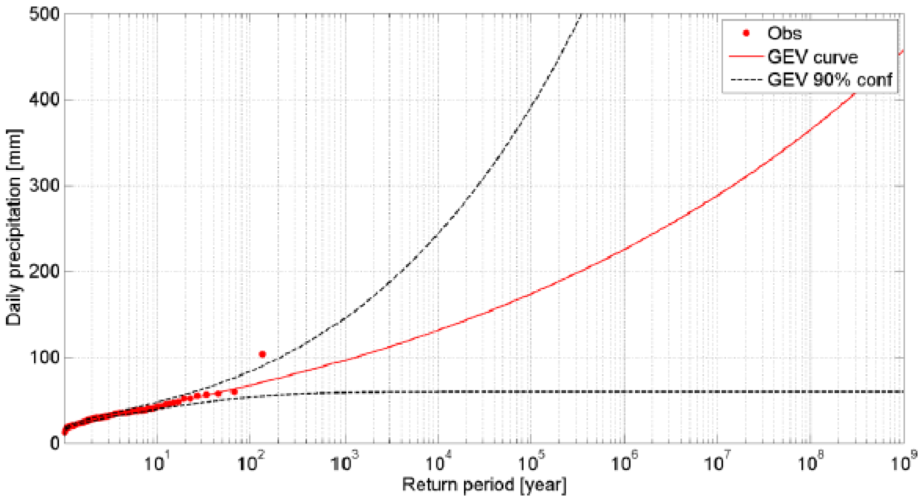

Figure 3: Hazard curve for 24 h cumulative precipitation based on 134 years of measurement data. Annual maximum method and fitting of the GEV distribution has been used.

For enthalpy and air temperature, hazard curves were evaluated for instant values and also for sustained values during longer time periods (6 h, 24 h and 7 days). To provide an example, the 24 hour sustained value for high air temperature determines a temperature above which the temperature sustains for 24 hours.

The probability evaluation of freezing rain includes large uncertainties because comprehensive measurement data is not available. Freezing rain has been studied by the Finnish Meteorological Institute within the Finnish Research Programme on Nuclear Power Plant Safety 2015 – 2018, SAFIR2018 (see for example [5] and [6]). Indicative return levels of freezing rain in Hanhikivi were estimated by using climate models and predefined filters for climate conditions that most probably lead to occurrences of freezing precipitation.

Tornadoes and downbursts are rare and local phenomena and thus the probability evaluation mainly relied on the observation reports made by people. Furthermore, the connection of these events with thunderstorms and the availability of lightning data was utilized. As a result, indicative annual probabilities (hazard curves) of tornadoes and downbursts belonging to different Fujita classes could be estimated. The Finnish data series utilized in the probability evaluations are presented for example in [7] and [8], whereas the actual project specific reports including the Hanhikivi site specific probability estimates are not publicly available.

3.3. Other probability evaluations

Category I (Table 2) includes several events related to sea that could result in the blockage of the sea water intake or screens. The probabilities of significant occurrences of algae or other organic materials in the sea water, frazil ice, sea ice and pack ice were determined based on the operational history of conventional power plants operating close to Hanhikivi in similar conditions. The total amount of operational history included in the study summed up to 57 years, and this data included 6 events related to algae and 2 events related to frazil ice that had led to loss of sea water cooling. Rough probability estimates of significant algae and frazil ice events potentially leading to loss of ultimate heat sink were given in [9]: $1.05 \cdot 10^{-1}$/y for algae and $4.17 \cdot 10^{-2}$/y for frazil ice. The probability of significant oil spill accident in the sea resulting in the blockage of sea water screens was determined based on accident history in the Baltic Sea and by performing event tree analysis: $4.2 \cdot 10^{-5}$/y [10] [11].

Concerning high sea water level, the hazard curves for "still water level" were evaluated based on the measurement data. The hazard curves were evaluated for the current climate and for the years 2050 and 2100 by considering the different scenarios of global sea level rise. Additionally, the impact of waves was determined separately based on wave run-up and overtopping studies. Wave studies were performed in two phases. At first, the wave impact at different locations in the Hanhikivi site was evaluated by assuming different wind directions and by performing wave simulations. The outcome of this study included the wave overtopping (liters per second per meter) to the elevated site area with different annual probabilities. In the second phase, a specific study was performed to evaluate the wave impact (at different probability levels) to a specific building located roughly 70 meters from the southern shoreline. Different methods (all including major uncertainties) were utilized in the second phase of the study (see [12], [13], [14] and [15]). Also a more deterministic evaluation of the maximum theoretical sea level was performed by assuming the most unfavorable combination of different factors affecting the sea water level: seasonal mean sea level affecting the sea level in the Baltic Sea, low pressure and on-shore winds, seiche, tide and meteotsunami. The resulting sea water level from this evaluation was approximately 3.1 meters (N2000 height system), which roughly corresponds to 10^{-7} annual probability and is significantly lower than the design value of the plant against high sea water level. The evaluations related to high sea water level are presented in [16], [17], [18] and [19].

Meteotsunamis (meteorological tsunamis caused by moving air pressure disturbance above the sea) have been actively studied by the Finnish Meteorological Institute within the SAFIR2018. According to the current understanding, the impact of meteotsunamis is considered low; the maximum meteotsunami height is limited in the Finnish coast and in the Hanhikivi site, and no significant dependency has been identified between high sea water level and the occurrence of meteotsunami [20].

The probability of an accidental airplane crash to the Hanhikivi site was estimated based on the locations of nearby airports and flight routes. Although the probability of the accidental crash was estimated small ($< 10^{-8}$/y), the plant is designed to withstand the crash of a large commercial airplane in accordance with the requirements of the YVL Guide A.11.

Several seismic hazard studies have been performed for the Hanhikivi site. The most comprehensive study, involving many experts and organizations from Finland and Sweden, was performed in 2013-2015 and updated in 2017-2018. The determination of seismic source areas is presented in [21]. In addition to the seismic hazard curve, the seismic ground response spectrum corresponding to the 10^{-5} annual probability was calculated. The logic tree used in the probabilistic seismic hazard assessment is presented in Figure 4 [22]. The first level of the logic tree includes two possible seismic source area models, and levels 2 and 3 take into account the uncertainty in the seismic activity parameters. On level 4, different possibilities for maximum magnitude are assumed, and on level 5, two ground motion prediction equations [23] [24] are considered.

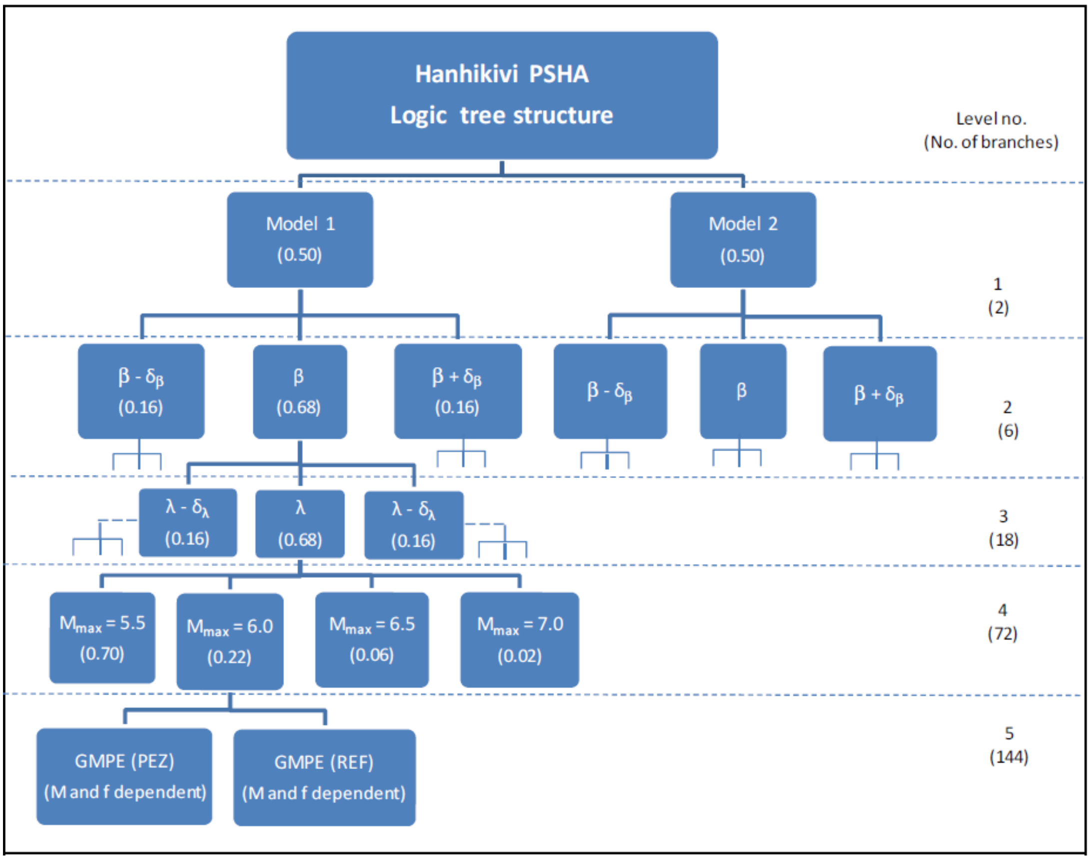

Figure 4: Seismic logic tree utilized in the probabilistic seismic hazard assessment for the Hanhikivi site [22].

A separate study was performed to evaluate the probability and duration of loss of offsite power [25]. Both technical failures and extreme weather conditions including lightning, strong wind, tornadoes, downbursts, freezing rain, wildfires, extreme temperature and heavy rainfall were considered as possible causes of external grid failure. Considering both 400 kV and 110 kV power lines, the frequency for a weather related power line failure was assessed to be $1.81 \cdot 10^{-2}$/y.

As mentioned in Section 3.2, a hazard curve was estimated for the lightning peak current in a 1 km^2 area. High targets are more probably hit by lightning, and thus a more detailed study was performed to evaluate the building specific lightning strike probabilities. The method used in the assessment is presented in [26]. Obviously the highest structures, the ventilation stack and the reactor building, are the most probable targets of a lightning strike.

3.4. External event combinations

External events relevant to nuclear safety were identified and evaluated based on the method and process defined in Figure 2. The following external event combinations were considered relevant (for more details, see [1] and [2]):

- High current lightning stroke + LOOP
- Heavy rainfall + LOOP
- Loss of ultimate heat sink + LOOP
- Loss of ultimate heat sink + LOOP + Snowfall
- Heavy snowfall + LOOP
- Low sea level + LOOP
- High current lightning stroke + Heavy rainfall
- High sea level + Waves
- High sea level + Waves + LOOP
- High air temperature + High sea water temperature

A majority of the identified combinations include loss of offsite power (LOOP), which is resulting from the fact that the external grid is more vulnerable to external events than the nuclear power plant.

3.5. Design values

Detailed design values were determined for external events for which hazard curves could be evaluated based on measured time series. Design values were specified for the following events: high and low air temperature, high enthalpy, strong wind, tornado, downburst, precipitation, snow load and snow depth, lightning stroke peak current, high and low sea water level, high sea water temperature and earthquake peak ground acceleration (PGA).

For the remaining external events in categories I and II (Table 2 and Table 3), design values were not specified. Nevertheless, also these events are considered in the plant design.

3.6. External event PRA

In the external event PRA, all single external events in category I and relevant external event combinations listed in Section 3.4 were considered as possible initiating events. The impacts of the events on plant safety were assessed. When possible the evaluation was performed separately for different hazard levels: below design values, between design and DEC C values and above DEC C values.

Obviously, no significant effects were identified in conditions below the design values since all safety significant systems, structures and components are designed to withstand these conditions. Nevertheless, loss of offsite power may result from strong wind, tornado, downburst or lightning. The plant site may also be isolated due to heavy snowfall, but the consequences of the isolation are minor because the plant is designed to be self-sufficient for a 72-hour period.

When exceeding the design values, the impact on plant safety is still minor since the systems, structures and components important to safety shall withstand also the more severe DEC C conditions.

In addition to the loss of offsite power and plant isolation, reactor trip may occur for example due to high air temperature if the operating conditions of some systems are exceeded. In addition, sea water cooling may be lost if the sea water level is exceptionally low.

When exceeding the DEC C values, passive heat removal systems included in the AES-2006 plant design may be operable, depending on the event. In certain events, core damage is conservatively assumed as detailed evaluation of the consequences is difficult in the plant design phase. Later during construction, it is possible to evaluate in more detail for example the effects of strong wind on individual buildings. In any case, the probability of exceeding the DEC C conditions is extremely small. The accident sequences including less severe conditions together with simultaneous, independent failure of safety systems may be more significant from the risk point of view.

In addition to the single external events, also event combinations with probability higher than 10^{-9}/y were modelled in the PRA as initiating events.

Based on the evaluation of different external hazards and hazard levels, the following external initiating events were modelled in the preliminary design-phase PRA:

- HAZ_TEMP_1: Loss of power supply sections as a result of high air temperature
- HAZ_SEA_LEV: Loss of heat removal due to low sea water level
- HAZ_SEA_L+W: Loss of heat removal due to low sea water level + strong wind causing LOOP
- HAZ_LIGHTNING: Loss of normal power supply and active systems due to high current lightning
- HAZ_AIRCRAFT: Accidental crash of a large aircraft
- HAZ_INTAKE_1: Loss of ultimate heat sink due to blockage of sea water intake
- HAZ_SNOW: Heavy snowfall causing blockage of air intakes and strong wind causing LOOP
- HAZ_INTAKE_2: Loss of ultimate heat sink due to blockage of sea water intake and strong wind causing LOOP
- HAZ_INTAKE_3: Loss of ultimate heat sink due to blockage of sea water intake, strong wind causing LOOP and heavy snowfall causing blockage of air intakes
- HAZ_TORNADO_1: Fujita class F4 or F5 tornado
- HAZ_WAVE_1: High sea water level, strong wind from west and waves causing flooding of buildings (for example emergency diesel building)
- HAZ_WAVE_2: High sea water level, strong wind from south and waves causing flooding of buildings (for example emergency diesel building, station blackout diesel building and pumping station)

4. CONCLUSION

In this paper, the evaluations of external events for the Hanhikivi nuclear power plant site were presented. Hanhikivi is a new nuclear power plant site, and thus it was necessary to perform comprehensive evaluations starting from the identification of the relevant events and continuing with detailed probability evaluation. Hazard curves were determined whenever measured time series were available. The main target of the external event evaluations has been to provide information for determining the design values of the Hanhikivi 1 nuclear power plant and to develop the external event PRA to provide insights about the risk significance of different external events.

The probability evaluations covering extremely rare events with return periods of millions of years always include major uncertainties. The probability estimates need to be extrapolated from measurement data with a typical time period of 50-100 years, and also the choice of the statistical distribution to be fitted into the data has a significant impact on the results.

Currently only a preliminary version of the Hanhikivi 1 design-phase PRA has been developed. Thus, the results presented in this paper shall be considered preliminary. The external event PRA will be updated when the design-phase PRA is completed in 2019. Furthermore, more detailed evaluation can be performed later during plant construction when more detailed plant specific information is available.

The scope and level of detail of the external event evaluations conducted for the Hanhikivi site can be considered generally sufficient. However, it is necessary to update the evaluations at regular intervals by taking into account the most recent measurement data and possible new knowledge related to different events.

Acknowledgements

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