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Original Article

Identification and Analysis of External Event Combinations for Hanhikivi 1 PRA

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ABSTRACT

Fennovoima's nuclear power plant, Hanhikivi 1, Pyhäjoki, Finland, is currently in design phase, and its construction is scheduled to begin in 2018 and electricity production in 2024. The objective of this paper is to produce a preliminary list of safety-significant external event combinations including preliminary probability estimates, to be used in the probabilistic risk assessment of Hanhikivi 1 plant. Starting from the list of relevant single events, the relevant event combinations are identified based on seasonal variation, preconditions related to different events, and dependencies (fundamental and cascade type) between events. Using this method yields 30 relevant event combinations of two events for the Hanhikivi site. The preliminary probability of each combination is evaluated, and event combinations with extremely low probability are excluded from further analysis. Event combinations of three or more events are identified by adding possible events to the remaining combinations of two events. Finally, 10 relevant combinations of two events and three relevant combinations of three events remain. The results shall be considered preliminary and will be updated after evaluating more detailed effects of different events on plant safety.

1. Introduction

Fennovoima's nuclear power plant, Hanhikivi 1, Pyhäjoki, Finland, is currently in design phase, and its construction is scheduled to begin in 2018 and electricity production in 2024. To apply the construction license, a design-phase probabilistic risk assessment (PRA) shall also be developed. The PRA of a nuclear power plant shall include all initiating events that could endanger the safe operation of the plant, including external events related to natural phenomena and man-made hazards. These external events could occur simultaneously and cause more severe consequences than single events. The importance of external event combinations has been identified in international guides and in the Finnish YVL guides, but methods for identifying event combinations and evaluating their probabilities are not presented. The objective of this paper is to develop a practical method for identifying event combinations and providing rough probability estimates for the relevant events. This method is applied in practice to the Hanhikivi nuclear power plant site, and thus the outcome of this paper is the list of relevant external event combinations with preliminary probability estimates for the Hanhikivi site. The probability estimates presented in this paper are preliminary and based on simplified methods. The most

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important event combinations should be evaluated in more detail later when the plant design evolves.

The single external events relevant at the site have been identified earlier. Furthermore, the probabilities (hazard curves) of the single events have been estimated with the support of Finnish Meteorological Institute and Swedish Meteorological and Hydrological Institute. These evaluations are used as input information for this work.

2. Material and methods

2.1. *Guides and standards*

The Finnish nuclear regulatory guides—the YVL guides—present no specific requirements related to the evaluation of combined external events. The YVL guide B.7 related to internal and external events states that the dependencies between natural phenomena shall be considered in the PRA [1]. External event combinations are not mentioned in the YVL guide A.7 related to PRA [2]. In the international guides and standards, the combined external events are rarely mentioned. The International Atomic Energy Agency SSG-3 states that external event combinations shall be considered, but no methodologies are described or referred [3]. A short method description for combined external event evaluation is given by Knochenhauer and Louko [4].

2.2. *Methods*

The method for creating a list of relevant event combinations for the PRA of Hanhikivi 1 plant is presented in Fig. 1. The method includes similar elements to those described by Knochenhauer and Louko [4].

A list of relevant single events with probability estimates shall be available prior to analyzing event combinations. Based on the single events, combinations of two events are identified and analyzed. A large share of the two-event combinations can be excluded using the following screening criteria. (1) Independent events: some of the selected events have no dependency with any of the other selected events and can be excluded from further event combination analysis. (2) Seasonal variation: some events have a strong seasonal variation and events occurring in different seasons cannot form a relevant combination. (3) Exclusive preconditions: certain events require specific preconditions related to weather and sea conditions, and events that have opposite preconditions cannot form a relevant combination. (4) Similar effects: the effects of some events are very similar, and it can be stated that if the first event has occurred, no further consequences are caused by the second event. These event combinations do not need to be considered. However, the event combination might still be relevant if the combined effect is significantly greater than the effect of a single event.

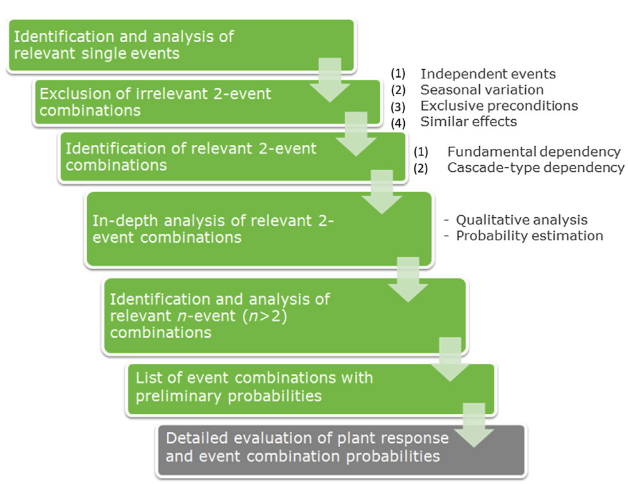


Fig. 1 – Identification and evaluation of event combinations in the Hanhikivi 1 probabilistic risk assessment (PRA).

After the obvious irrelevant combinations have been excluded, the remaining two-event combinations shall be considered one by one. A combination of events is assumed relevant only if the occurrence of the events is dependent. If two (rare) events occur independently, their combined occurrence can be estimated so improbable that the combination can be considered insignificant. Two types of dependencies are looked for: (1) fundamental dependency, the occurrence of events is related to same basic phenomenon or events are created by the same mechanism and (2) cascade-type dependency, the first event may inflict or strengthen the second event, increase its probability, or worsen its effect.

All the identified potentially relevant combinations of two events are analyzed in detail. If a combination is still considered relevant after qualitative assessment, the probability of the event combination is determined by using the probability estimates of the single events. The event with a lower probability is assumed to have occurred and the conditional probability for the other event to occur simultaneously is estimated. An event combination may be considered a relevant initiating event if it exceeds the general cutoff frequency (10^{-8}/y) used in the PRA. However, a lower cutoff frequency (10^{-9}/y) shall be applied if the conditional core damage probability after the event combination is assumed to be close to 1.

After the list of relevant two-event combinations is completed, event combinations with more than two events are identified by recognizing groups of events that are all dependent on each other. In practice, the two-event combinations (Events A and B) are browsed through, and in each case it is evaluated if an additional event (C) can be found that has a dependency with both events A and B. Similarly, event combinations including more than three events can be identified.

3. Results

3.1. *Single event analysis*

The relevant single external events that possibly need to be included in the Hanhikivi 1 PRA have been identified earlier by Helander [5]. (1) Meteorological events: air humidity, downburst, freezing rain, high or low air temperature, lightning, rain, snow, strong wind, trombs (tornadoes). (2) Sea-related events: algae or other organic material, frazil ice, high or low seawater level, high seawater temperature, meteotsunamis, oil spills, sea ice, waves. (3) Other events: earthquakes, geomagnetic currents, wildfires.

3.1.1. *Independent events*

The following events can be assumed independent of any other events: earthquakes and geomagnetic currents.

Earthquakes are related to sudden release of energy in the Earth's crust and are thus independent from any natural or man-made events occurring on the Earth's surface or atmosphere.

Geomagnetic currents are caused by highly energetic particles ejected from the sun (solar wind), which also create the aurora borealis. Space weather is independent from any events that originate on the Earth's surface or atmosphere.

3.1.2. *Seasonal variation*

The seasonal variation of each event is analyzed based on measurement data from nearby weather stations, weather simulations, documented observations, and expert judgment. In this paper, detailed evaluation of air temperature is presented, and for other events, only the end result is shown in Table 1.

Seasonal variation of air temperature according to Oulu weather station (roughly 80 km from the Hanhikivi site) measurements is presented in Fig. 2. The warmest month is July, and the coldest month is January. In general, warm temperatures can be expected between June and August and cold temperatures between December and February.

The relative occurrence of different external hazards during different months is presented in Table 1. High relative probability (++) indicates peak occurrence month(s). Moderate relative probability (+) indicates that the probability of occurrence is in the order of 10% when compared to the peak month. Low relative probability (–) indicates that the probability of occurrence is in the order of 1% when compared to the peak month. During other months, the relative probability is very low, and the event is practically nonexisting.

3.1.3. *Event preconditions*

Natural events related to atmosphere and sea typically require certain simple preconditions. The preconditions analyzed in this report are: air temperature (at ground level) above or below zero, wet/rainy or dry conditions, and open sea or sea covered by an ice sheet. Table 2 presents the preconditions required by different events.

Humid air requires high temperature because hot air can include more water vapor than cold air. Downbursts and trombs are typically related to thunderstorms, which require an adequate air temperature and are nearly always accompanied by rainfall. High air temperature requires dry conditions because rainfall cools down the air and direct sunlight cannot heat the Earth's surface because of the clouds. Frazil ice is formed most probably when the heat transfer from air to sea is efficient (cold air temperature, no sea ice sheet, and strong wind). High and low sea level require open sea because sea level fluctuations are significantly smaller when the sea is covered by ice and no interaction with wind is possible.

3.1.4. *Plant effects*

Table 3 includes some general plant effects related to different events based on the listing presented in [4]. These general effects are assumed in this paper, and more detailed effects of safety-significant event combinations will be evaluated later.

Structural effect can impact different plant parts, such as building roofs and walls, switchyards, or sea structures, depending on the event.

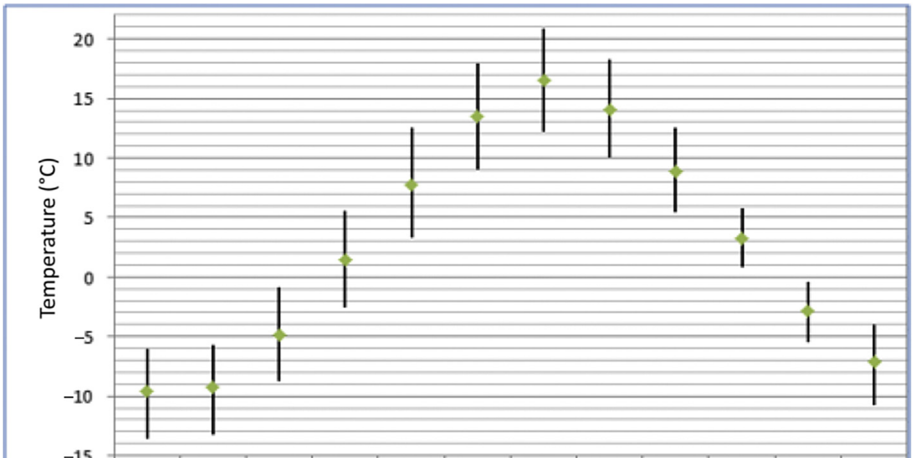
Ventilation can be affected by different mechanisms. Humid and hot conditions weaken the heat transfer capacity; the air intakes could be blocked by freezing rain, snow, or material detached by downburst or trombs; low air temperature could lower the room temperatures; pressure differences caused by strong winds might disturb the air movement; and dense smoke could enter the intakes if a fire occurs nearby.

The loss of heat sink could result if strong winds, downbursts, or trombs blow material into the cooling water intake

Table 1 – Relative monthly probabilities of external events.

	Event	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Air humidity					–	+	++	++	–			
2	Downburst					–	+	++	++	–			
3	Freezing rain	+	+	++	++	++	–			–	++	++	+
4	High air temperature					–	++	++	++	–			
5	Lightning				–	+	++	++	++	+	–		
6	Low air temperature	++	++	+	–						–	+	++
7	Rain	–	–	–	–	+	++	++	++	++	++	+	–
8	Snow	++	++	++	+	–				–	+	++	++
9	Strong wind	++	+	+	+	+	–	–	–	+	++	++	++
10	Trombs (tornadoes)				–	–	+	++	++	+	–	–	
11	Algae	–	–	–	–	+	+	+	+	++	++	++	+
12	Frazil ice	+	+	+	–						–	+	++
13	High sea level	++	++	+	–	–	–	–	–	+	++	++	++
14	High sea temperature						–	++	++	–			
15	Low sea level	++	++	++	++	++	+	+	+	+	++	++	++
16	Meteotsunami	–	–	–	+	++	++	++	++	+	+	+	–
17	Oil spill	+	+	+	+	+	+	+	+	+	+	+	+
18	Sea ice	++	+	+	++	+	–				–	+	++
19	Waves	–			–	+	–	–	–	+	++	++	+
20	Wildfires				+	+	++	++	++	+	+		

++, high; +, moderate; –, low.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily max	−6	−5.7	−0.9	5.6	12.5	17.9	20.9	18.3	12.5	5.8	−0.4	−4
Daily mean	−9.6	−9.3	−4.8	−1.4	−7.8	−13.5	16.5	14.1	8.9	3.3	−2.8	−7.1
Daily min	−13.6	−13.3	−8.8	−2.6	3.3	9	12.2	10.1	5.4	0.8	−5.5	−10.8

Fig. 2 – Average daily maximum, mean, and minimum temperatures in Oulu.

or because of low seawater level or high seawater temperature. The intake screens could also be blocked by algae, ice, or oil.

Loss of offsite power could be caused by different phenomena that cause structural or functional damage to grid components. Excessive wind, snow, and ice loads could cause damage to grid structures, and grid components could also fail because of lightning strikes, low air temperature, and heat or smoke from wildfires.

The source of flooding can be rainfall or high sea level, which may be worsened by simultaneous bottom or surface waves.

3.2. *Identification of relevant event combinations*

Table 4 presents the relevant event combinations identified for the Hanhikivi nuclear power plant site according to the method described in Section 2.2. The irrelevant event combinations are identified (seasonal variation, exclusive preconditions, similar effects). After the exclusion of irrelevant combinations, the remaining two-event combinations are considered one by one to identify dependencies (fundamental dependency, cascade-type dependency). Several event combinations could not be excluded, but also no dependency was found. These combinations can be considered irrelevant.

Table 2 – Preconditions of external events.

	Event	Air > 0°C	Air < 0°C	Wet/rainy	Dry	Open sea	Ice sheet
1	Air humidity	×					
2	Downbursts	×		×			
3	Freezing rain		×	×			
4	High air temperature	×			×		
5	Lightning	×		×			
6	Low air temperature		×				
7	Rain	×		×			
8	Snow		×	×			
9	Strong wind						
10	Trombs	×		×			
11	Algae (or other)						
12	Frazil ice		×			×	
13	High sea level					×	
14	High sea temperature	×				×	
15	Low sea level					×	
16	Meteotsunami					×	
17	Oil spill						
18	Sea ice						×
19	Waves					×	
20	Wildfires	×			×		

Table 3 – The general plant effects related to different external events.

	Event	Structure/ pressure	Structure/ missiles	Ventilation	Heat sink	LOOP	Flood	Electric	Other
1	Air humidity			×					
2	Downbursts	×	×	×	×	×			
3	Freezing rain			×		×			
4	High air temperature			×					
5	Lightning	×				×		×	
6	Low air temperature			×		×			Freezing of equipment & material
7	Rain	×					×		
8	Snow	×		×		×			Plant isolation
9	Strong wind	×	×	×	×	×			
10	Trombs (tornadoes)	×	×	×	×	×			
11	Algae				×				Seawater cooling of equipment
12	Frazil ice				×				Seawater cooling of equipment
13	High sea level	×					×		Plant isolation
14	High sea temperature				×				Seawater cooling of equipment
15	Low sea level				×				Seawater cooling of equipment
16	Meteotsunami	×					×		
17	Oil spill				×				Seawater cooling of equipment
18	Sea ice	×			×				Seawater cooling of equipment
19	Waves	×					×		
20	Wildfire			×		×			

LOOP, loss of offsite power.
Note. Adapted from "SKI report 02:27, Guidance for external events analysis," by M. Knochenhauer, P. Louko, 2003, The Swedish Nuclear Inspectorate.

3.3. *Probability evaluation*

In this paper, the detailed probability evaluation is presented for the combination of strong wind and algae. For other combinations, only the estimated probabilities are presented.

3.3.1. *Strong wind and algae*

According to probability estimations based on measurement data from nearby weather stations [6], the gust wind speed (3 seconds) exceeds 30 m/s with a probability of 3×10^{-2}/y. A wind this strong can create high waves and rough sea conditions that detach sea vegetation and accumulate it to the seawater intake. The probability for exceeding grid design basis 39 m/s is 2×10^{-4}/y.

According to experiences from power plants operating in the Bothnian Bay coast near Hanhikivi, the probability of a significant algae occurrence (an event that could cause loss of seawater cooling if no countermeasures are taken) in Hanhikivi is 1.05×10^{-2}/y [7].

The peak occurrence of both wind and algae is in the late autumn. If the wind blows to the east, large amounts of algae may be accumulated to the seawater intake and in the seawater system. The breakwaters around the seawater intake port may somewhat decrease the amount of algae that travels inside the intake port.

On average, the sea is covered by ice in Hanhikivi from mid-December to early May [8]. We may assume that wind cannot remove and carry large amounts of algae during this period. According to Fig. 3, roughly 50% of the annual wind maxima have occurred during this period and 50% during the rest of the year. The wind direction should be from SW-N so that it travels algae toward Hanhikivi. The probability for this is roughly 60% according to wind measurements and statistics. In the case of strong wind between May and December blowing from SW-N, we may conservatively assume that large amounts of algae and sea vegetation are accumulated near the seawater intake with a probability of 50%. Now, we may calculate the probability for simultaneous strong wind (gust speed, > 30 m/s) and heavy algae occurrence:

$$3 \times 10^{-2}/\text{y} \times 0.50 \times 0.60 \times 0.50 = 4.5 \times 10^{-3}/\text{y} \quad (1)$$

Similarly, we may calculate the probability for simultaneous strong wind leading to loss of offsite power (gust speed > 39 m/s) and heavy algae occurrence:

$$2 \times 10^{-4}/\text{y} \times 0.50 \times 0.60 \times 0.5 = 3.0 \times 10^{-5}/\text{y} \quad (2)$$

3.3.2. *Event combination probabilities*

The event combinations of two events presented in Section 3.2 were quantified based on Hanhikivi site-specific studies (e.g., [6–9]). Combinations were excluded from further evaluation if

Table 4 – Exclusion of irrelevant event combinations[a] and the identification of dependent combinations.[b]

Event	1 Air hum.	2 Down-burst	3 Fr. rain	4 High air temp.	5 Light.	6 Low air temp.	7 Rain	8 Snow	9 Str. wind	10 Tromb	11 Algae	12 Fraz. ice	13 High sea level	14 High sea temp.	15 Low sea level	16 Meteo-tsun.	17 Oil spill	18 Sea ice	19 Waves
1 Air humidity																			
2 Downburst																			
3 Freezing rain	bc	bc																	
4 High air temp.	ii	c	bc																
5 Lightning		i	c	c															
6 Low air temp.	bc	bc	c	bc	bc														
7 Rain		i	c	c	i	c													
8 Snow	bc	bc	i	bc	bc		c												
9 Strong wind	b	bd		b	i	ii	i	ii											
10 Tromb		d	bc	c	i	bc	i	bc	d										
11 Algae									ii										
12 Frazil ice	bc	bc		bc	bc	ii	c		ii	bc	d								
13 High sea level	b	b		b					ii										
14 High sea temp.			bc	ii		bc		bc	b		d	bcd	b						
15 Low sea level									ii		d	d	c	d					
16 Meteo-tsunami					i		i		ii				ii		ii				
17 Oil spill									ii		d	d		d	d				
18 Sea ice	b	b		b		ii			ii	b	d	cd	c	bcd	cd	c	d		
19 Waves	b	b		b					ii				ii	b	c		ii	c	
20 Wildfires	c	c	c	ii	c	bc	c	c	ii	c		bc						c	

Fr., freezing; Fraz., frazil ; hum., humidity; Light., lightning; Str., strong; tsun., tsunami.
[a] b, seasonal variation; c, exclusive preconditions; d, similar effects.
[b] i, fundamental dependency; ii, cascade-type dependency.

the probability estimate was below 1×10^{-8}/y. In addition to the combinations of two events, the following combinations of three events were identified: Wind + Snow + Algae, Wind + Snow + Frazil ice, and Wind + Snow + Sea ice. The final list of relevant event combinations with probability estimates is presented in Table 5.

4. Discussion

A systematic method was used to identify the relevant external event combinations in the Hanhikivi nuclear power plant site. All relevant external events were considered, and thus it is considered improbable that any relevant combinations would be missing. The results can be considered anticipated and consistent with the external event combinations modeled in the existing PRAs of the operating Finnish nuclear power plants. However, there are several differences because of specific conditions at the Hanhikivi site, such as thick sea ice conditions during late winter.

When analyzing the list of relevant event combinations, it can be noted that strong wind is included in almost each combination. This was expected because strong wind is a common phenomenon. Although it is highly unlikely that the plant design basis is exceeded, already weaker wind may cause certain consequences, such as loss of offsite power. Furthermore, wind is a phenomenon that has a tendency to trigger or worsen the effect of other events, such as snowstorm, algae occurrence, or frazil ice.

The event combinations estimated most probable are wind > 30 m/s together with algae and wind > 30 m/s together with snowstorm. The high probability of these events was anticipated, and sufficient provisions have been taken in the nuclear power plant design to prepare for the possible consequences related to these events, such as loss of offsite power, blockage of air intakes, and loss of the primary ultimate heat sink (the sea). Although the wind speed of 30 m/s can be considered strong, the effects on nuclear power plant

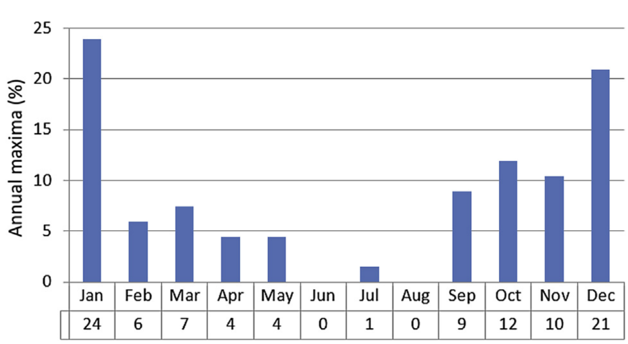


Fig. 3 – Monthly distribution of annual 10 min mean wind speed maxima in Oulu in 1960–2010.

Table 5 – Preliminary list of event combinations with probability estimates for the Hanhikivi site.

Event 1	Event 2	Event 3	Prob. (/y)
High air humidity	High air temperature	–	[a]
Lightning (power line area)	Downburst F1–F3	–	1.2×10^{-7}
Lightning (power line area)	Wind > 30 m/s	–	1.0×10^{-8}
Wind > 30 m/s	Low air temperature <−35°C for 24 h	–	1.7×10^{-6}
Wind > 30 m/s	Rain > 200 mm in 24 h	–	1.8×10^{-8}
Wind > 30 m/s	Snow	–	2.1×10^{-3}
Wind > 39 m/s	Snow	–	1.4×10^{-5}
Wind > 30 m/s	Algae	–	4.7×10^{-3}
Wind > 39 m/s	Algae	–	3.1×10^{-5}
Wind > 30 m/s	Frazil ice	–	2.6×10^{-4}
Wind > 39 m/s	Frazil ice	–	1.7×10^{-6}
Wind > 39 m/s	Oil spill	–	1.2×10^{-6}
Wind > 30 m/s	Sea ice	–	9.5×10^{-6}
Wind > 39 m/s	Sea ice	–	6.3×10^{-8}
Wind > 30 m/s	Snow	Algae	2.8×10^{-4}
Wind > 39 m/s	Snow	Algae	1.9×10^{-6}
Wind > 30 m/s	Snow	Frazil ice	2.6×10^{-5}
Wind > 39 m/s	Snow	Frazil ice	1.7×10^{-7}
Wind > 30 m/s	Snow	Sea ice	1.1×10^{-6}

[a] The combination of high air humidity and temperature, i.e., high enthalpy, has been evaluated separately by Saku and Jylhä [9].

operation are probably small, and it might be possible to exclude this external event from consideration after evaluating detailed effects on the plant from external events with different magnitude.

In general, the risks related to the external event combinations can be considered acceptable. The probabilities of event combinations that would cause an initiating event are relatively small. In addition, according to the preliminary PRA results, the conditional core damage probabilities related to single external events and event combinations are sufficiently small.

5. Conclusion

In this paper, all safety-significant combinations of external events that could occur simultaneously in the Hanhikivi site were identified, and preliminary probability estimates were also calculated. A method based on qualitative and quantitative measures was developed and applied to identify the potentially relevant combinations.

The initial list of relevant single events included 22 events, from which 14 relevant combinations of two events and five relevant combinations of three events were identified.

The list of relevant event combinations presented in this paper can be considered preliminary and shall be refined after the detailed effects on plant safety resulting from different events have been analyzed. Once the most significant event combinations have been identified, it is also recommended to perform a more detailed probability estimation for each combination by using more sophisticated statistical or meteorological analysis.

Conflicts of interest

The author certifies that there are no conflicts of interest.

Acknowledgments

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REFERENCES

[1] Finnish Radiation and Nuclear Safety Authority, YVL Guide B.7, Provisions for internal and external hazards at a nuclear facility [Internet]. 2013. Available from: https://www.stuklex.fi/en/ohje/YVLB-7.

[2] Finnish Radiation and Nuclear Safety Authority, YVL Guide A.7, Probabilistic risk assessment and risk management of a nuclear power plant [Internet]. 2013. Available from: https://www.stuklex.fi/en/ohje/YVLA-7.

[3] International Atomic Energy Agency, SSG-3, Development and application of level 1 probabilistic safety assessment for nuclear power plants [Internet]. 2010. Available from: www-pub.iaea.org/MTCD/publications/PDF/Pub1430_web.pdf.

[4] M. Knochenhauer, P. Louko, SKI Report 02:27, Guidance for External Events Analysis, The Swedish Nuclear Inspectorate, Kungsängen, Sweden, 2003.

[5] J. Helander, External Hazard PRA — Summary on Studies Performed and Identification of Further Study Needs, Fennovoima, Helsinki, Finland, 2013.

[6] M. Laapas, O. Hyvärinen, Extreme Value Analysis of Average and Gust Wind Speed for Pyhäjoki Region, The Finnish Meteorological Institute, Helsinki, Finland, 2014.

[7] H. Simpanen, Study of Power Plant Cooling Incidents in the Bothnian Bay Area, Pöyry Finland Oy, Helsinki, Finland, 2014.

[8] P. Alenius, Supon aiheuttaman vedenottamon tukkeutumisen estäminen, Analyysiä supon esiintymisriskistä Hanhikiven alueella [Analysis of Frazil Ice Occurrence in the Hanhikivi Area], The Finnish Meteorological Institute, Helsinki, Finland, 2014 [in Finnish].

[9] S. Saku, K. Jylhä, Extremes of Enthalpy in the Surroundings of the Pyhäjoki Region based on Observations and Future Projections, The Finnish Meteorological Institute, Helsinki, Finland, 2014.